LA. 1851

July 1980

An Assessment of Geothermal Development in the Imperial Valley of California

MASTER

*Volume 1 - Environment, Health
and Socioeconomics*

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Printed in the United States of America

Available from

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

NTIS price codes

Printed Copy: ^{14.10}~~\$10.75~~
Microfiche Copy: \$ 3.50

An Assessment of Geothermal Development in the Imperial Valley of California

Volume 1 - Environment, Health and Socioeconomics

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Office of the Assistant Secretary for Environment
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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 one of two comprising the final assessment report.

An Assessment of Geothermal Development in the Imperial Valley of California:

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.

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ACKNOWLEDGMENTS

We would like to thank the many individuals who provided us with technical information and reviews as we prepared the assessment of geothermal development in the Imperial Valley. We are particularly grateful for J. Hill, K. Pimentel, P. Gudiksen, D. Helm, J. Hanson, W. Martin, R. Ireland, and others at Lawrence Livermore National Laboratory who provided us with various kinds of technical support. Without such support, the assessment would have been difficult, if not impossible, to complete. We also acknowledge the assistance we received from Calvin Jackson and Lowell Miller of the San Francisco Operations Office (DOE). Their guidance and support, which continued throughout the life of the IVEP, was especially helpful. Finally, we appreciate the help and cooperation of the Department Heads of Imperial County. Special thanks are extended to David Pierson, Director of Public Works, for his support of the IVEP.

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ABSTRACT

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.

The most important impacts examined in the assessment involved air quality changes resulting from emissions of hydrogen sulfide, and increases in the salinity of the Salton Sea resulting from the use of agricultural waste waters for power plant cooling. If H_2S emissions are not abated, then the California air quality standard (30 ppbv, 1-h average) will be exceeded over a large fraction of the valley, based on a scenario of 3000 MW of development. Emissions would have to be abated to below 30 g/MWh to prevent violations of the H_2S standard. Power plants in the Salton Sea and Brawley resource areas would have to reduce emissions by approximately 82% to achieve that emission rate. Even if ambient levels of hydrogen sulfide are kept below the California standard, odor problems may not be eliminated because about 50% of the population can detect hydrogen sulfide at concentrations of 3 to 9 ppbv. Hydrogen sulfide, on the other hand, will have a fertilizing effect on crops grown in the valley. However, for enhanced growth to be significant, ambient levels would actually have to exceed the ambient air quality standard.

Extensive withdrawals of agricultural waste waters to support geothermal development will accelerate increases in the Salton Sea's salinity, putting added stress on its quasi-marine ecosystem. Large withdrawals of waste waters would not be necessary if steam condensate was used as the sole source of cooling water for flashed-steam power plants. At the present time, though, a county policy favors the full injection of withdrawn geothermal fluids in order to protect against land subsidence, and

therefore external sources of water will probably be needed for geothermal operations. For the most part, geothermal activities will be compatible with irrigated agriculture, but negative impacts of a site-specific nature caused by land subsidence, cooling tower drift, or accidental spills of geothermal fluids could occur. These effects should be the subject of further field studies when demonstration-type geothermal facilities are implemented in the valley.

Liquid and solid wastes will be produced from geothermal power plants, and such wastes will have to be disposed in ways that are environmentally acceptable. Residual geothermal fluids are the primary source of liquid wastes; these fluids will be disposed by subsurface injection to geothermal reservoirs. The reliability of geothermal power plants will depend a great deal on the ability of injection facilities to dispose large quantities of fluids (e.g., in excess of 30 kg/kWh) for long periods of time. Solid wastes will result from well drilling, the removal of suspended solids in spent brines prior to injection, scale removal, and hydrogen sulfide abatement. As much as 2000 acre-feet of these potentially toxic wastes could be produced with 3000 MW of geothermal energy production by the year 2010. Surface disposal sites will be needed to receive the solid wastes.

The socioeconomic consequences of future geothermal development will generally be beneficial. The county's economy will expand, and revenues from geothermal developments are expected to exceed the costs to local governmental units (i.e., county government and school districts). An exception would be cities in the valley. Their jurisdictions do not include areas where power plants will be sited, and consequently, cities may not be able to obtain revenues to offset costs associated with services that they may have to provide to new residents. Geothermal development may not help to reduce the county's high unemployment rate unless job training programs are introduced to provide workers with appropriate job skills.

To verify the impacts predicted in the assessment and to detect other impacts as they occur, post-operational environmental monitoring and effects studies are recommended. In particular, geothermal fluids should be chemically analyzed periodically to determine if the concentrations of different substances vary through time, and thus change the nature of potential environmental impacts. Data on air quality and water quality

should also be collected periodically to preserve the validity of previous measurements and to determine changes. Monitoring of subsidence and seismicity should continue to provide relevant time-series data.

SECTION 1. INTRODUCTION

This report provides a predictive assessment of the potential environmental and socioeconomic effects of developing the hydrothermal resources in Imperial Valley, California. This assessment is one of the major products of the Imperial Valley Environmental Project (IVEP), which was established by the Assistant Administrator for Environment and Safety of the U.S. Energy Research and Development Administration (ERDA).^{*} This study was initiated as the result of a contractual relationship between the ERDA Division of Geothermal Energy and the San Diego Gas & Electric Co. to build and operate a Geothermal Loop Experimental Facility near Niland in the northern part of Imperial Valley. This contract [No. E(04-3)-1137] included the statement:

"ERDA agrees to sponsor a coordinated baseline environmental study and assessment of the Imperial Valley. This baseline environmental study will consist of collecting and compiling existing data on the physical, biological and socio-economic environment of the Imperial Valley geothermal resources areas. In addition, field studies and measurements will be conducted to verify existing information and to provide data where deficiencies exist. The environmental studies will include a preliminary assessment using conceptual plant designs of substantial (500 MW electric) geothermal utilization development at each of the four major KGRA's. ERDA will structure the baseline and environmental study and assessment to provide the maximum feasible input data needed to support SDG&E's site qualification process. ERDA with SDG&E assistance will explore the possibility of participation by other agencies, public and private, in the environmental study program."

The Environmental Sciences Division of the Lawrence Livermore National Laboratory (LLNL) was given the responsibility to fulfill the above commitment on the ERDA's behalf, and to manage the IVEP. A detailed plan for the IVEP was prepared, and after approval of the plans, the IVEP was initiated in 1975. A major report (Phelps and Anspaugh, 1976) describing the project and its status has been published, and numerous additional reports have been published; these are referenced throughout this report.

The IVEP was organized under the leadership of a Project Leader and a Project Manager as an integrated project, and included the following elements:

^{*}ERDA was one of the predecessor agencies of the U.S. Department of Energy (DOE).

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

Efforts were made to achieve a broad participation in the IVEP, and coordination was achieved with all other identified studies relating to environmental and socioeconomic effects in Imperial Valley. LLNL worked closely with a number of universities and various federal, state, and local agencies and other groups to obtain the needed information. These efforts were funded in part through the IVEP. In addition, a great deal of cooperative work from other agencies was received, and in some cases their programs were reoriented to assist with problems specific to the development of geothermal resources in Imperial Valley. A summary of IVEP participants is given in Table 1-1.

In order to achieve coordination of activities and to review the plans and progress of the IVEP, an advisory panel was established and reported to the LLNL Associate Director for Biomedical and Environmental Research.

As the Department of Energy came into being in late 1977, the IVEP was continued under the auspices of the Assistant Secretary for Environment. The Socioeconomic and Integrated Assessment activities were funded through the Technology Assessments Division, Office of Technology Impacts. The other five elements were funded through the Divisions of Pollutant Characterization and Safety Research, Ecological Research, and Human Health and Assessments; Office of Health and Environmental Research. Additional support for remote sensing activities was received through the Operational and Environmental Safety Division, Office of Environmental Compliance and Overview (OECO).

This report is primarily a product of the integrated assessment activity of the IVEP, but it does draw heavily upon the results of the rest of the IVEP.

In addition to the IVEP activities discussed above, a closely related activity was sponsored by the OECO Environmental Control Technology

Table 1-1. IVEP participants. Participants in the IVEP were drawn from various county, state, and federal government agencies, universities and ERDA contract laboratories, geothermal developers, and utility companies. Involvement in the IVEP by individuals from these groups started in the early planning phases of the project. The level of participation has ranged from that of an advisor to taking a lead part in field and laboratory studies.

Imperial County	Department of Public Works Air Pollution Control District Planning Department Department of Health
State of California	Energy Resources Conservation and Development Commission Air Resources Board Water Resources Control Board Department of Health Services Department of Fish and Game
Federal	Environmental Protection Agency Fish and Wildlife Service Geological Survey Department of Agriculture National Science Foundation Bureau of Reclamation Bureau of Land Management
Universities, ERDA labs, others	California Institute of Technology St. Mary's College, Moraga University of California Battelle Pacific Northwest Laboratory Brookhaven National Laboratory E.G.&G. Electric Power Research Institute Pomona College Arizona State University California State University, Hayward North Carolina Central University
Developers	Chevron, USA, Inc. Imperial Magma Corporation Union Oil Company of California Republic Geothermal, Inc.
Utilities	San Diego Gas & Electric Company Southern California Edison Company Imperial Irrigation District

Division. This study examined all aspects of geothermal development in Imperial Valley in regard to environmental control needs, and the results are presented in a companion volume (Vol. 2) to this report.

The assessment process included the sequence of activities shown in Fig. 1-1. To start with, we obtained background information on the major attributes of the affected environment. Next, geothermal technologies were characterized according to their consumption of natural resources and their production of environmental residuals. Based on analyses of the information relevant to the affected environment and the operation of geothermal facilities, we identified potential environmental and socioeconomic impacts. Scenarios of energy production were then prepared to serve as a basis for assessments of the cumulative impacts of development. Assessments of impacts were then made, and where necessary, measures to mitigate impacts were evaluated. These activities were repeated as new information became available on baseline conditions as well as energy resources and technologies.

Fig. 1-1. Activities involved in the integrated assessment of geothermal energy production in the Imperial Valley.

We used material from existing sources (Layton and Ermak, 1976) along with environmental baseline data collected by survey groups in the IVEP to describe relevant features of the valley's land, air, water, and biological resources. Additional information on the sensitivities of various plant and animal species to pollutant stress was also obtained through the Ecosystem Quality element of the IVEP and other sources. Data on the physical and chemical properties of the geothermal fluids in the valley were obtained in order to quantify environmental residuals resulting from the operation of geothermal facilities. In addition, we made estimates of the consumption of geothermal fluids and cooling water as well as the land requirements for power plants and well fields.

After reviewing the information on the affected environment and geothermal resources and technologies, we identified a series of possible effects of geothermal operations in the Imperial Valley. Figure 1-2 shows several ways in which energy production could affect the valley's environment. The principal environmental concerns involve: (1) emission of H_2S from power plants and the effects of those emissions on crops and people, (2) possible damage to portions of the irrigation and drainage systems in the valley resulting from land subsidence caused by the extraction of geothermal fluids for power generation, and (3) the consequences of using alternative sources of water for power plant cooling. Additional concerns involve the accidental releases of geothermal fluids, the propagation of noise from geothermal operations, the nature of socioeconomic changes accompanying large-scale development, the disposal of liquid and solid wastes, and the siting of energy facilities.

To establish a basis for the assessment of the various impacts of geothermal energy production in the valley, scenarios of development were defined. These scenarios represent low, medium, and high forecasts of future growth. Analyses of cumulative impacts of development focused on the medium scenario of growth. In this scenario, energy production grows at 100 MW per yr starting in 1982 and reaches 3000 MW in 2010. Next, the impacts of geothermal operations were assessed using quantitative and qualitative techniques. We used computer models, for example, to simulate air quality

changes, water resource impacts, crop growth under pollutant stress, and land subsidence. Results of some of the modeling efforts were used in the analyses of the impacts on human health and fish and wildlife. Impacts that could not be easily quantified (e.g., the ecological effects of accidental releases of geothermal fluids) were assessed in qualitative terms. Methods of mitigating adverse impacts were then examined, and they are presented in Vol. 2.

Fig. 1-2. Diagram of some of the major environmental concerns related to geothermal energy production in the Imperial Valley.

SECTION 2. THE AFFECTED ENVIRONMENT

D. Layton

The most important attribute of the Imperial Valley is agriculture. Figure 2-1 shows the extent of agricultural lands and the location of major geothermal resource areas. Water is imported from the Colorado River to support crops grown on about 475,000 acres* of land. Drainage from agricultural lands flows into the Salton Sea via the New and Alamo Rivers. Besides being California's largest inland water body, the sea also supports a significant quasi-marine ecosystem. Another distinctive feature of the valley is tectonic activity that is reflected by active faults, earthquakes, and natural subsidence. These and other salient features of the valley are briefly summarized below.

Fig. 2-1. 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.

*Each section uses units of measure that are consistent with the units employed in the original analyses. Appendix A contains conversions for different measures used in the assessments.

AGRICULTURE

The unique climate of the valley and the availability of irrigation water from the Colorado River combine to make this area one of the most important agricultural areas of the United States (see Kercher and Buchanan, 1976). Gross revenues for field crops, vegetable crops, and livestock amount to approximately a half billion dollars annually. In 1978 the top sources of farm income were: Cattle (\$171.3 million), alfalfa (\$95.9 million), lettuce (\$75.8 million), cotton (\$53.6 million), wheat (\$37.5 million), cantaloupe (\$22.5 million), and sugar beets (\$22.2 million) (Livernois, 1979).

Normally there are less than 14 days with frost each year. The climate is such that most vegetable crops are grown in the winter months and most field crops are grown in the spring and summer months. An important problem facing irrigated agriculture in the Imperial Valley is soil salinity. To prevent soil salinities from rising to levels that severely affect the growth of crops, extra amounts of irrigation water must be applied to crops in order to leach saline water into subsurface pipe drainage systems. These systems are installed beneath nearly all of the fields in the valley. The average evapotranspiration requirement of crops is about 50 inches (Layton, 1978a), and an additional 10 to 15% is necessary for leaching, depending on soil properties and the types of crops grown. The control of weeds and insects is another important concern in the valley. To maintain the productivity of agricultural lands, large quantities of herbicides and insecticides must be applied to crops (Kercher and Buchanan, 1976).

GEOLOGY

The Imperial Valley occupies a part of the Salton Trough, a geologically-recent structural depression extending northwesterly from the Gulf of California to the upper end of the Coachella Valley. The Trough is bordered on the west by the coastal California mountains, and on the east by a series of low, block-faulted mountain ranges. It is the site of complex northwest-trending strike-slip fault zones of the San Andreas fault system. In addition to the horizontal movement of the San Andreas fault zone in this region, there is very substantial vertical movement.

Continuous subsidence of the Salton Trough for approximately the past 10 million years has provided a site for the accumulation of primarily detrital sediments as much as 6 km in thickness (Van de Kamp, 1973). These sediments consist both of outwash from the bounding mountains and deltaic sediments provided by the ancestral Colorado River, which during this entire period has discharged into the Trough from the east. The resulting sedimentary fill consists of complexly interbedded lenticular beds of sand, silt and mud of deltaic, alluvial, lacustrine and aeolian origin; it is virtually impossible to trace these beds for more than a few hundred meters. While most of the sediments are unconsolidated, thermal metamorphism associated with geothermal activity has resulted in local lithification (Muffler and White, 1969). Recent volcanism, believed to be associated with the fault systems, is known at several places in the Trough. These volcanics are believed to be the source of the heat at the geothermal anomalies in the region (Elders, 1975).

Crustal displacements in the valley have been accompanied by a great deal of seismic activity. As many as 12 earthquakes of 6.0 or higher on the Richter scale have hit the Salton Trough in this century (Palmer et al., 1975). In addition to the high magnitude quakes, many earthquakes below a magnitude of 5.0 occur in earthquake swarms.

WATER RESOURCES

Of the nearly 3 million acre feet (af) of water diverted to the valley each year, approximately 2 million af are consumed by crops, and the remaining 1 million af are discharged to the Salton Sea. To distribute irrigation water and remove unwanted waste waters, over 3000 miles of canals and drainage ditches cover the valley. Inflows to the sea from agricultural lands have generally exceeded evaporation and, consequently, the sea's surface elevation has continued to rise. The water quality in the valley ranges from about 900 mg/l total dissolved solids (TDS) for irrigation water to almost 39,000 mg/l in the Salton Sea. Natural recharge to aquifers in this arid region is low, however, millions of acre feet of water have been added to shallow aquifers on East Mesa from unlined canals.

BIOLOGICAL RESOURCES

The Imperial Valley contains important aquatic and terrestrial ecosystems. The Salton Sea, for example, supports a quasi-marine ecosystem that includes a major sport fishery consisting of orange mouth corvina and sargo. The primary stress on the ecosystem is a gradual increase in salinity due to the accumulation of salts in the sea. State and federal refuges near the southern border of the sea provide wintering areas for large numbers of migratory waterbirds traveling the Pacific Flyway. Wetlands adjacent to the sea also support small populations of the Yuma Clapper Rail, an endangered species. The desert areas on either side of the agricultural lands include plant and animal species of special interest. A rare plant known as the desert buck wheat, for example, is located on East Mesa. The Imperial Sand Hills (see Fig. 2-1), east of the Coachella Canal, is the habitat for the Andrew's dune scarab beetle, which has been proposed for threatened status (USFWS, 1978a).

SOCIOECONOMICS

The economy of Imperial County is dominated by agriculture and associated support services. While strong in agricultural sectors, the county's economy is weak in manufacturing and construction compared to the rest of the state (Layton and Ermak, 1976). Within the county, El Centro is the center of industrial and retail activity. In 1978 the county's population was approximately 90,000. About half of the population of this border county is Mexican-American. Unemployment has traditionally been high in the county, and in 1979 it was estimated to be over 26% (CEDD, 1979). Employment in agriculture has been decreasing in recent years as agriculture has become more mechanized.

CLIMATE

The Imperial Valley has an arid climate with hot, dry summers and mild winters (see Layton and Ermak (1976) for a general discussion of the valley's climate). The average temperature in January is 55°F, whereas in July it is 90°F. Annual diurnal temperature ranges are 20 to 30°F throughout

the year. Average annual rainfall is about 3 inches, but it can reach as high as 8 inches in some years. The average relative humidity was 26% in 1975. During most of the year the prevailing wind direction is mainly from the west. In the summer, though, there is a strong southeasterly component to winds because of the presence of a thermal low pressure area over the valley (Gudiksen et al., 1979). Stable atmospheric conditions are prevalent throughout the year, but they are more frequent in the winter months. Concentrations of suspended particulates often violate the California air quality standard of $100 \mu\text{g}/\text{m}^3$ for a 24-h average. Baseline measurements made as part of the IVEP indicate that maximum-hourly concentrations of O_3 occasionally exceed the state standard of 100 ppbv (Gudiksen et al., 1979). Baseline measurements also showed that H_2S concentrations rarely violated the California hourly average standard of 30 ppbv.

SECTION 3. GEOTHERMAL RESOURCES AND ENERGY TECHNOLOGIES

D. Layton

Before the various consequences of geothermal operations in the valley can be properly assessed, information is needed on the physical and chemical properties of geothermal fluids and the operational characteristics of energy technologies. Information on resource characteristics and technologies is needed to quantify the consumption of natural resources (e.g., land and water) as well as the production of environmental residuals (e.g., emissions of noncondensable gases). In this section we describe the resource potentials of the different geothermal areas in the valley, characterize the relevant physical and chemical features of geothermal fluids, and review the basic attributes of fluid production and energy conversion technologies.

RESOURCE POTENTIALS

The nation's energy potential for liquid-dominated hydrothermal resources is estimated to be the equivalent of 21,000 MW generated for 30 yrs (Muffler, 1979). This estimate is only for identified resources; the energy potential for undiscovered resources could be considerably higher. Almost a third of the identified, liquid-dominated resources are located in the Imperial Valley. Figure 3-1 depicts the energy potentials of the hot-water resources in eight western states, including Hawaii. The valley's resources are significantly larger than those of any other individual state. They amount to over 50% of California's energy potential for hot-water resources. Table 3-1 presents a series of estimates made by the U.S. Geological Survey for the years 1975 and 1978 on the energy potentials of the valley's geothermal resources. There is nearly a 50% increase in the 1978 estimate. Most of the increase was due to the discovery of a new geothermal field near Westmorland, representing over 1700 MW of additional energy potential. Changes in the estimates for the other resource areas are the result of adjustments made in the parameters (e.g., temperature and areal extent of a geothermal reservoir) used to calculate energy

Fig. 3-1. Energy potentials for the hot-water geothermal resources in eight western states. The resources of Imperial Valley have the potential of producing 6760 MW for 30 years. This represents almost a third of the nation's total identified energy potential for these resources.

potentials. As exploration continues and more information is obtained on the geothermal resources in the valley, resource estimates will be modified accordingly. And if the magnitude of the valley's geothermal energy potential continues to increase, the environmental ramifications of full-scale energy development will also change.

Table 3-1. Estimates of the energy potentials for hot-water geothermal resources in the Imperial Valley made by the U.S. Geological Survey for the years 1975 and 1978 (White and Williams, 1975; Muffler, 1979).

Resource Area	Energy potential (MW for 30 years)	
	1975 Estimate	1978 Estimate
Salton Sea	2787	3400
Brawley	333	640
Heber	973	650
East Mesa	487	360
Westmorland	----	1710
TOTALS	4580	6760

RESOURCE CHARACTERISTICS

The geothermal fluids in the valley differ greatly in their chemical and physical characteristics. Fluid chemistry, for example, changes from resource area to resource area and even between wells within the same area. Table 3-2 shows how the chemistry of fluids varies among the main resource areas. The fluids from the Salton Sea area contain extremely high concentrations of dissolved solids, including elevated levels of toxic substances like arsenic, boron, lead, copper, and zinc. The least toxic fluids are found in the East Mesa resource area. The fluids there range from below 2000 mg/l TDS in several wells, to over 25,000 mg/l TDS in

Table 3-2. Chemical analyses of geothermal fluids from geothermal resource areas in the Imperial Valley (Pimentel et al., 1978).

Parameter	Salton Sea	Westmorland	Brawley	Heber	East Mesa
		(mg/l)			
Na	52000.	10000.	22000.	4200.	2600.
K	14000.	1400.	3800.	260.	190.
Ca	24000.	690.	8100.	880.	130.
Mg	106.	188.	34.	5.4	3.4
Cl	145000.	18000.	46000.	7900.	3900.
SO ₄	84.	57.		99.	155.
HCO ₃	140.	2900.	49.	27.	490.
TDS	240000.	37000.	76000.	14000.	7600.
As	11.		2.6	0.1	.16
B	350.	63.	140.	14.	5.4
Ba	433.		363.	3.8	2.2
Cu	4.	.07	.11	.53	.03
F	9.	2.24		1.6	2.0
Fe	2300.	.3	65.	22.	2.2
Li	211.	48.	100.	9.5	6.3
Mn	1200.	2.8	190.	2.7	.42
Ni	4.				.03
Pb	100.	3.6	1.1	1.9	.09
Sr	500.		340.	53.	38.
Zn	660.	.04	14.	.83	.07

one well (USBR, 1977; RGI, 1978). Concentrations of noncondensable gases in fluids from wells within the Salton Sea and East Mesa resource areas are presented in Table 3-3. Hydrogen sulfide is the most important gas from an environmental perspective, even though it is present in much smaller concentrations than the primary noncondensable gas, CO₂. The composition of volatile organic compounds in geothermal fluids from wells on East Mesa is shown in Table 3-4. Some of these volatile compounds can act as precursors to photochemical oxidants.

The complex geochemistry of geothermal fluids is exemplified not only by the variations of the H₂S concentrations within each resource area as shown in Table 3-3, but also by changes taking place through time. In one case, the H₂S levels in fluids extracted from a well in the Salton Sea area are reported to have decreased during several years of intermittent operation (Quong et al., 1979). Such variations make it difficult to accurately estimate future emissions of gases from geothermal power plants.

Table 3-3. Concentrations of noncondensable gases in geothermal fluids from the Salton Sea and East Mesa resource areas (Ermak et al., 1979)

Gas	Salton Sea		East Mesa	
	Range	Mean (mg/kg of fluid)	Range	Mean
H ₂ S	1.6 - 6.0	3.2	0.12 - 1.6	0.54
NH ₃	20 - 40	35	1.3 - 8.1	4.5
CO ₂	1100 - 3800	1700	270 - 2300	1100
CH ₄	3 - 10	6.0	4.0 - 56	33
H ₂	0.0016 - 0.002	0.0018	0.005 - 0.007	0.0064
Rn	540 - 1080 ^a	810. ^a	420 - 540 ^a	480. ^a

^a pCi/kg of fluid.

Table 3-4. Volatile organic compounds measured in geothermal fluids from two wells completed by Republic Geothermal, Inc. at East Mesa (Layton et al., 1979).

Volatile organic compound	Weight percent in noncondensable gases		Concentration in geothermal fluid (mg/kg) ^a	
	<u>minimum</u>	<u>maximum</u>	<u>minimum</u>	<u>maximum</u>
Benzene (C ₆ H ₆)	.015	.065	.14	61
Propane (C ₃ H ₈)	.084	.114	.79	1.03
Ethane (C ₂ H ₆)	.062	.139	.57	1.30
Toluene (C ₆ H ₅ CH ₃)	.000	.004	.00	.004

^aThe content of noncondensable gases in the geothermal fluids is .094% by weight (940 ppm).

GEOTHERMAL TECHNOLOGIES

The technologies required to produce electrical energy from geothermal resources can be grouped into two categories. In the first category are the technologies related to fluid extraction, transmission, and injection; the second category includes those technologies involved with the surface processing of the fluids to generate electricity.

Fluid Production, Transmission, and Injection

From an environmental standpoint, the most important aspects of well field development are well drilling and testing. These activities consume land, generate noise, and produce liquid, solid, and gaseous wastes. It takes about .80 ha of land to drill a geothermal well in the valley. Land is taken up by a large sump, the drilling rig and supporting equipment (e.g., mud tanks, diesel engines, pipe racks, trailers, etc.). After a well is completed, the area required for the maintenance or reworking of a well can be reduced to about .20 ha (Goldsmith, 1976). If slant drilling is employed, as many as 10 wells can be completed from a single drill pad to form what is known as a production island. Approximately 1.5 to 2.5 ha of

land would be permanently required for each island (VTN, 1978; WESTEC Services, Inc., 1979a).

Wells are drilled with rotary rigs using drilling muds composed of bentonite clays mixed with additives such as caustic soda. The drilling muds are pumped down the drill pipe, out the drill bit, and from there they carry the rock cuttings up to the surface. The cuttings are separated at the surface and deposited into a sump. The heavy muds inhibit the release of gases during drilling so that little if any H_2S is emitted (Snoeberger and Hill, 1978). After a well is cased and cemented, an initial well test is conducted in which reservoir fluids are discharged containing residual drilling muds, cuttings, and sands. The discharged fluids are usually held in sumps and allowed to evaporate. Later the solid residues can be removed for disposal elsewhere. During prolonged well testing, fluids are usually injected back into the reservoir through a disposal well.

A completed well field will probably consist of individual well sites plus multi-well production islands. Geothermal fluids will be transported from the well sites to power plants via pipelines that run next to the borders of fields or access roads to minimize the use of land. Production islands, where the wells have been slant drilled, have the advantage of reducing the number of pipelines needed for fluid transmission. This lowers the amount of heat lost through pipelines. Normally fluids would not be transported more than 1.6 km because of excessive heat losses. Another advantage of production islands is that steam can be separated from fluids produced from several wells with central flash units and then transported to a nearby power plant utilizing steam to run a turbine. After the steam is separated, the residual fluids are then disposed by subsurface injection to the reservoir. Fluid injection to a geothermal reservoir does the following (Sanyal, 1978):

- Isolates geothermal wastes from the surface environment and from shallow aquifers that could contain water of drinking water quality,
- Mitigates subsidence caused by the extraction of geothermal fluids,
- Minimizes the declines of reservoir pressure, which would reduce the productivity of wells, and
- Provides a mechanism of recovering additional heat contained in the reservoir rock.

In some instances the injected fluids may have to be pretreated to remove suspended solids and scaling substances (e.g., silica and calcium carbonate) that could plug the injection well and the geologic formation receiving the fluids. Pretreatment will produce solid wastes that will have to be disposed at a suitable waste disposal site. Residual fluids from power generation at the Salton Sea resource area will require the most intensive pretreatment due to the high dissolved solids content in the geothermal brines.

Energy Conversion Cycles

There are two types of geothermal power systems that are being considered for use in the Imperial Valley: flashed-steam and binary fluid conversion cycles. Of the two conversion technologies, the flashed-steam method is the only one that has been implemented on a commercial scale (Austin and Lundberg, 1975). A single one-stage flash cycle is shown in Fig. 3-2a. Electricity is generated through the following process: (1) steam is separated from a liquid-steam mixture as it comes from a geothermal well or well field; (2) the separated steam is expanded through a turbine that runs a generator; (3) steam exhausted from the turbine is condensed by a direct contact or surface condenser; and (4) condensate is either sent to an evaporative cooling system (e.g., a wet cooling tower) as make up water or is disposed by injection along with the spent geothermal fluids (Bechtel, 1976). A 150-MW flashed-steam power plant using fluids of around 20,000 ppm TDS is already operating to the south of the Imperial Valley in Cerro Prieto, Mexico. However, at that facility, spent fluids are discharged to a large pond.

The binary process, unlike the previously described conversion cycle, does not use steam to drive a turbine. Instead, the geothermal fluid is used to vaporize a secondary fluid that expands through a turbine. A simple binary cycle is illustrated in Fig. 3-2b. A downhole pump sends geothermal fluids to a heat exchanger on the surface that transfers the heat of the fluids to a binary fluid that drives a turbogenerator. After the geothermal fluids are passed through the heat exchanger, they are disposed by injection. Any gases that are insoluble in the spent fluid may have to be

Fig. 3-2. Simplified conversion cycles for the flashed-steam and confined-flow, binary systems. a. Single-stage, flashed-steam conversion cycle. b. binary fluid conversion cycle.

vented to the atmosphere if it is infeasible to inject them back into the reservoir. Also, if spent liquids need preinjection treatment (e.g., removal of suspended solids), there is a possibility that noncondensable gases will be released. One disadvantage of a binary fluid cycle is that external supplies of water must be consumed for power plant cooling since no condensate is produced. Downhole pumps for geothermal applications have been tested at the Heber and East Mesa KGRAs, but it is not clear whether such pumps could withstand the more corrosive fluids associated with the Brawley and Salton Sea resource areas. A conversion facility testing the binary cycle has been built at East Mesa.

The actual sites for either type of power plant must be large enough to encompass the fluid processing equipment (i.e., heat transfer devices and turbogenerator), cooling towers, electrical switch yard, and support buildings. The basic land requirement of these components for plants ranging from 50 to 100 MW (net) should be no more than 8 ha.

Aside from design differences between the conversion cycles, the amount of fluids extracted for each kWh of electricity produced is primarily a function of resource temperature. More specifically, as the temperature of a geothermal resource rises, the conversion efficiency of a given geothermal power cycle increases, reducing the demand for fluids. Table 3-5 contains a series of estimates for the fluid requirements of power plants using geothermal resources of different temperatures. A plot of the values (Fig. 3-3) shows how the fluid requirements decline with higher resource temperatures. The most immediate consequence of the changing fluid requirements is the number of wells that are needed to support power plants. If it is assumed that an average well produces about 227×10^3 kg/h, then approximately 26 wells would be necessary for a 50 MW power plant using resources of around 175°C. For geothermal resources of 285°C, like those of the Salton Sea resource area, about 7 wells would support a generating facility of the same size. More wells would be necessary if well productivities are lower.

The quantity of fluids that must be disposed also varies inversely with the temperature of geothermal resources. With lower resource temperatures, larger amounts of fluids are needed to operate a power plant, and therefore larger quantities of spent fluids must be disposed. A 50 MW flashed-steam

power plant using resources of 175°C would have to extract and dispose approximately 6×10^6 kg of geothermal fluids each hour. Over a year's time, such a facility would have to dispose approximately $42 \times 10^6 \text{ m}^3$ of fluids, assuming a fluid density of 1000 kg/m^3 and operation at .80 of capacity. The same size plant using fluids of 285°C would have to dispose about $12 \times 10^6 \text{ m}^3$ of fluids each year. The reliability of geothermal power plants will depend a great deal on the ability of fluid disposal systems to handle large quantities of spent fluids for long periods of time.

Table 3-5. Fluid requirements for geothermal power plants using resources of varying temperature.

Conversion System	Resource Temperature ($^{\circ}\text{C}$)	Fluid Requirement (kg/net kWh)	Reference
Binary	143	141	DiPippo, 1978
Flashed-Steam	168	132	Layton <u>et al.</u> , 1979
Binary	180	83	Walter <u>et al.</u> , 1975
Flashed-Steam	182	109	Bechtel, 1976
Binary	190	68	DiPippo, 1978
Binary	200	59	Pines and Green, 1976
Flashed-Steam	260	49	WESTEC Services, Inc., 1979a
Flashed-Steam	288	33	Bechtel, 1976
Binary	300	31	Pines and Green, 1976
Flashed-Steam	316	29	U.S. Dept. of Energy, 1979

Fig. 3-3. Fluid requirements of power plants utilizing fluids having different temperatures. As temperatures increase, conversion efficiencies increase accordingly, and hence less fluids are needed to produce electricity.

SECTION 4. FUTURE GEOTHERMAL DEVELOPMENT IN THE IMPERIAL VALLEY

D. Layton and D. Ermak

In order to analyze and assess the cumulative impacts of geothermal energy production in the valley, it was necessary to make a series of assumptions regarding rates of energy growth, ultimate levels of production in each resource area, and siting patterns for geothermal facilities. Accordingly, low, medium, and high scenarios of energy growth were prepared that reflect a range of alternative assumptions about future development. The assessment focuses primarily on the impacts associated with the medium energy scenario, which has 3000 MW as the ultimate level of geothermal energy production. This scenario was emphasized because it is more consistent with existing plans of developers than the other scenarios.

PROJECTIONS OF ENERGY GROWTH

The rate at which geothermal development will take place in the Imperial Valley will depend on economic, technical, political, and environmental factors. At the present time only a 10 MW binary power plant has actually been built, but several other geothermal facilities have been announced by various developers. Most of the current geothermal activity in the valley involves the exploration for geothermal resources, the drilling of wells, and the testing of components for power plants. There do not appear to be any major technical problems related to the production of geothermal energy from the East Mesa and Heber KGRAs because of their relatively low salinities. In the Salton Sea area, however, saline fluids pose problems of corrosion and scaling that must be resolved, perhaps through the operation of demonstration facilities.

Politically, there is a favorable climate for the early utilization of the valley's geothermal resources. This is true at both the local and state levels of government. Imperial County, for instance, has already adopted a geothermal element in its general plan, and it is being used to guide the development of geothermal resources in the county (Imperial County, 1977). Furthermore, the majority of the county's recognized leaders are in favor of geothermal development (Butler and Pick, 1978). The California Energy Commission (CEC), which is responsible for the licensing of power plants that

have a net generating capacity over 50 MW, has an expedited 12-month review process for geothermal facilities. From the CEC's perspective, geothermal energy is a particularly important supply option for California, and the Commission is actively encouraging geothermal development (CEC, 1979). The federal government also supports geothermal development via tax incentives and guarantees of loans for geothermal projects.

Despite the presence of conditions that are conducive to the production of geothermal energy in the Imperial Valley, predictions concerning the rates and levels of energy generation must remain speculative because of various uncertainties. For one thing, high voltage transmission lines will have to be constructed to transmit electrical energy from the valley to major load areas in the south coast area (i.e., San Diego to Los Angeles). At present no such lines exist, although options for energy transmission are now being explored (WESTEC Services, Inc., 1979b). If transmission facilities are not completed in a timely manner, geothermal growth will be constrained. Moreover, if utilities in southern California rely on different sources of electrical energy (e.g., imports of electricity from utilities in Arizona and New Mexico and other western states or geothermal energy from the Cerro Prieto resource area in Mexico) to meet their energy needs in coming years, then geothermal development in the valley will be delayed.

As a means of expressing the combined effects of economic, technical, political, and other external factors on future geothermal development, low, medium, and high forecasts of energy production were prepared (Ermak, 1978). In the scenario of low growth, the first 100 MW of energy is produced in 1986, and through a growth rate of 40 MW per yr, reaches 1000 MW in the yr 2010. It represents the situation in which growth is restricted by technical, economic, political, or other problems. The contribution of the four KGRAs to the total amount of energy produced in the valley is depicted in Table 4-1. The medium forecast has a growth rate of 100 MW per yr, and goes from 100 MW in 1982 to 3000 MW in 2010. The high forecast attains 8000 MW in 2010 after increasing at a rate of about 250 MW per yr from an initial 100 MW in 1980. Accelerated growth, as assumed in the high forecast, could only occur if highly favorable conditions are present and if additional geothermal resources are discovered that can support the energy potentials that are specified. It is unlikely that geothermal production will follow the

high growth scenario in the near term. The ultimate levels of energy production in the low and medium forecasts are generally within existing estimates. Implicit in each of the scenarios are the following assumptions (Ermak, 1978): the economic feasibility of geothermal conversion facilities is proven within the next decade, technologies are developed that can overcome the scaling and corrosion problems associated with the Salton Sea KGRA, and the demand for geothermal energy exceeds the capacity to produce it. The socio-economic assessment (Section 12) is based on a scenario used by Rose (1977) to examine the economic consequences of future geothermal development in the Imperial Valley. According to that scenario, energy production starts in 1984, and increases at a rate of 125 MW per year until 4,500 MW of capacity are installed by the year 2020. The medium scenario described earlier has a rate of growth that is only slightly smaller.

Table 4-1. Scenarios of geothermal energy production in the Imperial Valley (Ermak, 1977).

Year power level attained			Power distribution, MW				
High growth	Medium growth	Low growth	Power Level MW	Salton ^a Sea	Brawley	Heber	East Mesa
1982	1985	1994	400	100	100	100	100
1984	1991	2010	1000	300	300	300	100
1991	2010	Never	3000	1400	600	700	300
2010	Never	Never	8000	4000	1400	1800	800

^a Energy production from the Westmorland resource area is included in the forecast for the Salton Sea KGRA.

A number of developers have established plans for future geothermal facilities in the Imperial Valley. The cumulative production from the planned units (CEC, 1979) is compared with our low, medium and high projections in Fig. 4-1. Planned additions fall between the high and medium scenarios of energy growth. The low projection is still valid, however, since there remain several uncertainties regarding economics, construction of transmission lines, etc., that could delay development. Our assessments focus mainly on the medium scenario of energy production because of its similarity with current plans of developers.

The location of energy facilities in the Imperial Valley will directly affect both local and regional impacts. Changes in air quality, as an example, will vary across the valley according to the location of power plants

Fig. 4-1. Cumulative energy production from planned facilities versus the low, medium, and high projections used in the assessment.

with respect to the direction of prevailing winds. Similarly, local socio-economic effects are essentially a function of the location of facilities with respect to the geographic boundaries of governmental units like school districts and municipalities. As a means of identifying plausible sites of power plants in the valley's geothermal resource areas, we developed a set of siting criteria involving resource and technology constraints and various land use considerations. The criteria were then used to prepare facility siting patterns for each of the ultimate levels of geothermal energy production presented in Table 4-1 (Ermak, 1977).

FACILITY SITING PATTERNS

The siting of geothermal facilities is uniquely different from nuclear and fossil-fueled power plant siting. The basic difference is that geothermal power plants must be situated in the immediate vicinity of their energy source, that is, a geothermal reservoir. In electric applications geothermal fluids can only be transported relatively short distances (less than 1.6 km) because of heat losses in the pipelines. This limits the places where energy conversion facilities can be sited. Another constraint deals with the spacing of wells in a well field. To maintain the productivity of a geothermal reservoir over a 30-yr period, the bottom-hole spacing of wells will probably vary between 8 and 12 ha per well, depending on reservoir characteristics and extraction rates. Assuming a well spacing of 12 ha per well, the areal extent of well fields that support 100 MW (net) power plants could range from less than 3 km² in the Salton Sea KGRA, to over 5 km² in the Heber and East Mesa resource areas. The primary reason for the smaller size of well fields in the Salton Sea area is the higher temperature of fluids, which means that fewer production wells are required to supply fluids to power plants. The placement of injection wells on the periphery of a well field, though, increases the actual area needed to support a power plant. For the purpose of siting facilities, we assumed that well fields in the Salton Sea resource area would consume 3 km² per 100 MW (net) power plant, while well fields in the other areas would use 6.5 km² for the same size plant. These values could change as experience is gained in the operation of well fields in the valley.

Other criteria related to resources and technologies that we used to site plants include the following:

- Commercial geothermal resources are located within the boundaries of the Salton Sea, Brawley, Heber, and East Mesa KGRAs. However, for the high growth scenario, which has a maximum of 8000 MW of installed capacity, geothermal resources are assumed to extend into the Westmorland area between the Salton Sea and Brawley KGRAs. Power plants are constrained to these areas.
- Power plants are sited in 100 MW (net) units with a 30-yr life span.

The sites selected for geothermal power plants must be compatible with existing and proposed land uses, established land use policies, and applicable zoning regulations. Important land use guidelines are contained in the county's General Plan, with its Ultimate Land Use Plan, Conservation, Geothermal, and Open Space elements (Imperial County, 1973, 1977). Regulations found in the Terms, Conditions, Standards, and Application Procedures for Initial Geothermal Development, adopted by Imperial County (1971), also influence facility siting. Based on the constraints embodied in these documents and the nature of existing land uses, we formulated the following general land use criteria to identify plausible sites (Ermak, 1977).

- Power plants are excluded from within 1.6 km of hospitals and .8 km from schools or municipal boundaries.
- Facilities are excluded from wildlife refuges and within .4 km of the New and Alamo Rivers.
- No plants are situated over the Salton Sea.
- Facilities are prohibited within .40 km of either side of a major fault so as to limit the risk of damage caused by earthquakes.
- Use of "G" overlay zones permits geothermal activities in agricultural zones A-2 (general agriculture), A-2-R (general agriculture, rural), A-3 (heavy agriculture), and M-2 (heavy manufacturing). Development is restricted from all residential, commercial, recreational, and open space zones.

Using both sets of criteria dealing with resources and technologies as well as land use restrictions, we identified power plant sites, starting in areas where successful wells had been completed in each KGRA. Additional sites were located adjacent to the initial sites chosen in a resource area. The sites identified for the low levels of power production were included in the higher levels. For instance, the 3000 MW level of production is made up of the ten sites of the 1000 MW level plus another 20 sites to achieve an

additional 2000 MW. An exception occurs in the siting patterns for the year 2020. By that time, generating facilities constructed between 1980 and 1990 will have been decommissioned, and so their sites are deleted from the siting patterns for 2020. Figures 4-2a through 4-2f depict the siting patterns associated with the 1000, 3000, and 8000 MW levels of development, which correspond to the maximum production levels for the low, medium, and high energy scenarios. At the 8000 MW level of production in 2010 (Fig. 4-2e) nearly all the land available for facilities is utilized. By 2020 (Fig. 4-2f) some plants have been deleted, and replaced by facilities between the Salton Sea and Brawley KGRAs.

Fig. 4-2. Power plant siting patterns for the low, medium, and high levels of geothermal development. a. 1000-MW power level prior to 2010. b. 1000-MW level in 2020. c. 3000-MW level prior to 2010. d. 3000-MW level in 2020. e. 8000-MW level in 2010. f. 8000-MW level in 2020.

Fig. 4-2. Continued, c. through f.

SECTION 5. AIR QUALITY CHANGES

D. Ermak and D. Layton

Noncondensable gases released from flashed-steam geothermal power plants are a potential problem because such releases could degrade the valley's air quality. Noncondensable gases include CO_2 , H_2S , NH_3 , Hg, and Rn. The principal constituent of gaseous emissions is CO_2 ; however, CO_2 is not expected to have any negative, valley-wide impacts. Emissions of H_2S are a cause of concern, though, because ambient concentrations as low as $7 \mu\text{g}/\text{m}^3$ can be detected by humans (see Section 10). Furthermore, the emissions of H_2S associated with major geothermal development increase the possibility that ambient levels of H_2S might exceed the California air quality standard of $42 \mu\text{g}/\text{m}^3$ for a 1-h average. At The Geysers KGRA in northern California, where 13 generating units produce over 650 MW of electricity, emissions of H_2S have already become the primary environmental issue related to geothermal development (Ermak and Phelps, 1978). Because of unacceptable ambient concentrations of H_2S (the state standard is exceeded at monitoring stations in The Geysers KGRA (Rosen and Molenkamp, 1978)), air quality regulations are being adopted that will eventually require between 90 to 95% H_2S control at generating facilities (Joyce and Fontes, 1978).

Will future geothermal operations in the Imperial Valley result in similar air quality problems involving H_2S or other gaseous emissions? To address that question, an air quality assessment was carried out as part of the IVEP. In that effort, Ermak *et al.* (1979) used computer models to predict the air quality changes expected to occur with a total production of 3000 MW, generated by thirty 100-MW power plants. The assessment also addressed changes in air quality caused by the operation of a 100 MW power plant to examine localized impacts. This section is based primarily on their analyses of the production of 3000 MW and the operation of a single power plant.

METHODOLOGY

The quantities of noncondensable gases emitted from geothermal facilities depend on the concentration of each gas in geothermal fluids, the types

of conversion technology implemented, fluid requirements of power generation, the amounts of pollution abatement, the number and location of power plants, and the regional meteorology. To support the air quality assessment, data on gas concentrations in geothermal fluids were obtained from several geothermal wells in the Imperial Valley. The gas emission rate per power plant has been calculated on the basis of representative energy conversion efficiencies that are consistent with the temperature of geothermal fluids. No reduction in the emission rate due to the use of abatement controls is assumed. Thus, the analyses should lead to conservative results, and they can be used to estimate the level of emission control that is necessary to prevent unacceptable ambient concentrations of pollutants.

The air quality assessment is based on the predictions of numerical atmospheric transport models. Along with the emission data, the major input to these models is meteorological data, obtained from continuous monitoring over a 1-yr period at six locations within the valley. The models predict the average concentration for each pollutant (i.e., H_2S , SO_2 , NH_3 , Hg, CO_2 , and Rn) over the entire region. Averaging times were varied from one hour to as long as a year, depending on the applicable air quality standards.

BASELINE MEASUREMENTS

As part of the IVEP, background air quality and meteorological data were measured at six stations in the valley (see Fig. 5-1). The baseline measurements have been summarized by Gudiksen et al. (1979a); analyses of the data are contained in Gudiksen et al. (1979b). Ambient levels of H_2S , SO_2 , O_3 , NO , NO_x , CO_2 , Hg, and particulates were monitored. The primary pollutant as far as geothermal development is concerned is H_2S . It is usually present in the noncondensable gases that are released whenever geothermal fluids are flashed to steam. Oxidation of H_2S in the atmosphere results in the formation of another pollutant, SO_2 . Figure 5-2 depicts the annual frequency of occurrence for different ranges of 1-h concentrations of H_2S and SO_2 from all stations. The majority of the H_2S concentrations were below $14 \mu g/m^3$. The California standard for H_2S (there is no federal standard) is $42 \mu g/m^3$, 1-h average. This standard was exceeded by less than 5% of the daily maximum hourly concentrations. Releases

Fig. 5-1. Locations of the six air quality and meteorological monitoring stations in the Imperial Valley.

of H_2S into the atmosphere resulting from the use of liquid sulfur fertilizers in irrigation water could account for excursions above the standard. Odor complaints have arisen when these fertilizers are applied to crops (Hahn, 1979a). SO_2 concentrations were considerably lower than the California hourly standard of $1310 \mu\text{g}/\text{m}^3$. Background concentrations of CO_2 are also of interest because CO_2 makes up over 97% of the noncondensable gases emitted from many flashed-steam geothermal power plants. As might be expected, baseline CO_2 data exhibited considerable diurnal variability caused by the photosynthesis of crops. The average of the six stations was $640 \text{ mg}/\text{m}^3$, with a standard deviation of approximately $65 \text{ mg}/\text{m}^3$ (Ermak et al., 1979). Particulate concentrations generally exceeded the California standard of $100 \mu\text{g}/\text{m}^3$ for 24-h. The air quality of the valley is also affected by the numerous volatile chemicals given off by feedlots. The odors caused by feedlot emissions have resulted in complaints (Hahn, 1979a).

Data obtained from meteorological measurements made at the stations displayed a high frequency of stable atmospheric conditions (as shown in Fig. 5-3.), average wind speeds between 2 m/s and 3 m/s, and winds prevailing from the west (Ermak et al., 1979). These data were used to simulate the dispersion of air pollutants from geothermal fluids.

ATMOSPHERIC TRANSPORT MODELS

The primary model used in this study is ATMAS (Ermak et al., 1978), which numerically solves the three-dimensional advection-diffusion equation for atmospheric transport. In this model, the advection term represents the average wind velocity and the diffusion term represents eddy diffusion due to turbulence in the atmosphere. ATMAS generates a three-dimensional, time-varying wind field from average wind velocity data taken at several locations within the region of interest. Eddy diffusion is assumed to occur in a Gaussian manner, with the dispersion rate (σ_y) calculated from the measured variation in the wind direction (σ_θ).

The computer code uses the particle-in-cell concept (Welch et al., 1965; Amsden, 1966; and Sklarew et al., 1971) to solve the advection-diffusion equation. This method relies upon a large number of marker particles (10,000 to 20,000) to represent the mass distribution of the emitted species within

Fig. 5-2. Yearly histograms of the ambient, 1-h average concentrations of H_2O and SO_2 , based on data from six monitoring stations in the Imperial Valley (Ermak *et al.*, 1979).

Fig. 5-3. Yearly histogram of Pasquill-Gifford stability classes for the Imperial Valley. Class F is the most stable atmospheric condition; class A is the least stable. Classes F and E are the dominant atmospheric conditions (Ermak *et al.*, 1979).

a three-dimensional Eulerian grid. The concentration of the particles is defined at the cell centers using a weighted sum of the surrounding particles. The locations of the marker particles are defined by their individual coordinates within the Eulerian grid. The marker particles are transported through the grid with a pseudo-velocity derived from the transport equation and defined at the cell corners. In a typical time cycle, each marker particle in a given cell is transported for one time step with the velocity obtained from a weighted sum of the pseudo-velocities at the eight corners of the cell. This permits a new set of particle coordinates to be computed and results in a new concentration distribution. In source regions, marker particles are continually injected into the grid at a rate consistent with the source strength.

ATMAS is designed to assess the long-term air quality impacts of continuous emissions from multiple area sources. The code is a simplified and computationally faster version of the transport code ADPIC (Lange, 1978). Its speed is due primarily to the use of flat terrain, a coarser advection grid, and the assumption of Gaussian diffusion. It does, however, retain the important effects of a time and spatially varying wind velocity and wind shear. Extensive validation of the ADPIC code has been performed against closed solutions of the advection-diffusion equation and against numerous tracer experiments out to a distance of about 100 km. Since ATMAS is based on the same model equations as ADPIC and has also been validated against closed solutions of the advection-diffusion equation, we believe that it has been adequately verified.

The principal output of ATMAS is a time sequence of hourly averaged ground-level concentrations on a two-dimensional grid of the region. There is a separate sequence for each species studied. These data are analyzed to determine longer averages (e.g., monthly or yearly), the probability of exceeding a given threshold or standard, and other statistical descriptions. Regional data are presented in the form of contour plots, while data for a single location are presented in the form of histograms, graphs, and bar plots.

A minimum simulation period of one year was desired to provide predictions of air quality levels in future years. Although ATMAS is computationally much faster than more complex versions of the code, it still requires considerable computer time (approximately 4 hours on a CDC 7600 to simulate

one month). Consequently, ATMAS was used to simulate only one month in each season (April, July, October, and January, 1977-78). The assessment of the remaining months was based on the results of the atmospheric transport model MSDM (Ermak and Nyholm, 1978).

The MSDM code solves the atmospheric advection-diffusion equation using the steady-state assumption, which results in a Gaussian plume type model. The wind field is assumed to be constant for each case so that the effects of spatial variations in the wind field are neglected. The principal meteorological data required by the code are atmospheric stability, wind speed, and wind direction. The MSDM code can operate in either a climatological or instantaneous mode. The climatological mode calculates average concentrations over periods of months to years using a joint frequency distribution to describe the probability of meteorological conditions; the instantaneous mode calculates average concentrations for periods of minutes to hours for a specific set of meteorological conditions. The meteorological data used in these calculations were obtained from the meteorological station closest to each source.

As a check to ensure that these simplifications did not lead to erroneous results, the MSDM code was also run for the four months in which ATMAS was used, and the results of the two codes were then compared. The agreement was found to be quite good. In regions of high concentrations, the values were generally within a factor of 1.5 of each other. On a regional scale, the isopleth contour plots of the average concentrations were found to be in very good agreement.

The main output of MSDM when run in either the climatological or instantaneous mode is a regional plot of ground-level concentration contours resulting from the combined emissions of all sources considered. The impact of individual sources is also analyzed. Typical output for single-source calculations includes the plume center line and average concentration, the probability of exceeding short-term standards as a function of downwind distance from the source, and contour plots of the average concentration.

GASEOUS EMISSIONS

The emission rate of a particular gas will depend on the concentration of that gas in the geothermal fluid, the rate of geothermal fluid consumption, and the fraction of the gas released from the power plant. The fraction of the gas released will vary depending on the type of geothermal technology used (e.g., flashed-steam, or binary fluid) and the efficiency of the abatement system if one is used. For the purposes of the assessment, it is assumed that all gas entering the power plant is released to the atmosphere. This situation represents a flashed-steam process in which the gases are vented to the atmosphere with no abatement.

The concentration of the gases of interest in the geothermal fluid (H_2S , NH_3 , CO_2 , Hg , and Rn) was measured by investigators from Battelle Pacific Northwest Laboratories (Robertson et al., 1978) and from LLNL. Samples were obtained from a number of geothermal wells in the Salton Sea and East Mesa KGRAs. Investigators were unable to obtain access to the other areas. The data reveal that even in wells within the same KGRA, the concentration of a specific gas may vary over an order of magnitude.

The rate of fluid consumption in geothermal power production is largely a function of the temperature of the geothermal fluids. The geothermal fluids in the Salton Sea and Brawley KGRAs have a higher temperature and therefore will be consumed at a lower rate than the fluids in the Heber and East Mesa KGRAs. On the basis of the physical and chemical characteristics of the geothermal fluids and the current designs of proposed flashed-steam power plants, we assume that power plants in the Salton Sea and Brawley KGRAs consume an average of 50 kg of fluid per kWh of generated power. Actually, facilities in the Salton Sea area would consume somewhat lower quantities of fluids because of higher resource temperatures. For the Heber and East Mesa KGRAs we assume that facilities consume twice as much fluid for the same output. Using these consumption rates and the average concentration of each gas in the geothermal fluid, we obtained the emission rates shown in Table 5-1. The emission rates for the Brawley KGRA are taken to be the same as the Salton Sea rates, and the Heber emission rates are taken to be the same as the East Mesa rates. Table 5-1 also contains the average emission rates of noncondensable gases released from power plants at The Geysers vapor-dominated field in northern California. Average emissions of H_2S from

those facilities are an order of magnitude higher than the expected emissions from geothermal facilities in the Salton Sea resource area.

Table 5-1. Estimated unabated emission rates for geothermal power plants in the Salton Sea and East Mesa resource areas (Ermak et al., 1979). Average unabated emissions at The Geysers resulting from the production of 502 MW are shown for comparison (PG&E, 1975; Ansbaugh, 1978).

Gas	Salton Sea	East Mesa	The Geysers
(Emissions, g/MWh)			
H ₂ S	160	55	1800
NH ₃	1750	455	1540
CO ₂	8.5×10^4	1.1×10^5	2.6×10^4
CH ₄	300	3.3×10^3	1540
Hg	0.090	0.6	0.01
²²² Rn	41 ^a	49 ^a	120 ^a
Benzene	-	61 ^b	-

^a Radon emission rate is μ Ci/MWh.

^b This is based on a maximum concentration found in two wells completed at East Mesa by Republic Geothermal, Inc. (Layton et al., 1979) and a fluid requirement of 100 kg/kWh for a flashed-steam power plant.

ASSESSMENT OF THE 3000 MW SCENARIO

The main power level to be assessed in this study is 3000 MW. This level represents the maximum capacity for full-field development in a medium growth estimate for the valley. The medium growth scenario projects that electrical capacity first comes on-line in the early 1980s and then increases at a rate of about 100 MW per year until the year 2010, when the 3000 MW level is reached. It is assumed that the 3000 MW is produced by 30 power plant units each with a 100 MW average output. The units are distributed as follows: 14 in the Salton Sea KGRA, 6 in the Brawley KGRA, 7 in the Heber KGRA, and 3 in the East Mesa KGRA. The siting pattern for each cluster of units is shown in Fig. 4-2c of Section 4.

Hydrogen Sulfide

An isopleth plot of the annual average H_2S concentrations throughout the valley is given in Fig. 5-4. The concentration contour levels run from 1 to $30 \mu g/m^3$. As would be expected, the higher levels are found in the areas surrounding the power plant clusters. The highest levels are in the area of the Salton Sea KGRA, where a maximum average concentration of about $34 \mu g/m^3$ occurs. The average level in the Salton Sea area is about five times as great as that in the Heber and East Mesa areas. This is due to the large number of power plants located in the Salton Sea KGRA and also to a higher emission rate per power plant for this area. The contours surrounding the Brawley and Salton Sea power plant clusters merge due to their proximity.

The noxious odor of H_2S is the main concern and, therefore, the short-term average concentration is of major importance. We have calculated the probability that the 1-h average H_2S concentration will exceed $42 \mu g/m^3$, the California ambient air quality standard for 1-h averages of H_2S . The results are shown in Fig. 5-5 in the form of a contour plot of probability levels. The 1% contour encloses an area of about $1500 km^2$ surrounding the Salton Sea and Brawley power plants. In the vicinity of the Salton Sea power plants, the H_2S standard is exceeded about 25% of the time.

Fig. 5-4. Isopleth plot of the annual average ground level H_2S concentration in $\mu g/m^3$ resulting from the production of 3000 MW. The highest levels are in the vicinity of the Salton Sea KGRA, where the H_2S emissions are greatest.

Fig. 5-5. Isopleth plot of the probability that the H_2S ground level concentrations will exceed the California ambient air quality standard of $42 \mu g/m^3$, averaged over one hour.

As a supplemental analysis, we selected 22 points throughout the valley (see Fig. 5-6), including the centers of most of the cities, and calculated: (1) the number of days per year in which there was at least one violation of the $42 \mu\text{g}/\text{m}^3$ level and (2) the average length in hours of such episodes. The results of those calculations are presented in Table 5-2. The cities at the northern end of the valley (i.e., Niland (1), Calipatria (2), Westmorland (3), and Brawley (4)) experience violations of the hourly standard of $42 \mu\text{g}/\text{m}^3$ from 72 to 228 days per year, with average episodes lasting 2 to 3 h per day. This is a very significant fraction of the year, and episodes appear to occur throughout the year. The cities in the Heber and East Mesa areas--Heber (7), Calexico (11), and Holtville (10)--have episodes on about 14 days per year. Mexicali was calculated to have three 1-h episodes, but this number is too small to be statistically meaningful. There were no calculated episodes exceeding the $42 \mu\text{g}/\text{m}^3$ level in the cities of Imperial and El Centro.

Fig. 5-6. The locations of the 22 sites used in evaluating the frequency that H_2S concentrations will exceed the California air quality standard.

Table 5-2. The number of days per year with at least one violation of the California Standard for H₂S and the average length in hours of such episodes at 22 locations in the Imperial Valley.

Location ^a	Number of days with violations	Average duration of episodes in hours
1.	108	2.0
2.	228	3.3
3.	72	2.4
4.	72	1.5
5.	0	0.0
6.	0	0.0
7.	12	2.3
8.	3	1.0
9.	0	0.0
10.	15	1.4
11.	15	1.0
12.	0	0.0
13.	207	3.3
14.	324	5.7
15.	258	4.0
16.	0	0.0
17.	0	0.0
18.	0	0.0
19.	3	1.0
20.	15	1.6
21.	0	0.0
22.	32	1.8

^a See Fig. 5-6.

Sulfur Dioxide

In these calculations, it is assumed that sulfur dioxide is produced by chemical transformation of hydrogen sulfide in the atmosphere. To approximate this, the models use first-order chemical transformation of H_2S to SO_2 with a half-life of 13 h (Sprung, 1977). The resulting annual average SO_2 concentration is shown in Fig. 5-7. Compared to the federal standard for an annual average ($80 \mu\text{g}/\text{m}^3$), the values we forecast for the valley are quite low. The maximum level ($7.4 \mu\text{g}/\text{m}^3$) occurs over the Salton Sea.

In addition to the annual SO_2 standard, there are standards for shorter periods of time in both California and federal regulations. The California SO_2 standards are more stringent, so they will be considered here.

The California 24-h standard is $105 \mu\text{g}/\text{m}^3$, and the 1-h standard is $1310 \mu\text{g}/\text{m}^3$. Our calculations indicate that neither of these standards would be violated under the 3000 MW scenario. In the areas where SO_2 levels were expected to be highest, the calculated 1-h-average SO_2 concentration was below $5 \mu\text{g}/\text{m}^3$ at least 80% of the time. A few excursions

Fig. 5-7. Annual average ground-level SO_2 concentrations in $\mu\text{g}/\text{m}^3$.

into the 100-to-400 $\mu\text{g}/\text{m}^3$ region were observed, but even these maximum levels are far below the 1-h standard. Calculations of the 24-h average showed only a few episodes into the 40-to-90 $\mu\text{g}/\text{m}^3$ region.

Other Emissions

The changes in the concentrations of ammonia, mercury, and radon were found to be insignificant. The federal occupational standard for ammonia is an 8-h time weighted average concentration of $3.5 \times 10^4 \mu\text{g}/\text{m}^3$ (approximately the odor threshold), and the maximum ammonia concentration calculated throughout the valley was more than a factor of 10 below that level. The federal occupational standard for mercury is an 8-h time weighted concentration of $100 \mu\text{g}/\text{m}^3$, and the maximum level calculated throughout the valley was more than a factor of 200 below that. The federal standard for radon and its short-lived daughters in unrestricted areas is $10^3 \text{ pCi}/\text{m}^3$. The maximum level calculated in the valley was more than 2 orders of magnitude below the standard. Air quality changes resulting from emissions of benzene were not simulated because data for the Salton Sea and Brawley resource areas were not available. However, if power plants in the Salton Sea and Brawley resource areas emitted benzene at the rate of 61 g/Mwh, the maximum hourly concentration at site 14 within the Salton Sea resource area would have been $100 \mu\text{g}/\text{m}^3$. This is 32 times lower than the proposed occupational standard of $3200 \mu\text{g}/\text{m}^3$ (see Section 10).

Carbon dioxide is the major gaseous emission from geothermal power plants, and one might expect that it could have a beneficial impact on the surrounding agricultural industry by increasing crop growth rates. Air quality measurements taken throughout the valley indicate that the average baseline CO_2 level is $640 \text{ mg}/\text{m}^3$ with a standard deviation of $\pm 10\%$. The maximum calculated values for this scenario were an incremental concentration of less than $100 \text{ mg}/\text{m}^3$, and typical values were less than $20 \text{ mg}/\text{m}^3$. Thus, the increase in the CO_2 level due to geothermal energy production is expected to be within the range of natural fluctuations in this region.

Another class of atmospheric emissions is non-methane hydrocarbons. These emissions can play a role in the formation of photochemical oxidants. Preliminary measurements of non-methane hydrocarbons in geothermal fluids from wells in the Salton Sea resource area indicate that they can amount to between 5 to 10 percent of the methane concentrations. If we assume that the ratio of non-methane hydrocarbons to methane is constant for the fluids in all the resource areas, then at the 3000 MW level of geothermal development, total emissions from geothermal facilities would range from 5 to 10 tons per day. These daily emissions would be a significant component of the volatile organic compounds produced in the valley. In 1977, for example, emissions of organic gases in the valley amounted to approximately 43 tons on an average day (Imperial County, 1978a). The potential problem of non-methane hydrocarbon emissions from geothermal facilities was analyzed by staff of the California Air Resources Board (Austin, 1979). They concluded that the photochemical reactivity of ethane (a principal component of the non-methane hydrocarbons - see Table 3-4) was so low that it would not have a significant effect on the formation of ozone in the valley.

ASSESSMENT OF EMISSIONS FROM A SINGLE SOURCE

The grid size used in assessing regional impacts is too large to resolve individual plumes from each emission source. For this reason, we consider in this section the impact of a single source. The source is assumed to be an elevated Gaussian one with a height of 30 m and a standard deviation of 20 m in the horizontal direction and 10 m in the vertical direction. The results for all locations within the valley are very nearly the same, so only the results for one location will be presented.

In Fig. 5-8 the annual average concentration from a unit source (emission rate = 1 unit/s) is shown (in micro-units per cubic meter). The concentration for any source strength can be readily obtained by multiplying the contour level by the source strength. For example, if the source strength for a particular emission were 5 g/s, then all the contour levels in Fig. 5-8 would be multiplied by a factor of 5. Table 5-3 shows the factor by which each concentration contour should be multiplied in order to correspond to the emission levels used in this study. Noting that the peak concentration for the unit source is below 4 micro-units/m³, it is readily seen that the

maximum average concentrations of NH_3 , Hg, and Rn are far below the federal standards.

Fig. 5-8. Isopleth plot of the annual average ground level concentration in micro-units/ m^3 for a unit source. The peak concentration is about 4 micro-units/ m^3 .

Table 5-3. Emission factors for a 100-MW single source.

	Salton Sea and Brawley power plants, g/s	Heber and East Mesa power plants, g/s
H_2S	4.4	1.5
NH_3	49	13.
CO_2	2400	3100.
Hg	0.0025	0.017
Rn	1.200 ^a	1.400 ^a
Benzene		1.7 ^b

^a The emission units for Rn are $\mu\text{Ci/s}$.

^b Based on maximum concentrations found in two wells on East Mesa.

ABATEMENT OF HYDROGEN SULFIDE

Our air quality analysis of the 3000 MW level of development shows that if H_2S emissions are unabated, the California hourly standard for H_2S would be frequently exceeded at different locations in the valley. State and federal air pollution laws, however, will require the installation of pollution control devices to prevent such violations. To guide the implementation of available control technologies, it is necessary to estimate the level of abatement that will be needed to avoid infractions of the H_2S standard associated with the production of energy from individual facilities well as multiple power plants. The distinction between individual and multiple units is important because the controls on emissions from single power plants should be stringent enough to eliminate violations of the H_2S standard when multiple plants are sited in the same region. Otherwise, the cumulative emissions from additional plants could eventually result in ambient concentrations of H_2S that are above acceptable levels. In that case, future development would be constrained unless extra controls were installed.

To prevent infractions of the H_2S standard within a 1-km radius of a single source, calculations made using the MSDM code indicate that emissions must be reduced to about 0.8 g/s. This corresponds to an emission rate of 30 g/MWh. By comparison, the Northern Sonoma County Air Pollution Control District (where The Geysers is located) will restrict emissions from geothermal facilities located in its jurisdiction to 50 g/MWh by the year 1985 (Joyce and Fontes, 1978). To attain an emission rate of 0.8 g/s, power plants in the Salton Sea and Brawley resource areas would have to reduce H_2S emissions by 82%, while those in the Heber and East Mesa areas would only have to have 47% abatement because of the lower amounts of H_2S in geothermal fluids. If the unabated emission rates of future geothermal facilities are different from the rates used in this study (e.g., 4.4 g/s for Salton Sea/Brawley resource areas and 1.5 g/s for the Heber and East Mesa areas), then the degree of control necessary to meet the H_2S standard will have to be adjusted accordingly.

It might be noted that to keep the peak concentrations (as opposed to 1-h-average concentrations) below $42 \mu g/m^3$ beyond 1 km, the emission rate must be reduced by another order of magnitude. It should also be noted that the peak concentrations near the source are highly dependent on the wind

speed and occur when the wind speed is low. A small change in a low wind speed can result in a change in the concentration by a factor of two to three or more. Consequently, the calculated concentrations can vary considerably depending on the wind speeds used in the study. In addition, the resultant concentrations will depend highly on the height and size of the source as well as the source rate and meteorology. For these reasons, the calculated distances, beyond which the levels will not exceed the standard, are only approximations.

The degree of control that is required to prevent violations of the H_2S standard resulting from the cumulative emissions of multiple sources can be inferred from air quality changes predicted for the 3000 MW level of development. Of the 22 sites that were used to study the frequency of hourly concentrations of H_2S , site 14 in the Salton Sea resource area (see Fig. 5-6) had the highest number of violations. The peak hourly concentration for H_2S at that site during January, the month with the most stable atmospheric conditions, was calculated to be about $260 \mu g/m^3$. To reduce that ambient, ground-level concentration to below the air quality standard (e.g., $42 \mu g/m^3$), 85% control (i.e., 0.7 g/s) would be needed for facilities in the Brawley and Salton Sea resource areas. The maximum hourly concentration of H_2S predicted for the towns of Heber (7), Calexico (11), and Holtville (10) was approximately $50 \mu g/m^3$. This level reflects the lower amount of emissions in the Heber and East Mesa resource areas. Emissions would only have to be rolled back 16% to reach the standard. However, 47% (0.8 g/s) control would still be necessary to prevent violations within a 1-km radius of individual facilities.

In the preceding analyses, the reference point for calculating the levels of H_2S control was the California hourly standard of $42 \mu g/m^3$. This ambient concentration is above the threshold at which most people can detect H_2S (see Section 10 for a discussion of the threshold detection levels for H_2S). Therefore, more stringent emission controls may eventually be necessary to avoid odor annoyances.

CONCLUSIONS

This assessment of the impact of a 3000 MW level of geothermal electrical energy production on air quality in the Imperial Valley, California has led to the following conclusions:

- The California 1-h standard for H_2S ($42 \mu\text{g}/\text{m}^3$) would be exceeded at ground level a significant amount of time over a large fraction of the valley, if H_2S emissions are not abated. The standard would be violated at least 1% of the time over an area of approximately 1500 km^2 surrounding the power plants in the Salton Sea area and extending over the power plants in the Brawley area. Similar episodes would probably occur over areas of approximately 5 to 10 km^2 surrounding the clusters of power plants in the Heber and East Mesa areas.

- The northern cities in the valley would receive the highest H_2S exposure. The standard would be exceeded 10% of the time in Calipatria on about two-thirds of the days each year, and Niland and Brawley would experience similar violations 2% of the time on about 20% of the days each year. In the cities of Heber, Calexico, and Holtville in the southern part of the valley, the standard would be exceeded on about 4% (14 days) of the days each year, and in Mexicali, Mexico, a couple of days each year. No breaches of the H_2S standard are predicted for the central valley cities of El Centro and Imperial.

- Model calculations for a single, 100 MW power plant indicate that the H_2S standard is not exceeded beyond a distance of about 1 km when the emission rate is less than 0.8 g/s.

- To achieve an emission rate of 0.8 g/s (equivalent to 30 g/MWh), power plants in the Salton Sea and Brawley resource areas would have to reduce emissions by approximately 82% (assuming an unabated emission rate of 160 g/MWh); facilities in the Heber and East Mesa resource areas would only have to have 47% abatement because of lower expected emission rates (55 g/MWh).

- At the 3000 MW level of development, the highest predicted hourly concentration of H_2S at a site within the Salton Sea resource area (where the greatest number of power plants were sited) was $260 \mu\text{g}/\text{m}^3$. If emissions were rolled back to 0.7 g/s at power plants in the Salton Sea and

Brawley resource areas, the maximum ambient concentration under the same atmospheric conditions would have been lowered to below the standard.

- The SO_2 standards would probably not be exceeded at the 3000 MW power level. At higher power levels, the SO_2 standard still would not be exceeded as long as the H_2S standard were not exceeded. This assumes that H_2S is not converted to SO_2 at the source and that the half-life of H_2S in the atmosphere is 13 h or greater.

- The levels of CO_2 produced by geothermal power plants would be within the normal fluctuations in the ambient concentration levels.

- The maximum ground-level concentrations of ammonia would be at least a factor of 10 below the federal standard for occupational exposure.

- The maximum ground-level concentrations of mercury would be at least a factor of 200 below the federal standard for occupational exposure.

- The maximum ground-level concentrations of radon and the short-lived radon daughters would be a factor of 100 below the federal standard.

- Assuming an emission rate of 1.7 g/s, the maximum hourly concentration of benzene would be more than 32 times lower than the proposed occupational standard.

SECTION 6. WATER-RELATED IMPACTS

D. Layton

The extent to which the geothermal resources of the Imperial Valley are developed for electricity production will depend a great deal on the availability of cooling water for power plants. There are five possible sources of cooling water. These are water imported from the Colorado River for irrigation, agricultural waste waters, steam condensate produced from power plants using flashed-steam energy conversion technologies, ground water underlying East Mesa, and water from the Salton Sea. Despite the presence of multiple cooling water sources, the use of the different supplies is complicated by problems involving quality, quantity, and distribution; the use and disposal of water; and various institutional, legal, and political constraints. A basic problem facing geothermal developers in the valley is how to acquire and use water without producing unacceptable impacts on the environment as well as agriculture.

In the water assessment, which is based on a study by Layton (1978a), we focus on the constraints and impacts that could be associated with the use of different water supplies to support large-scale geothermal development in the Imperial Valley. The analysis of water supply constraints relies on (1) a series of alternative water policies affecting the use of irrigation water, agricultural waste water, and steam condensate for cooling and (2) different conditions of agricultural water use affecting the future availability of irrigation water and agricultural waste water. A companion analysis is included on the changes in the elevation and salinity of the Salton Sea resulting from the consumption of agricultural waste waters for cooling. To complete the assessment of water-related impacts, we briefly examine some of the implications of inadvertent releases of geothermal fluids.

WATER RESOURCES OF THE IMPERIAL VALLEY

The driving force in the Imperial Valley's water balance, as shown in Fig. 6-1, is the amount of water used by crops. Irrigation water is distributed to fields in a 1629 mi system of main canals and laterals (IID,

Fig. 6-1. Components of the Imperial Valley's water balance. The driving force in the water balance is the evapotranspiration of crops.

1978). The flow of irrigation water to the valley, displayed in Fig. 6-2, for example, changes monthly in response to the water demand of crops, which is a function of cropping pattern, climate, and cultural practices. Waste water flows composed of canal losses, surface runoff from irrigated fields, subsurface drainage, and some discharges of ground water also fluctuate monthly and are related to inflows of irrigation water. Effluents from agricultural lands are collected in a drainage system consisting of about 1400 mi of surface drains. These drains, with few exceptions, discharge to

Fig. 6-2. Average monthly inflows of imported Colorado River water below Drop No. 1 (see Fig. 2-1) on the All American Canal for the years 1971 to 1975. The inflows vary according to the evapotranspiration demand of the crops planted.

the New and Alamo Rivers flowing to the Salton Sea. Figure 6-3 depicts the make up of the waste waters discharged from the valley's drainage system. Surface runoff from fields represents about 50% of the waste water discharges. In the future, however, increased efficiencies in the application of irrigation water will probably reduce this component of waste water discharges.

Baseline data on the quality of the valley's water resources was collected as part of the water quality element of the IVEP. Knowledge of background water quality conditions is needed in order to evaluate the possible effects of inadvertent releases of geothermal fluids on surface and ground waters. Table 6-1 presents summary statistics of the chemical composition of different waters in the valley. When irrigation water is

Fig. 6-3. Composition of waste waters discharged from the valley for 13-month periods (August to August) during the years 1974 to 1975 and 1975 to 1976.

applied to a field, either through flood or furrow irrigation, part ends up as runoff, part is lost to crop evapotranspiration, and some percolates through the soil column, removing dissolved salts as it flows downward. Leachate from fields is collected by a system of subsurface tube drains that are normally about 6 ft below the surface, with drainage lines spaced at 50 to 150 ft intervals across a field. These drains are located beneath nearly all the fields in the valley. Without the leaching they provide, soil salinities would reach toxic levels in the root zones of crops. Subsurface drainage is discharged to sumps or directly to surface drains where it mixes with surface runoff. Most of the surface and subsurface drainage eventually ends up in the New and Alamo Rivers. The chemistry of the different classes

of water in the valley bears out these relationships. In Table 6-1, note that the chemistry of the water in the surface drains comprises a mixture of agricultural waste water from the sumps and excess canal water.

Table 6-1. Chemical analyses of water samples taken from canals, sumps, drains, and rivers in the Imperial Valley. Samples were collected from April, 1976 through January, 1978 at over 70 stations (Pimentel, 1980).

Parameter	Dissolved concentrations in four classes of water, mg/l ^a			
	Canal ^b	Sump	Drain	River ^c
Na	150.	1600.	510.	860.
K	5.6	19.	11.	24.
Ca	94.	570.	210.	220.
Mg	33.	270.	94.	120.
Cl	140.	2300.	640.	1300.
HCO ₃	140.	360.	280.	220.
SO ₄ ^d	350.	2100.	1100.	910.
TDS ^d	930.	7600.	3300.	3700.
Ag	0.001	0.002	0.001	0.001
As	<0.01	<0.01	<0.01	0.01
B	0.28	1.9	0.74	1.70
Ba	0.10	0.17	0.12	0.17
Br	0.064	0.46	0.15	0.51
Cd	0.003	0.009	0.004	0.005
Cr	0.003	0.004	0.002	0.002
Cu	0.003	0.011	0.005	0.006
F	0.46	0.92	0.58	1.15
Fe	0.013	0.058	0.029	0.03
Hg	0.003	0.002	0.002	<0.005
Li	0.064	0.44	0.19	0.45
Mn	0.007	1.3	0.15	0.16
Ni	0.011	0.039	0.017	0.02
Pb	0.035	0.10	0.044	0.05
Rb	0.006	0.02	0.015	0.07
Se	0.003	0.013	0.007	0.006
Si	4.4	7.8	5.5	7.1
Sr	1.4	8.1	2.9	3.7
Zn	0.008	0.03	0.017	0.015

^aValues shown are the 10%-trimmed means of the available data. Each entry is the arithmetic mean of the remaining data after the largest 10% and smallest 10% of the values are discarded. This statistic is far less sensitive to outliers than the true arithmetic mean.

^bCanals contain water imported from the Colorado River.

^cNew and Alamo Rivers.

^dTotal dissolved solids.

Major water-related impacts of geothermal development involve changes in the Salton Sea's elevation and salinity caused by decreased inflows of agricultural waste waters. The sea was formed in the year 1905 when flood waters from the Colorado River destroyed the head gate of the Alamo Canal. The canal was then carrying water to the Imperial Valley via a route through Mexico, and the loss of the headgate allowed the entire flow of the river to enter the valley (Hundley, 1975). Since then the sea has been sustained by agricultural drainage from the Imperial and Coachella Valleys. From about 1925 to the present inflows have generally exceeded evaporation, and the sea's level has continued to rise. And as the amount of salt in the sea has accumulated over time, its salinity has also risen. In Fig. 6-4 recent trends in the sea's elevation and salinity are depicted. Future changes in the sea will depend on the magnitude of water and salt inflows. These inflows will be affected by practices of water use in agriculture, precipitation patterns, and changes in salinity in the Colorado River.

Fig. 6-4. Historic changes in the Salton Sea's salinity and elevation. The Sea's elevation has been increasing because inflows have exceeded evaporative losses. The large increase in salinity over the years 1966 to 1969 was a result of higher than normal accumulations of salt due to increases in the salinity of irrigation water imported to the valley from the Colorado River.

Increased efficiency in the use of water in irrigation (resulting in decreased discharges of surface runoff) coupled with the use of agricultural waste waters by geothermal facilities would decrease the sea's elevation and increase its salinity.

Ground water underlying East Mesa represents another important source of water in the valley. Millions of acre-feet of water have been recharged to aquifers beneath the Mesa from the unlined All American, East Highline, and Coachella Canals. Average seepage losses from the Coachella Canal alone are in the vicinity of 100,000 acre-feet per year (af/yr). Preliminary indications are that although aquifers contain significant quantities of water (Loeltz et al., 1975), additional geohydrologic studies are needed to confirm the extent of the resource.

REQUIREMENTS FOR COOLING WATER

Waste heat from geothermal facilities will have to be rejected to the atmosphere through the use of either evaporative cooling systems, once-through cooling, dry cooling towers, or hybrid wet-dry towers. Evaporative systems applicable to the Imperial Valley consist of mechanical-draft wet cooling towers and spray ponds. Wet cooling towers would be the favored method of cooling in the resource areas dominated by irrigated agriculture (i.e., the Heber, Brawley, and Salton Sea KGRAs) because they would displace less agricultural land than spray ponds. Either type of evaporative system could be implemented at the East Mesa KGRA since land-use problems are unlikely to occur there. Once-through cooling, using waste waters flowing in rivers or drains, is a remote possibility for two reasons. First, geothermal plants with their high heat rejection rates would need to withdraw large amounts of water. For example, a 100-MW plant using geothermal fluids of 300°C would require over 250×10^3 af/yr of water to pass through condensers operating with a 20°F temperature rise (Goldsmith, 1976). Second, the corresponding thermal discharges to a drain, river, or the Salton Sea would be prohibited unless "such a practice will maintain the existing water quality and aquatic environment of the State's water resources" (CSWRCB, 1975). Use of irrigation water for once-through cooling, however, would be an attractive option if positive benefits resulted from using the discharged warm water for irrigation. Further study

is needed before this cooling alternative can be implemented because biocides and corrosion inhibitors introduced to a cooling system could make discharges unacceptable for agricultural uses (Garrett, 1978). The use of dry cooling towers that do not consume water or hybrid wet-dry towers that significantly reduce water consumption is also improbable in the foreseeable future because these towers are much more expensive than other cooling systems (Fay et al., 1976).

Unless economic and technical circumstances change to favor other heat rejection methods, wet cooling towers will be the primary method of power plant heat rejection. Therefore, the water consumption estimates made in this study are based on that cooling technology. The quantity of water required by wet towers is equal to the total amount of water lost to evaporation, discharged as blowdown, and emitted to the atmosphere in the form of drift. Evaporative cooling losses associated with the operation of future geothermal plants were estimated by making the following two assumptions (see Ermak, 1977): (1) energy facilities in the Salton Sea KGRA have an average conversion efficiency of 0.14--facilities in the other KGRAs have an efficiency of 0.10--and (2) evaporative losses are 1.5% of the condenser flow rate. The resulting evaporation rates are 50 af/MW-yr for plants in the Salton Sea KGRA and 75 af/MW-yr for plants in the other KGRAs.

The amount of blowdown discharged from a cooling tower depends on the number of cycles the source water is concentrated by evaporation. As the number of cycles of concentration (C) increases, the discharge of blowdown decreases. The blowdown rate is equal to the tower evaporation rate divided by C-1. Usually the cycles of concentration associated with a particular water supply are a function of available options for the disposal of blowdown and the cooling system's ability to withstand saline circulating waters. We made the following assumptions to calculate blowdown discharges: irrigation water is concentrated four times and discharged to surface waters; steam condensate is concentrated 10 times and disposed of by subsurface injection; ground water, agricultural drain water, and Salton Sea water are concentrated 10, 5, and 2 times, respectively, and disposed of by subsurface injection or discharge to evaporation ponds (Layton, 1978b).

WATER SUPPLY ALTERNATIVES FOR POWER PLANT COOLING

There are no assured supplies of cooling water available for geothermal operations. Laws, regulations, environmental impacts, governmental policies, resource uncertainties, economics, and technical problems will all play a role in controlling the selection of cooling waters to support major geothermal energy production in the Imperial Valley (Layton, 1978a). The following discussions focus on the important ramifications of using irrigation water, steam condensate, agricultural effluents, ground water, and Salton Sea water to support geothermal operations.

Irrigation Water

Irrigation water imported from the Colorado River by the Imperial Irrigation District (IID) is an attractive source of cooling water. It can be transported directly to each of the geothermal resource areas through existing irrigation canals; and its chemical quality is much better than water from either agricultural drainage or the Salton Sea, the alternative surface water supplies in the valley. Furthermore, blowdown produced by concentrating irrigation water three to four times can be discharged to surface waters without exceeding present salinity standards. Water imported from the Colorado River cannot be used for power plants unless approval is obtained from the IID's board of directors. However, the board is unlikely to allocate substantial amounts of water for geothermal developments if that action limits the amount of water available to its primary constituents--the valley's farmers. Imperial County, by virtue of its authority to establish regulations controlling geothermal operations, is also in a position to control the use of irrigation water.

The county's present water policy, as expressed in the geothermal element in the county general plan, is to limit irrigation water to demonstration or experimental plants generating a maximum of 75 MW (net energy) in each "economic" geothermal anomaly for the first five years of operation. Consumption of irrigation water beyond the initial five years would only be permitted if it were demonstrated that "it is not economically and environmentally feasible to use alternative sources of water" (Imperial County, 1977). If the existing water policy of the county and the

allocation preference of the IID toward agricultural water users remain unchanged, then future geothermal facilities will not be able to rely on irrigation water as a major source of cooling water.

The underlying concern of the water policy adopted by the county is that geothermal development should not compete with agriculture for fresh water supplies. Accordingly, just 75 MW can be generated in each KGRA using irrigation water for cooling. But, expanded use of irrigation water by geothermal facilities might be possible if a policy were adopted that allowed the use of excess irrigation water for cooling power plants. Surplus water conditions would occur if efforts to conserve water continue by the IID and the valley's irrigators, no new lands are brought into production, and use of water by crops (as determined by annual cropping patterns) is not unusually high. Excess water would be used as a supplemental source of cooling water for power plants using waste waters from irrigated agriculture. Use of irrigation water whenever it is available would be advantageous because its treatment and disposal costs would be lower than those for agricultural waste waters.

If surplus irrigation water is used to bring new lands into agricultural production, particularly arable lands on West Mesa, then little if any water would be available for geothermal facilities. At this point though, it is not clear whether such lands will be developed. The following discussion describes the circumstances that would allow irrigation water to be distributed to geothermal facilities, assuming that water surpluses do exist in the future.

The distribution of irrigation water to industrial users will be governed by the interpretation of existing state water laws and laws affecting the Colorado River. California water users receive a basic allotment of 4400×10^3 af/yr, and it is distributed to users by priorities established in the Seven-Party Agreement of 1931. The agreement includes an annual allocation of 3850×10^3 af according to the following priorities: Priority 1--the Palo Verde Irrigation District; Priority 2--the Yuma Project; and Priority 3--the Imperial Irrigation District and lands served by the All-American Canal in the Imperial and Coachella Valleys (some additional lands in the Palo Verde Irrigation District are also contained in the third priority) (CRBC, 1969).

At such time that the agricultural users are limited to 3850×10^3 af/yr (probably when the Central Arizona Project is completed), water will be allocated by priority; the Palo Verde Irrigation District and Yuma Project would withdraw water first, and the remaining water would be left for the IID and the Coachella Valley County Water District (CVCWD). Assuming that the beneficial consumptive use of the first two priorities continues at the historic rate (i.e., 479×10^3 af/yr since the year 1964), then approximately 3370×10^3 af/yr would be available to lands served by the All American Canal in the Imperial and Coachella Valleys. The IID could conceivably divert all the available water because it is the senior appropriator to the CVCWD, (USBR, 1973), but that is improbable. Instead, IID diversions will probably remain near the historic rate of about 3000×10^3 af/yr. With that diversion rate, about 370×10^3 af/yr would remain for the CVCWD, considerably lower than the CVCWD's past withdrawal rate of 507×10^3 af/yr. Fortunately, the first 49 miles of the Coachella Canal (see Fig. 2-1) are going to be lined with concrete, saving nearly 132×10^3 af of water each year (USBR, 1973). Therefore, when the IID withdraws 3000×10^3 af/yr and the other priority users consume 479×10^3 af/yr, the remaining 371×10^3 af/yr would provide essentially the same amount of water as did the previous diversion rate of 507×10^3 af/yr.

Under those water supply and use conditions, surplus water would exist whenever the IID's annual diversion was below 3000×10^3 af. But the allocation of that water to geothermal facilities could be subject to a compromise agreement (USBR, 1973) reached between the IID and the CVCWD in the year 1934, which clarified water right priorities in the Seven Party Agreement of 1931. The compromise states

"Imperial Irrigation District shall have the prior right for irrigation and potable purposes only and exclusively for use in the Imperial service area as herein after defined or here under modified to all water apportioned to said Imperial Irrigation District and other lands under or that will be served from the All-American Canal in Imperial and Coachella Valleys as provided in the Third and Sixth Priorities..."

Emphasis on "irrigation and potable purposes" implies that those uses have priority over industrial uses. If interpreted that way, water used for irrigation purposes in the Coachella Valley would have priority over that used for geothermal purposes. Surplus water would then become available for geothermal operations when irrigation water consumption of the agricultural water users in the first three priorities was below 3850×10^3 af/yr.

Under extreme water shortage conditions, when California's allotment of 4400×10^3 af/yr could not be satisfied, surplus water would be non-existent. The IID would then depend on a "present perfected" water right, defined in the Arizona vs California Supreme Court Decree as a right existing before the Boulder Canyon Project Act became effective on June 25, 1929. The IID has claimed a present perfected right of 2600×10^3 af/yr (Purtich and Rogozen, 1977).

The IID is authorized to distribute water that is determined to be surplus by Section 22259 of the California State Water Code. It states

"If its board deems it to be for the best interests of the district, a district may enter into a contract for the lease or sale of any surplus water not then necessary for use within the district, for use either within or without the district."

The "best interest of the district" implies that such a contract would have the prior support of the valley's farm community; and support would undoubtedly require assurances that sufficient surpluses did indeed exist, and agricultural and domestic users would not be cut back. Even with the necessary assurances that existing water users would not be affected, resistance to the delivery of irrigation water to power plants would remain. The California Farm Bureau Federation, for example, opposes the use of water of irrigation quality for power plant cooling (Hendrickson, 1977) and could not be expected to support the consumption of Colorado River water by geothermal facilities. To alleviate fears that continued use of surplus irrigation water by geothermal plants would pre-empt agricultural water uses, any contracts for such water would have to be short term--perhaps one year in duration. Contracts longer than three years must have the approval of the California Districts Securities Commission.

One other mechanism for obtaining imported water from the Colorado River to cool power plants is to implement the Lanterman Act. Under the provisions of that act, the Metropolitan Water District (MWD) of Southern California would be able to provide water (including up to 100×10^3 af/yr of Colorado River water) to power plants located outside of its service boundaries. It is stipulated in the act that most of the power generated from plants receiving water must be used "directly or indirectly through exchange, within the district, or for pumping, producing, treating, or reclaiming water for use in the district." Furthermore, the act requires that low quality water (i.e., agricultural waste waters and brackish ground

waters) be used for cooling to the extent practical. If future geothermal power plants in the Imperial Valley meet the requirements of the act, and other cooling waters are not feasible, Colorado River water would then be available for cooling. Irrigation water delivered to energy facilities by the IID would come from MWD's share of the Colorado River. The applicability of this cooling water option will remain questionable, however, until other cooling water supplies in the valley are exhausted or are shown to be impractical for technical, economic, or regulatory reasons.

Steam Condensate

Geothermal plants that have flashed-steam designs could use steam condensate as cooling water, thus eliminating or greatly reducing the need for an external water supply. The number of flashed-steam conversion systems and the nature of subsidence control policies will determine the role steam condensate eventually plays in meeting the cooling water requirements of geothermal facilities. To prevent, or at least reduce, potential impacts of subsidence on irrigation structures, and subsurface drainage systems, current Imperial County policy (Imperial County, 1977) requires the full injection of all fluids withdrawn for geothermal operations in the irrigated portion of the valley (i.e., the volume of fluids withdrawn = volume of fluids injected). Deviations from that policy would only be considered by the county after the California Division of Oil and Gas approved the initial injection program. A full injection policy requires external water supplies to support the operation of a geothermal power plant. One available option with a full injection policy is to use an external supply, such as irrigation water or agricultural waste water, for cooling and to inject all of the residual geothermal fluid. This option would be necessary for binary fluid conversion power plants, because condensate that could be used for cooling would not be produced. A second option is to use condensate from flashed-steam power plants as cooling water and an external water supply for injection. Salton Sea water, for example, could be used as an injection fluid for flashed-steam facilities near the sea. Similarly, agricultural effluents could be used for injection at KGRAS in the valley. The injectability of those water supplies, though, has yet to be fully proven.

If partial injection were allowed, then condensate could be used as cooling water and no external supplies would be necessary. Although partial injection would be favored from the standpoint of water supply, three uncertainties are associated with the implementation of such a practice: (1) what would be the effect on subsidence if only 75 to 80% of the withdrawn fluids were injected over the 30-yr life of a power plant? (2) how sensitive are drainage systems and irrigated lands to changes in land elevation? and (3) what are the costs of mitigating the effects of subsidence?

Answers to these questions could eventually be obtained by conducting partial injection experiments. If results are positive, then condensate use might be permitted on a case by case basis for flashed-steam facilities in the irrigated part of the valley (see Section 8 for a discussion of subsidence). The most plausible location for partial injection is the East Mesa KGRA, because it is in the valley's nonagricultural desert region where subsidence effects are not likely to be serious. But there too, subsidence will need to be carefully monitored to ensure that any unforeseen problems and undesirable impacts do not arise.

Agricultural Waste Water

Drainage from agricultural lands, composed primarily of surface runoff from irrigation, subsurface drainage, and water losses from the canal system, is a third source of cooling water. Imperial County water policy favors the use of agricultural water effluents over irrigation water for rejecting power plant heat, because its quality is generally unsuitable for irrigation. The California State Water Resources Control Board (CSWRCB, 1975) also supports the use of agricultural waste waters for power plant cooling. Waste water entering the Salton Sea from the Imperial Valley amounts to approximately 1000×10^3 af/yr each year, making it a significant water resource in this arid region. However, the following considerations must be dealt with before agricultural waste waters can be used extensively for power plant cooling.

o Saline blowdown resulting from the use of waste waters cannot be discharged to agricultural drains or the valley's rivers because of water quality regulations. Consequently, blowdown must be disposed of by

subsurface injection or surface disposal to either evaporation ponds or, perhaps, a regional waste disposal site. Disposal to ponds would generally be unacceptable in agricultural areas because of possible conflicts arising from use of the land (e.g., a 100-MW power plant discharging 700 af/yr of blowdown would require about 121 acres of land for evaporation, assuming an annual evaporation rate of 5.78 ft). Subsurface injection would then be the only acceptable alternative. A regional Class II-1 waste disposal site could receive saline blowdown (CSWRCB, 1977), however, the costs of transporting blowdown to such a site could be prohibitive.

● Large scale consumption of agricultural effluents not only would cause the Salton Sea's elevation to decline but, at the same time, would cause its salinity to rise. The sea's salinity has been gradually rising through time--except in periods of high rainfall or agricultural drainage--and reductions of waste flows resulting from power plant withdrawals for cooling purposes would aggravate the situation. As the salinity rises, it will reach a point where the productivity of the sea's sport fishery will be adversely affected. Also, the water quality control plan adopted by the Regional Water Quality Control Board (CRWQCB, 1975) states

"Until a salinity control project is implemented, the objective is to limit the rate of increase of total dissolved solids of the Salton Sea to the lowest possible value, consistent with its primary purpose as a reservoir to receive and store agricultural drainage and seepage water."

At the present time no salinity control projects are contemplated, and therefore, major withdrawals of waste water for cooling are likely to need the approval of the regional board. A beneficial impact of waste water withdrawals for cooling would be a decline in the sea's elevation. Rising water levels in recent years have damaged shoreline property, inundated irrigated lands, and flooded parts of the Salton Sea National Wildlife Refuge as well as the Salton Sea KGRA. A stable or decreasing sea level would reduce adverse impacts on those areas. But a decreasing elevation would result in higher salinity levels and adverse impacts on the sea's aquatic ecosystem.

● Waste flows that are unevenly distributed in time and space could pose difficulties with the acquisition of cooling water for some power plant sites. The Heber and East Mesa KGRAs, for example, are near the boundaries of the drainage system where waste flows are not as great as they are in the

northern part of the valley. Seasonal variations in agricultural effluents resulting from changes in cropping patterns further complicate the use of waste waters in those resource areas. In addition, long term water conservation efforts by irrigators and the IID will mean that smaller volumes of waste water will be available for power plant cooling.

● Ownership of waste water flowing in the New and Alamo Rivers may have to be determined. Section 1201 of the State Water Code states

"All water flowing in any natural channel, excepting so far as it has been or is being applied to useful and beneficial purposes upon, or in so far as it is or may be reasonably needed for useful and beneficial purposes upon lands riparian thereto, or otherwise appropriated, is hereby declared to be public water of the State and subject to appropriation in accordance with the provisions of this code."

Thus, if the rivers are considered to be flowing in "natural channels," the water could be appropriated by a user putting the water to beneficial use, and the State Water Resources Control Board would then have jurisdiction over that water. On the other hand, the rivers do flow within the boundaries of the IID, and Section 22076 of the State Water Code states

"A district may do any act in order to put to any beneficial use water under its control."

And by Section 22078, the IID is empowered to recapture and salvage any water for the beneficial use of the district. Since nearly all of the water in the rivers is derived from Colorado River water imported to the valley by the IID, the district may indeed have control over that water.

● Even though historic flows in the New River crossing the United States-Mexican border have averaged over 100×10^3 af annually, the long term availability of water from the New River for major geothermal development in the Heber KGRA will remain uncertain until an agreement is reached between the two countries that guarantees the quantity of Mexican inflows. The current agreement dealing with flows from Mexico is Minute 197 of the International Boundary and Water Commission, United States and Mexico (USDS, 1951). Under Minute 197, water discharged from the Mexican irrigation system (i.e., unused irrigation water) entering the United States cannot exceed an annual average of 35,000 af/yr for any five-year period. This flow restriction was implemented to promote the beneficial use of Colorado River water delivered to Mexico. It does not cover discharges of irrigation runoff or municipal wastes. A new agreement governing flows from Mexico that is favorable to geothermal development would not only have to be

consistent with the purposes of Minute 197, but it would also have to address the quality of Mexican inflows, which include untreated domestic wastes.

- Salt drift emitted from cooling towers using drain waters having a high TDS content could cause crop damage in the vicinity of power plants located in agricultural areas (see Section 9).

- Consumption of agricultural drain waters to support large scale geothermal development will alter flows in the New and Alamo Rivers and affect riparian habitats as well as fish populations. If unacceptable damage is done, limitations may eventually be placed on appropriations of river water in order to protect in-stream uses.

East Mesa Ground Water

Ground water will not become a major source of cooling water for geothermal development in the valley--even with substantial proven reserves--unless it can be transferred to the Heber, Brawley, and Salton Sea KGRAs; but there does not seem to be an effective method to transport it at this time. Ground water could conceivably be pumped into one of the canals crossing East Mesa, thereby allowing an equivalent volume of irrigation water to be delivered to geothermal facilities elsewhere in the valley. Before that could be done though, the quality of the water would probably have to be better than, or at least the same as, canal water. Existing water quality data (Loeltz et al., 1975) show that ground water quality varies a great deal on East Mesa, but some water might be suitable. In addition to the question of water quality, the legal implications of making such a transfer need to be examined. Use of pipelines is the only other method of transporting ground water to the valley's geothermal resource areas--but whether they will be economically feasible or not is uncertain.

Water from the Salton Sea

As a source of cooling water, the Salton Sea has several drawbacks. First of all, its salinity would pose problems of scaling and corrosion, and specially designed salt-water cooling towers would be necessary. Extensive chemical conditioning of the seawater would also be required to control the

formation of calcium and silica precipitates. Furthermore, large quantities of saline blowdown would have to be disposed of in some acceptable manner and that could be difficult because subsurface injection faces technical uncertainties and surface disposal requires substantial land for evaporation ponds. Another potential problem involving the use of seawater in a cooling tower involves salt drift that could cause crop damage when deposited on crops in the vicinity of a tower.

Salton Sea water could be more suitably used as an injection fluid for subsidence control purposes. In that use, it would serve as makeup water injected to a geothermal reservoir so that steam condensate could be used for cooling when full injection is required. The sea's salinity would also be lowered by withdrawing water for reservoir injection. That would happen because salts as well as water would be removed from the sea. But for such withdrawals to have a significant impact on salinity, thousands of acre-feet would have to be removed annually. In studying this aspect of sea water injection, Goldsmith (1976) concluded that even with 2000 MW on-line in the Salton Sea KGRA in the year 1982, approximately 40 yrs of injection at 120,000 af/yr would be needed to stabilize the sea's salinity at 35,000 ppm TDS.

COOLING WATER AND FUTURE GEOTHERMAL DEVELOPMENT

In order to analyze possible water-related constraints to geothermal energy production, five policies were specified that affect the distribution of water supplies to geothermal facilities. Six combinations of the separate policies were selected to represent the scope of future regulatory controls on the use of cooling water. Two trends in agricultural water use were used to simulate future water balances in the valley. A conservation case was chosen to represent increased efficiencies in the distribution and application of irrigation water. A reference case based on the assumption that present practices of water use in agriculture will continue unchanged was selected as the other. Annual flows of irrigation and waste water associated with the two cases were predicted for low, medium, and high values of crop evapotranspiration.

The quantity of water available from the various supplies to meet the cooling requirements associated with three scenarios of energy production was a function of the water policy combinations, the efficiency of water use

in irrigation, and the level of crop evapotranspiration. The policy combinations controlled the allocation of cooling water supplies; the reference and conservation cases of water use plus the level of crop water use controlled the physical availability of surplus irrigation water and agricultural waste waters.

Future Water Supply Conditions

The physical availability of irrigation water as well as agricultural waste waters will be controlled by the amount of water actually used by crops in evapotranspiration (ETa) and the efficiencies with which water is conveyed, distributed, and applied to crops. Two cases were used to represent future efficiencies of water use: a reference case (REF), which is based on the assumption that existing efficiencies remain constant, and a conservation case (CON), which is based on the assumption that efficiencies improve with time. With increased water conservation and lower crop water requirements, surplus irrigation water could become available for nonagricultural uses, because less water would be imported from the Colorado River. At the same time, though, waste waters resulting from irrigation would be reduced. The amounts of irrigation water potentially available for use by future geothermal developments were calculated by subtracting the annual inflows predicted at Imperial Dam to support crop water requirements under the REF and CON cases from 3000×10^3 af and multiplying the difference by 0.66. The amount of excess water was adjusted downward by a third to account for inaccuracies in forecasting the amounts of water needed for agricultural operations and the amount of water available from the Colorado River. In the REF case, 162×10^3 af/yr of irrigation water were available after the irrigation requirements associated with the low level of crop ETa were met; 8.7×10^3 af/yr were available with the medium ETa; and none was available with the high level ETa. In the CON case, with its increasing water use efficiencies, 471×10^3 af/yr would become available in the year 2010 with the low ETa level, 284×10^3 af/yr with the medium ETa level, and 177×10^3 af/yr with the high ETa level. Surplus water would be unavailable with the high level of crop water use until the early

1990s when inflows of water to the valley were predicted to fall below 3000×10^3 af/yr. Prior to that time, we assumed that annual inflows to the valley could exceed 3000×10^3 af because of surplus water in the Colorado River.

Agricultural waste waters, unlike irrigation water, must be collected from a river or drain and then transported to a power plant. The Salton Sea and Brawley KGRAs could use river water because of their proximity to the New and Alamo Rivers that together carry most of the valley's agricultural drainage to the Salton Sea. The Heber and East Mesa KGRAs have less access to waste waters because they are near the borders of the drainage system. The variability of discharges in rivers and drains, caused by daily and monthly changes in crop irrigation, further complicates the use of agricultural effluents for cooling. Without any surface storage at power plants, the annual safe or dependable yield of a particular waste water stream can be conservatively defined as the annual equivalent volume of the lowest expected rate of discharge. The amounts of water from the New and Alamo Rivers available for use in the Salton Sea and Brawley KGRAs under the REF and CON cases are depicted in Fig. 6-5. The reliable yields of the rivers were assumed to equal the annual equivalent volume of the smallest monthly discharge expected to occur each year for the three levels of crop evapotranspiration and degree of water conservation in agriculture. Yields for the Heber and East Mesa KGRAs are presented in Fig. 6-6. Water for Heber resource area was derived from water in the New River flowing across the border from Mexico plus drainage within the KGRA. Waste water from the East Mesa KGRA was derived from two drainage areas in the vicinity of the resource area.

Water Supply Constraints

The amount of cooling water available from each source will be controlled by water policies that emerge at the local, state, and federal levels of government. If these policies prove overly restrictive, then geothermal energy production will be constrained. We examined the extent of possible restrictions on water supplies using six combinations of policies affecting the availability of irrigation water, steam condensate, and agricultural waste waters; the three scenarios of energy growth in the

Fig. 6-5. Agricultural drainage flows available to the Salton Sea and Brawley KGRAs. Drainage discharges are predicted for low, medium, and high levels of crop evapotranspiration (ETa) under both existing water use practices (REF case) and increased conservation (CON case). a. Salton Sea KGRA. b. Brawley KGRA.

Fig. 6-6. Agricultural waste waters available to the Heber and East Mesa KGRAs. Annual discharges of agricultural waste waters from irrigated lands are predicted for low, medium, and high levels of crop evapotranspiration (ETa) under existing water use practices (REF case) and increased conservation (CON case). a. Heber KGRA. b. East Mesa KGRA.

valley; and estimates of future water supply conditions (see Layton, 1978a).

Five policies affecting either the use of steam condensate, irrigation water, or agricultural waste water were chosen to represent possible geothermal water policies. Policies affecting Salton Sea water and ground water were not included because their use is more likely to be controlled by nonpolicy factors such as technical feasibility, economics, or availability of resources. Two of the policies selected involve steam condensate, two involve the use of irrigation water, and one involves agricultural waste water. Six combinations of the policies were then identified and the consequences of adopting different sets of policies were studied.

Policy I. Power plants on East Mesa are the only facilities allowed to use condensate for cooling without the need to inject an equivalent volume of an external water supply for subsidence control purposes.

This policy is based on the assumption that East Mesa lands are less susceptible to impacts caused by subsidence than are the agricultural lands within the central portion of the valley. Thus, condensate could be used without injecting an equivalent volume of some other water to control subsidence. The importance of steam condensate as a source of cooling water will also be a function of the technology mix of flashed-steam conversion facilities and binary-fluid facilities incorporating down-hole pumps that do not allow geothermal fluids to flash to steam. For assessment purposes, it is assumed that 50% of the electrical output from the East Mesa KGRA is produced by flashed-steam plants and the other 50% by binary plants.

Policy II. Partial injection of geothermal fluids is permitted for all geothermal facilities in the valley's four KGRAs.

It is conceivable that a policy of partial injection (e.g., 80% of the withdrawn fluids are injected) might be adopted to allow flashed-steam plants in the Heber, Brawley, and Salton Sea KGRAs to consume condensate for cooling if future subsidence, related to the production of geothermal fluids in the irrigated part of the valley, proves to be minor and does not significantly disrupt agricultural operations. It is assumed here that 50% of the projected electrical output from the East Mesa, Heber, and Brawley KGRAs will be produced by flashed-steam facilities. However for the Salton Sea KGRA, it is assumed that 75% of the electricity generated will be from flashed-steam plants and 25% by binary technologies relying on down-hole

pumps. The reason for the lower percentage of binary technologies is the possibility that corrosion and scaling problems will hinder the use of down-hole pumps with the brines of the Salton Sea resource area.

Policy III. Irrigation water is limited to the first 75 MW of energy produced in each KGRA.

Imperial County's geothermal water policy is essentially the same as Policy III; however, with Policy III irrigation water can be used indefinitely.

Policy IV. Irrigation water is allocated to geothermal facilities only when surpluses exist.

In years when the diversions of water from the Colorado River to the IID fall below 3000×10^3 af and the other priority agricultural users in California divert less than 850×10^3 af, surplus water could be available for geothermal facilities. The surplus would be a replacement for agricultural waste waters used for power plant cooling. The benefit of this policy is that it would compensate for reductions in flows of waste water that result from low levels of crop water use, as well as increased conservation efforts by the IID and the valley's irrigators.

Policy V. Agricultural waste water is permitted for power plant cooling in all of the KGRAs.

Waste water effluents from irrigated agriculture will always be an important source of cooling water because they are generally unsuitable for other uses. Nevertheless, there are legal, technical, and environmental constraints that may eventually serve to limit the extent to which agricultural waste waters are used for cooling. Policy V, though, does not include any limitations on waste water used by geothermal facilities.

The water policies were combined in six ways to create a range of policy combinations (A through F in Table 6-2) representing some of the ways in which they might be jointly implemented. Each of the policy sets differs according to the amounts of cooling water it makes available for geothermal operations and the impacts it causes.

The water supplies available from each set of water policies to satisfy the cooling water requirements associated with a projected level of energy production were allocated in this order: steam condensate, then irrigation water, and finally, waste water. Surplus irrigation water is consumed before agricultural waste waters, even though it is considered a supplemental supply for cooling systems designed to use waste waters, because the

Table 6-2. Water policy combinations representing future regulatory controls.

Water Policies		Policy Combinations					
		A	B	C	D	E	F
I. ^a	Limited condensate	X	X			X	
II. ^b	Increased condensate			X	X		X
III. ^c	Fixed allocation of irrigation water	X		X			
IV. ^d	Variable allocations of irrigation water		X		X		
V. ^e	Unrestricted agricultural waste water use	X	X	X	X	X	X

- ^a Policy I allows the partial injection of geothermal fluids in the East Mesa KGRA so that steam condensate can be used for cooling. It is assumed that 50% of the energy is produced by flashed steam power plants with the remaining 50% generated by binary plants using down hole pumps that do not allow geothermal fluids to flash to steam.
- ^b Policy II permits the use of condensate in all of the Valley's resource areas for power plant cooling. Half of the energy generated in the East Mesa, Heber, and Brawley KGRAs is assumed to be from flashed-steam facilities, and 75% in the Salton Sea KGRA.
- ^c Policy III limits the use of irrigation water to the first 75 MW of energy generated in each KGRA.
- ^d Policy IV allocates surplus irrigation water to geothermal facilities for use as cooling.
- ^e Policy V supports the unrestricted use of agricultural waste waters for cooling, regardless of possible impacts.

treatment and disposal costs are lower for irrigation water. If the condensate and irrigation water made available by a policy combination do not meet the cooling water requirements of power plants in a KGRA, then agricultural waste waters are used to satisfy the remaining demand. Water supply deficits arise when the safe yields of waste water flows are smaller than the requirements for cooling water. Under this allocational procedure, the East Mesa KGRA receives annual water supplies first, followed by the Heber, Brawley, and Salton Sea resource areas. This sequence was chosen because it represents one way in which development could occur, that is, from resource areas having the least saline geothermal fluids to areas having the highest.

None of the water policy combinations produced water supply deficits in any of the KGRAs with the low and medium scenarios of energy growth. This means that substantial geothermal development could occur in the valley,

provided that no restrictions are placed on the use of agricultural waste waters for cooling. For the high growth scenario, only the Heber and East Mesa KGRAs had deficits. Policy combinations A and E produced consistent water supply deficits in those KGRAs because of restrictions on the use of condensate and irrigation water for cooling. The most constraining policy set is E. Condensate use is limited to 50% of the projected energy production at the East Mesa resource area. The remaining energy production at that KGRA as well as the other KGRAs relies on agricultural waste waters for cooling or for injection. Reliance on water flows in drains and in the New River because of policy set E would limit energy production to approximately 800 MW of production in the Heber KGRA. But if Mexican inflows in the New River became unreliable for some reason, energy production would be severely curtailed because water in the New River represents about 80% of the total waste water supply available to the KGRA. However, if the actual energy potential of the Heber KGRA is lower than 800 MW, then geothermal development will not be constrained.

Policy sets C and F allow the use of condensate for cooling with flashed-steam facilities without the need for an external supply of reservoir-injection fluid to control subsidence. This results in limited deficiencies of cooling water. The deficits could be eliminated if flashed-steam technologies made up a larger portion of the assumed technology mix. Variable allocations of surplus irrigation water, included in policy combinations B and D, greatly reduced water supply deficits except when all of the imported irrigation water was needed to irrigate crops for the high water use case.

No major water supply problems are evident for the East Mesa KGRA except in the CON case where increased water conservation results in reduced flows of waste water. This creates deficits with policy combinations A, C, E, or F. The largest deficit results in the production of about 600 MW, or over 200 MW less than the amount forecast. Of the 600 MW generated, steam condensate supported 400 MW, or half of the projected output in the year 2010, and agricultural waste waters only supported 200 MW. Waste waters could support another 100 MW with REF water use efficiencies and low crop ETa. However, if the diversion of waste water flows is uneconomical, then steam condensate, irrigation water, and possibly ground water would have to support geothermal development.

Without any cooling water constraints to energy production under the high growth scenario and using all the KGRAs, 8000 MW would ultimately be produced. With water policy combination E and average crop water use, though, maximum growth would be limited to about 7000 MW for the REF water case and 6800 MW for the CON case. Power production would be slightly lower in both water cases for low crop ETa because there would be less surface runoff from the irrigation of crops. Maximum production could be reduced further if the use of steam condensate at East Mesa was restricted or if water inflows from Mexico in the New River proved to be an unreliable source of cooling water for the Heber resource area.

IMPACTS ON THE SALTON SEA

The most important water-related impacts of geothermal development involve changes in the Salton Sea's elevation and salinity because of decreased inflows of agricultural waste water. The response of the sea's surface elevation to reduced inflows of agricultural effluents can be predicted by relating changes in the sea's volume (resulting from inflows, precipitation, and evaporation) to elevation. We used a recursive water balance model that predicts the volume of the sea at the end of year $t + 1$ as a function of the sea's volume at year t plus the change in volume between the year t and $t + 1$. Once the volume is determined for year $t + 1$, the elevation is calculated (Layton, 1978a).

Of all the policy combinations affecting the acquisition of cooling water supplies, combination E would have the greatest effect on the sea because it promotes the greatest use of agricultural waste waters. In Fig. 6-7 predictions of future elevations are shown for the REF and CON cases without geothermal development and for the REF case with the medium scenario of energy growth and policy combination E. The predictions are based on normal hydrologic conditions and average crop evapotranspiration. Policy combination E and medium energy growth does result in lower surface elevations, yet it takes nearly 30 yr before the 1975 elevation is reached. Elevation declines associated with the CON case indicate that increased efficiencies in irrigation would have an even greater impact on elevations than medium energy growth. Reductions in surface elevations resulting from geothermal development will vary according to the amount of agricultural

Fig. 6-7. Elevations of the Salton Sea predicted for existing and improved irrigation efficiencies (REF and CON cases) with no geothermal development, and the REF case with medium energy growth and policy set E. Predictions are based on normal hydrologic conditions and average crop evapotranspiration.

waste water used for cooling power plants, or alternatively, for reservoir injection. Consequently, policy combinations like B and D, which minimize the use of waste water would cause smaller surface level changes than combination E, which promotes the greatest use of agricultural effluents. With medium crop ETa, the effects of the various policy combinations in decreasing order are: E, A, F, B, C, and D. Using policy sets B, C, and D results in smaller declines in the sea's elevation, because the use of steam condensate and irrigation water for cooling is encouraged.

The cumulative amount of salt added to the sea in the year $t + 1$ dissolved in the volume of water at that time determines the sea's salinity. Figure 6-8 presents the salinity changes for the REF and CON cases without geothermal development and the REF case with the medium scenario of energy growth and policy set E. The CON case exhibits faster increases in salinity than the REF case because higher irrigation efficiencies result in reduced inflows of irrigation drainage to the sea. With smaller inflows to dilute the sea, its salinity rises more quickly. In addition, we assumed that the salinity of water imported from the Colorado River gradually increases with time, whereas in the REF case it was held constant. These predictions indicate that water conservation in agriculture, as specified in the CON case and without geothermal

Fig. 6-8. Salinity of the Salton Sea predicted for existing and improved irrigation efficiencies (REF and CON cases) with no geothermal development, and the REF case with medium energy growth and policy set E. Predictions are based on normal hydrologic conditions and average crop evapotranspiration.

development, has a greater potential for increasing salinities than does geothermal development following the scenario of energy production under the REF case. The most rapid increases in salinity would occur if geothermal development coincides with water conservation represented by the CON case. Policy combinations C and D would minimize the effects on the sea due to geothermal operations because a greater burden of the cooling requirements of power plants would be met by steam condensate.

The effects of these salinity changes on the sea's aquatic ecosystem are discussed in the Section 11.

INADVERTENT RELEASES OF GEOTHERMAL FLUIDS

The quality of surface waters and ground waters in the valley could be adversely affected by accidental releases of geothermal fluids (Layton and Pimentel, 1980). Accidental releases, however, do not represent a major environmental concern because there are methods to prevent or mitigate releases (e.g., carefully placed containment berms). If surface spills occur as geothermal development proceeds, the severity of each spill will vary according to: (1) the chemical composition of both the geothermal fluid and the surface water with which it mixes, (2) the volume of the geothermal fluids reaching the surface water, and (3) the flow rate in the drain or river. Subsurface leaks through improperly completed wells are also of concern because they could contaminate ground waters.

There are two ways in which a spill could contaminate surface waters within the irrigated portion of the valley. First, a spill could enter a drainage ditch or river by overland flow from where the release occurs. The effect of the spill would be most severe where the fluid enters the surface water; however, the effect would be transient because of the movement of water in the drain or river. Subsurface drains that are normally used to remove saline water from the root zones of crops could also collect leachate derived from a surface spill and discharge it to a surface drainage ditch. This is the second mechanism by which a spill could affect water quality. Because of the slow movement of water toward subsurface drains, it could take years before contaminated leachate reaches subsurface drain lines (see Jury and Weeks, 1978). The results of a study completed by Pimentel et al. (1978) as part of the IVEP indicate that Li and B can be used as chemical

"finger prints" to determine if leachate discharged from subsurface drains located beneath a spill is contaminated. The severity of spills would diminish southward across the valley because the salinity of geothermal fluids generally decreases in this direction.

Ground water contamination is a potential concern on the east side of the valley between the Alamo River and the East Highline Canal. In that area there are a number of domestic wells. However, no major geothermal resources are now associated with this part of the valley, and so the possibility that geothermal operations would affect ground water there is remote.

CONCLUSIONS

- Irrigation water imported from the Colorado River is presently dedicated to agriculture, and it is unlikely that large amounts of this water will be made available to geothermal facilities on a long term basis. There is a slight possibility, though, that surplus irrigation water may become available in the years ahead as a supplemental source of cooling water if water conservation in agriculture continues to improve.

- Steam condensate from flashed-steam power plants can supply all, or nearly all, the water requirements of those facilities. No external supplies of cooling water would then be needed. 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 fluids. Thus, developers cannot rely on condensate as the sole source of cooling water unless they can show that subsidence would be inconsequential if the condensate is not injected along with the spent geothermal fluids.

- Waste water from agricultural lands in the Imperial Valley amounts to about one million acre feet annually, making it a significant water supply in this arid region. Agricultural waste waters could sustain almost 7000 MW of geothermal energy development even if increased water conservation in irrigation reduces discharges of drain water.

- The consumption of waste waters for power plant cooling will accelerate increases in the Salton Sea's salinity. Such increases would place added stresses on the sea's ecosystem (see Section 11). If waste

waters were used to support geothermal energy production following the medium scenario of growth, salinities could reach 50,000 ppm TDS by the year 2000, assuming normal hydrologic conditions persist (i.e., average rainfall and evaporation) and discharges of drain waters from irrigated lands are the same as the historic average. Without geothermal development, the salinity of the sea in the year 2000 is predicted to be just over 40,000 ppm TDS under normal conditions. However, with increased water conservation in agriculture, much higher salinity levels would be reached.

- Withdrawals of agricultural waste waters for power plant cooling would have the beneficial effect of decreasing the elevation of the sea, which has been rising in recent years. However, even with the medium scenario of energy growth, it could take up to 30 years before the 1975 elevation is reached again, assuming normal discharges of agricultural waste waters and average hydrologic conditions.

- Saline blowdown from cooling towers using agricultural waste waters cannot be discharged to drains under present water quality regulations. If blowdown cannot be disposed in some acceptable manner (e.g., subsurface injection), then agricultural waste waters could not be used directly for cooling. An alternative would be to use steam condensate for cooling and inject an equivalent volume of agricultural waste water into a geothermal reservoir.

- Geothermal fluids entering a drainage ditch after an accidental spill could produce a severe, but temporary change in water quality. Geothermal fluids from the Salton Sea resource area represent the greatest hazard to surface water quality because of their salinity. Extra precautions (e.g., containment berms) may be necessary to ensure that these fluids do not enter surface waters.

SECTION 7. LIQUID AND SOLID WASTES

W. Morris and D. Layton

Liquid and solid wastes will be generated during all phases of geothermal development. The primary liquid waste will be residual geothermal fluids produced from the operation of power plants. Saline water (termed blowdown) discharged from evaporative cooling systems in order to control the salinity of water circulating in such systems will be another liquid effluent. 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 H_2S control systems. In order for large-scale geothermal development to occur in the valley, liquid and solid wastes will have to be disposed in an environmentally safe manner.

Subsurface injection is the principal method of disposing liquid wastes. Surface disposal at special sites is the preferred method for isolating solid wastes. In this section we review the different sources of liquid and solid wastes and provide estimates of the volumes of wastes that will have to be disposed. Methods of waste disposal are briefly addressed here; Vol. 2 covers them in more detail.

LIQUID WASTES

A 100 MW flashed-steam power plant using geothermal resources of $175^{\circ}C$ would have to dispose about $84.0 \times 10^6 m^3$ of residual fluids per yr; with resource temperatures of $285^{\circ}C$, approximately $23.0 \times 10^6 m^3$ per yr would have to be disposed. Additional quantities of fluids produced from short term well tests will also require disposal. The only environmentally acceptable way of disposing the large volumes of residual fluids is subsurface injection. Needless to say, the success of future geothermal development in the valley will depend on the reliability of subsurface injection. A second source of liquid wastes is blowdown from wet cooling towers.

The blowdown rate is a function of the number of times the cooling water is concentrated by evaporation. As the number of cycles of

concentration increases, the discharge of blowdown from a tower decreases, but its salinity increases. The salinity of blowdown is equal to the product of the number of concentration cycles and the salinity of the make-up water used in the cooling system. Constraints involving water conservation, blowdown quality, and amounts of corrosion and scaling must be considered when selecting the number of cycles the cooling water is to be concentrated. If a need to conserve water exists, the amount of blowdown discharged can be reduced by increasing the number of cycles. But as the salinity of blowdown rises, disposal becomes more difficult. Blowdown discharged into one of the valley's rivers or drains, for instance, cannot exceed the water quality objective for those receiving waters, which is 4000 ppm TDS, annual average (CRWQCB, 1975). Irrigation water in the Imperial Valley normally varies between 800 ppm TDS and 1000 ppm TDS, and therefore it could be concentrated up to four times and still be discharged to a river or drain. Similarly, steam condensate with a low salinity (less than 500 ppm TDS) could be concentrated several times and the resulting blowdown would still meet the TDS limit. However, if toxic substances like arsenic or ammonia were present in blowdown derived from steam condensate, then either the number of concentration cycles would have to be adjusted or the blowdown would have to be treated prior to discharge. Agricultural waste waters concentrated more than twice by evaporation in a cooling tower would exceed the salinity objective for surface waters. The alternative is to increase the number of concentration cycles beyond 2, thereby reducing the blowdown discharges, and dispose the saline blowdown by subsurface injection.

Based on the above considerations, the cycles of concentration used with cooling waters will probably range from four (with irrigation water) to approximately ten (with condensate). The blowdown rates corresponding to four concentration cycles would vary from 21.0×10^3 to 31.0×10^3 $\text{m}^3/\text{MW-yr}$, for cooling tower evaporation rates of 62.0×10^3 and 92.0×10^3 $\text{m}^3/\text{MW-yr}$, respectively (see Section 6). With ten cycles and the same evaporation rates, blowdown discharges would vary from 6.0×10^3 to 10.0×10^3 $\text{m}^3/\text{MW-yr}$. Thus, a 100 MW power plant would discharge between 6.0×10^5 and 3.0×10^6 m^3 of blowdown each year, depending on the tower evaporation rate and the cycles of concentration. The methods of disposal used would depend on the quality of the blowdown.

The disposal options for liquid wastes are addressed in Volume 2. The potential consequences of accidental spills of fluids are covered in Sections 6,9, and 11 of this Volume.

SOLID WASTES

The safe disposal of solid wastes from geothermal operations is important from an environmental standpoint because of the potential toxicity of these wastes and the large volumes that could be produced as development proceeds. The chemical composition of solid wastes and the amounts produced will vary according to the physical and chemical characteristics of the geothermal fluids utilized for power generation in the different geothermal resource areas, the types of energy conversion processes implemented and their conversion efficiencies, the types of cooling water consumed, and the method(s) of H_2S abatement. The disposal of solid wastes to surface disposal sites will be governed by regulations administered by both the California Water Resources Control Board and the California Department of Health Services. At the present time efforts are now being made to establish waste disposal facilities that meet state requirements. An important consideration in the design and implementation of a suitable site or sites is the volume of wastes that could be produced by geothermal operations. Disposal sites must have enough capacity to store the quantities of wastes associated with future energy production or else continued production would be threatened.

Solids Associated With Well-Drilling

The principal solid wastes accumulated are drilling muds and formation cuttings. Drilling muds used in the Imperial Valley are composed basically of bentonite clays, caustic soda, and lignite. A typical composition is given in Table 7-1. The principal functions of the mud are to cool the drill bit, remove formation cuttings from the hole and release them at the surface, to control the reservoir pressure, and to prevent formation damage and caving of the walls.

Table 7-1. Composition of drilling muds recirculated into the well bore (WESTEC Services, Inc., 1979).

Component	Quantity
Magcogel (bentonite)	13,600 kg
Tannathin (lignite)	2,540 kg
Caustic soda	1,680 kg
Barite (barium sulfate)	450 kg
Bicarbonate of soda	225 kg
Soda phosphate	725 kg
Soda ash	680 kg
Geo-Gel (sepiolite)	31,400 kg
WL-100 (sodium polyacrylate)	662 liters
Drilling detergent	56.8 liters
Water	680,000 liters

During drilling operations the mud is pumped into the well and circulated so that the formation cuttings are lifted out of the well along with the mud. On exiting the well, the mud and cuttings pass over a fine screen shaker where the cuttings are separated and dumped into a reserve pit. The mud passes through the screen, settles into a tank and is recirculated into the well.

In geothermal drilling it is not uncommon to lose mud circulation during drilling due to fractures in the formation especially at depths below about 900 m. Sealing of these fractures is sometimes completed with such materials as fibers, mica flakes, or cottonseed hulls; however, it is oftentimes necessary to cement-off fractures. As a result of these occurrences, mud must be replenished from a reserve mud system.

Most of the debris from a well-drilling job is accumulated in the reserve pit. This includes the mixture of formation cuttings and mud accumulated over the course of drilling operations. With the drilling-phase completed, the wellbore is cleaned out by flowing geothermal fluid out of the well into steel Baker tanks or a sump. This procedure removes residual drilling mud, fibrous material, cuttings and extraneous debris from the walls of the wellbore. The materials accumulated in the reserve pit and the Baker tanks are usually allowed to dry by evaporation and are removed from the well site and transported to an approved disposal area. Alternatively, the fluid in the Baker tanks can be pumped into an injection well.

The number of wells necessary for the operation of a geothermal power plant is determined by: (1) the fluid requirements of the plant - which increase with decreasing resource temperature, (2) the productivity of wells completed in the geothermal reservoir, and (3) the replacement rate of wells. Because these factors can differ for each resource area, the number of wells drilled each year to support geothermal projects could vary considerably. To accommodate uncertainties about future drilling activity, we assumed that from 50 to 70 wells would be drilled annually in the valley to sustain a growth rate of 100 MW per year for 30 years. Production, injection, replacement, and deep exploratory wells are included in the estimated rates of well drilling. The quantity of solid waste generated per well was calculated using estimates provided by well-drilling contractors experienced in the Imperial Valley. Their information indicated that muds and cuttings could range between 19 m^3 and 41 m^3 per 100 m of well. The divergence in the waste production estimates can be partially attributed to problems encountered in drilling (e.g., loss of mud circulation) and the amounts of water remaining in waste solids.

As a means of establishing bounds on the quantities of drilling wastes expected with the medium scenario of energy growth, we calculated minimum and maximum values for total wastes. For an average well completion depth of 1500 m and waste production of 19 m^3 per 100 m of well casing, a single well would generate 285 m^3 of muds and cuttings. Thus, a drilling rate of 50 wells per year would generate $4.2 \times 10^5 \text{ m}^3$ of wastes after 30 years. The high values of waste production and well drilling would produce $13.0 \times 10^5 \text{ m}^3$ of wastes.

It is expected that wellbore cleanout, consisting primarily of brine fluid, will be injected rather than dried by evaporation and disposed as solid waste. However, because of unforeseen circumstances and the lack of injection wells during initial drilling operations at new power sites, we have projected that wellbore cleanout residue from 10% of all wells drilled will be disposed as solid waste. Up to $1.4 \times 10^3 \text{ m}^3$ of saline fluid can be accumulated for each well as a result of wellbore cleanout. The volume can be reduced by 80 to 90 percent through evaporation thus leaving a maximum solids residue of up to 283 m^3 per well. If we assume that wellbore cleanout fluid will be dried and disposed as solid waste for 10 percent of all wells drilled, then the minimum and maximum amounts of solids over a 30 year period would become about 4.7×10^5 and $1.3 \times 10^6 \text{ m}^3$. The average of these values would be $9.1 \times 10^5 \text{ m}^3$.

Solids Separated From Residual Geothermal Fluids

The separation of solids from spent geothermal fluids -- especially brines -- will be necessary in order to prepare the fluids for injection. When saline geothermal fluids are cooled in the energy conversion process, constituents that were barely soluble at the higher well-head and down-hole temperatures are now precipitated in the spent brine (Austin et al., 1977). Most of the solids, consisting primarily of silica and heavy metal sulfides, remain suspended and unless these solids are removed before injection, they would tend to clog the well and the receiving aquifer (Snoeberger and Hill, 1978). Based upon silica solubility chemistry (Barnes and Rimstidt, 1975), and incubation experiments (Harrar et al., 1979), it has been found that greater quantities of solids will precipitate from spent brine solutes initially containing high concentrations of NaCl and CO_2 . In view of this, one should expect that relatively larger amounts of solids will precipitate in the spent brines of a Salton Sea geothermal plant compared, for example, with an East Mesa plant.

Reliable data characterizing the amounts and compositions of precipitates in spent brine taken under realistic temperature and pressure conditions of injection are relatively sparse. Hill and Morris (1976) have performed a sampling experiment that approaches the appropriate conditions. In their experiment two-phase (vapor-liquid) samples were taken from the

Sinclair #4 well in the Salton Sea KGRA by means of a probe inserted in the brine feed line at a point 7.6 m from the wellhead exit. The samples were collected in stainless steel sample bottles that were subsequently cooled to ambient temperature whereupon insoluble precipitates formed. The sampling and analysis procedures were designed to provide compositional data on the vapor, liquid, and solid phases from which the composition of the original whole brine could be calculated. The precipitates ranged from 590 to 1100 mg/l in the cooled brine and they contained Si (as SiO_2) at concentrations up to 75%. Approximately 10% Fe (elemental) was also present along with relatively minor amounts of other elements. The experiments showed that most of the Si (85%) and only relatively small amounts of Fe (5%) precipitated from the original brine solutions.

In another study of brine chemistry (Harrar et al., 1979), effluent brines from a four-stage flash system were incubated under controlled conditions. The level of precipitated solids averaged about 500 mg/l in the brine, which was from the Magmamax #1 well in the Salton Sea KGRA. As in the case of the Hill and Morris experiments, the precipitates were composed primarily of SiO_2 .

Methodologies for separating suspended or precipitated solids prior to injection have been under investigation for some time (Morrison et al., 1977). To date, a standard or well-established process has not been fully demonstrated. However, a treatment system called the Reactor-Clarifier has been developed by Envirotech Corp. and operated successfully by Imperial Magma Corporation (Van Note et al., 1978) in conjunction with the Geothermal Loop Experimental Facility (GLEF) at the Salton Sea KGRA. Solids are precipitated in a reactor under controlled conditions by a seeding process. A clarification unit is used for solids separation. Solids are then allowed to thicken and then they are filtered and pressed into a cake. Tests performed on this system using Magmamax #1 brine have provided the only practical data to date on the quantities of solid waste separated from spent brine prior to injection. Data on one such test are given in Table 7-2. The relative quantity of solids separated by the process, .05%, is in good agreement with the laboratory experiments described above. Comparable data from other KGRA's are not available.

Injection technology is relatively important to the ultimate development of geothermal power in the Imperial Valley and it is virtually certain that solids will have to be separated to achieve injection of spent

Table 7-2. Separation of solids from spent brine based on reactor-clarifier test data for Magmamax #1.

Parameter	Measured value
Flow rate of brine	143,600 kg/n
Brine density	1148 kg/m ³
Separation rate of solids	68 kg/h
Percent of brine as solids	.05%
Density of the filtered and pressed cake	1600 kg/m ³
Percent water in cake	30 - 35%

geothermal fluids. The largest amounts of separated solids are expected to be accumulated from geothermal operations in the Salton Sea KGRA. In the medium scenario of energy production, the ultimate capacity of the Salton Sea resource is assumed to be 1400 MW (see Table 4-1). That amount of development would result in the generation of about 1.2×10^6 m³ of solids, based on a growth rate of 50 MW/yr for 25 years after an initial production of 100 MW by 1985.

There are virtually no experimental or test facility data from the Brawley, Heber, or East Mesa KGRA's on the amounts and compositions of solids precipitated from spent geothermal fluids. Obviously this makes it difficult, if not impossible, to project values for solid waste accumulations for these areas. However, as noted earlier there are laboratory experimental data showing a tendency for the precipitation of lesser amounts of solids in residual fluids originally containing relatively lower concentrations of NaCl and CO₂. The latter constituents are lower by factors of 20 to 80 in the Heber and East Mesa brines compared to those of the Salton Sea KGRA. Thus, one should expect that relatively small amounts of precipitated solids will be present in East Mesa and Heber spent-fluids. Qualitative evidence confirming this fact has been obtained from the Geothermal Test Facility at East Mesa where spent fluids from a

holding pond are pumped through a sand filter and filter bag system into an injection well. The system has been operated for prolonged periods and it is maintained in successful operation by periodic backflushing of the sand filter to relieve back-pressure caused by solids collection in the filter. Apparently no large accumulations of solids result from the back flushing operation. Thus the limited evidence to date indicates relatively little accumulation of solid waste associated with spent-fluids from East Mesa geothermal operations. This finding probably applies to operations in the Heber area also.

On the other hand, geothermal brines from the Brawley KGRA have relatively high levels of total dissolved solids (i.e., about 80,000 mg/l), and significant levels of solid precipitates may form. Unlike the East Mesa KGRA, we have no well-injection information from operations in the Brawley area. Therefore, we have chosen to predict a value for accumulated solids based upon the relationship of precipitated solids with the NaCl concentration in the brines. The NaCl content of the Brawley fluids is approximately 40% of that of the Salton Sea fluids, and so we assume that separated solids will amount to .02% of the flow of spent brines. Facilities in the Brawley area would ultimately produce a total of about $3.0 \times 10^5 \text{ m}^3$ when the 600 MW level of development is attained in 2010, according to the medium scenario.

Quite obviously, there are uncertainties in the above projections of solid wastes. We have attempted to make calculations based upon what is known about the geothermal resources and technology developed to date. Future developments in technology and further exploration in the Imperial Valley will undoubtedly change the estimates of solids production. Our best estimate is that approximately $1.5 \times 10^6 \text{ m}^3$ of solids will have to be separated from brines in the Brawley and Salton Sea areas by 2010 to support the injection of fluids associated with a combined production of 2000 MW in both resource areas.

Solids Associated With Scale Buildup

Scale will be a continuing problem in geothermal power plants in the Salton Sea KGRA in spite of efforts to alleviate it by acidification of the

brine or the addition of special additives. The deposition rate of scale depends upon the composition of the geothermal fluid, temperature, pressure, flow rate, and turbulence. Cooling of hypersaline brine is a major factor in scale deposition and therefore, most of the scale (up to 90%) will be deposited in cooler locations of power plants such as the flow lines leading to injection wells.

It is expected that physical methods will be used periodically to remove scale from critical locations in the power plants. One such method, called hydroblasting, is under test by Daedalean Associates for the San Diego Gas and Electric Company. The process uses high velocity water to fracture the scale and remove it from the system. This is only one example of a scale-removal process and it is cited here to reveal a significant source of solid waste that will require disposal.

Although scale represents only a small fraction of the total mass of brine that passes through a power plant, it can be significant from a disposal point of view because of the high TDS and high flow rates of the brines. There are virtually no quantitative data on the amounts of scale deposited on a known surface area by a brine of known composition flowing at a measured rate. Because of this it will be difficult to project the quantity of scale-related solid waste.

Periodic measurements of scale deposition in a number of locations of the GLEF were made over 2400 hours of operation. Heaviest scaling was observed in the brine effluent piping of the fourth stage separator and in the 10 inch diameter lines leading to the injection well. The scale thickness measurements were used to calculate scale deposition rates which were found to range from 50 $\mu\text{m}/\text{hour}$ down to 3 $\mu\text{m}/\text{hour}$. It should be understood that the GLEF was operated under widely varying conditions during the prolonged period over which the scale was deposited. Thus the measurements are probably not indicative of normal powered-up conditions.

Scaling rate studies have been carried out by Lawrence Livermore National Laboratory (Austin et al., 1977) at the Sinclair No. 4 well. Brine was flowed at wellhead conditions through a tapered expansion tube equipped with thermocouples for temperature monitoring. Temperatures at equally spaced intervals along the length of the tube were measured during the brine flow experiment. Upon completion of a run, scale thicknesses were measured

at each cross-sectional location where the temperature measurements were logged. From the thickness measurements the scaling rates were calculated to be 26 $\mu\text{m}/\text{hour}$ to 348 $\mu\text{m}/\text{hour}$ as a function of decrease in temperature from the inlet (above 200°C) to the exit (near 100°C) of the 70-cm expansion tube. Scaling in terms of scale-mass deposited per unit cross-section per unit time, g/cm-hr, was also determined. The mass deposition rate ranged from 1.2 g/cm-hr to less than 0.1 g/cm-hr in the temperature range of approximately 100°C to 200°C. From these data and the expansion tube brine flow-rate we calculated that the percent brine deposited as scale would be .014% for a brine temperature of 110°C.

The experimental measurements of scale described above are not to be construed as indicative of scaling that will occur in an actual power plant. They are presented only to indicate some order of magnitude of scaling that may occur. The expansion tube experiment was run at a brine flow rate far below that expected in a power plant. Not only will higher rates of brine-flow occur, but also greatly different turbulence conditions are likely to prevail. The point to make here is that if the scale produced were of the order of .014% of the amount of brine used in power production, then large quantities of solid waste could accumulate as a result of periodic scale removal.

For the Salton Sea area, the rate of scale formation would be about 11 $\text{m}^3/\text{MW-yr}$. Approximately $1.8 \times 10^5 \text{ m}^3$ of scale would accumulate over 25 years with a growth rate of 50 MW/yr after an initial production of 100 MW in 1985. Without data on scale build-up rates for facilities in the other resource areas, it is difficult to estimate the amounts of scale they would produce. Accordingly, the $1.8 \times 10^5 \text{ m}^3$ prediction should be considered a low estimate.

Solids Associated With Hydrogen Sulfide Abatement

Five candidate processes for the removal of H_2S from power plant effluents are: (1) the EIC Corporation (EIC) CuSO_4 process, (2) the Stretford process, (3) the Dow Oxygenation procedure, (4) the iron catalyst method and (5) scrubbing with spent geothermal fluids (Stephens et al., 1980). Of the five, the most promising for Imperial Valley power plants are

probably the EIC and Stretford processes. In the Stretford process H_2S is absorbed in aqueous Na_2CO_3 and oxidized to free sulfur with VO_3^- . Upon regeneration of VO_3^- by oxidation in air with 2,7-anthraquinone disulfonic acid, sulfur separates as a froth and is removed by filtration or centrifugation.

In the EIC process, H_2S in steam or noncondensable gases is reacted with a solution of $CuSO_4$ to form insoluble copper sulfide. The insoluble sulfides are separated and oxidized to $CuSO_4$ for recirculation back into the process. Sulfuric acid which is produced during the oxidation of $CuSO_4$ is reacted with an ammonia solution to form ammonium sulfate.

Both of the above processes yield potentially recoverable residual products the amounts of which are directly proportional to the H_2S present in the steam being processed.

For purposes of calculating the solid wastes associated with the abatement of H_2S , the EIC process serves as a practical example. The process has been tested by Pacific Gas and Electric Company at The Geysers geothermal area and it has been found that the residual $(NH_4)_2SO_4$ produced is virtually in direct proportion to the amount of H_2S present in the process steam. Some boric acid is also present in the residue. Investigations are now underway to devise techniques for commercial separation and recovery of the $(NH_4)_2SO_4$ and boric acid. It is conceivable therefore, that the accumulation of solid waste requiring disposal may not occur as a result of H_2S abatement if commercial recovery techniques can be developed.

We used the following assumptions to calculate the amount of solid wastes from the abatement of H_2S using the EIC process: the Salton Sea and Brawley fluids contain 3.2 mg/kg of H_2S and fluids from the Heber and East Mesa resource areas contain .54 mg/kg; facilities in the Salton Sea and Brawley areas consume 50 kg of fluid per kWh and facilities in other areas use 100 kg of fluid per kWh; the efficiency of the abatement process is 95%. At a growth rate of 100 MW/yr over 30 years, the accumulated amount of wastes, as $(NH_4)_2SO_4$, would be $1.2 \times 10^5 \text{ m}^3$.

Wastes Associated with Cooling Waters

Potential sources of solid wastes associated with the operation of cooling towers include suspended solids separated from cooling waters and solids that accumulate in evaporation ponds receiving blowdown. To prevent the build-up of solids in the basin of a cooling tower, it is necessary to remove suspended solids from cooling water. The treatment of agricultural waste waters containing 200 mg/l of suspended solids, for example, would yield 11 m^3 of solids per MW-yr, based on 75% solids removal and a water use rate of about $1.0 \times 10^5 \text{ m}^3$ per MW-yr. For the medium scenario of geothermal energy growth, the maximum amount of solids removed would be approximately $5.0 \times 10^5 \text{ m}^3$, assuming that all generating facilities relied on agricultural waters for cooling. Blowdown derived from agricultural waste waters used in cooling towers could be a major source of solid waste, provided that blowdown is discharged to evaporation ponds instead of being disposed by subsurface injection. We calculate that nearly 290 m^3 of solids would accumulate in ponds for every MW-yr of electricity generated. After 30 years of energy production following the medium growth rate of 100 MW/yr, as much as $1.3 \times 10^7 \text{ m}^3$ of solids would have entered evaporation ponds, assuming agricultural waste waters were the sole source of cooling water.

TOXICITY OF WASTES

The selection of the methods to be used for disposing or treating liquid and solid wastes from geothermal operations will depend a great deal on whether the wastes contain substances that could be hazardous to wildlife or humans. In California waste that contains toxic substances must be removed to special disposal sites (CAC, 1972). These sites (designated as Classes I and II-1) meet strict design and operational requirements that are meant to keep hazardous wastes isolated. For wastes that do not contain toxic substances, restrictions on the method of disposal are likely to be minimal--unless large volumes are produced.

Geothermal wastes derived from the removal of scale, the precipitation of solids from spent fluids, and well-drilling debris contain, or have the

potential to contain, toxic substances. Solids precipitated from geothermal brines of the Salton Sea resource area, for example, could contain lead sulfides, which as a lead compound would be considered a hazardous waste according to standards established by the California Department of Health Services. (CAC, 1979). Well drilling-debris, including drilling muds that come in contact with geothermal fluids containing elevated levels of toxic substances like Ba, As and Pb, would become contaminated, and as a consequence, special disposal may be necessary. Solids filtered from agricultural waste waters prior to use for power plant cooling or injection to a geothermal reservoir, on the other hand, are not apt to be toxic, and therefore disposal to Class I or II-1 sites would be unnecessary. Disposal problems could be partially reduced if certain wastes are processed to produce substances that are valuable elsewhere. Examples of recycled materials include ammonium sulfate from H_2S abatement systems and minerals derived from solids precipitated from geothermal brines.

In order to properly determine the toxicity of the different types of wastes, chemical analyses will have to be performed on a case by case basis of the wastes that are actually produced from geothermal facilities. Measurements of the terrestrial radioactivity at an abandoned sump near the Sinclair 4 well in the Salton Sea resource area indicated that the radioactivity of ^{40}K was 78.9 pCi/g. This concentration is over 3 times higher than background measurements made elsewhere in the valley as part of the IVEP (Nyholm and Anspaugh, 1977). This radionuclide will probably be dissolved in geothermal fluids, and then be disposed by subsurface injection. However, it would be worthwhile to measure the radioactivity of solids separated as part of the preinjection treatment of brines in order to determine if this is indeed the case.

CONCLUSIONS

- The generation of electricity by geothermal power plants will require the extraction and disposal of large volumes of geothermal fluids. In order for large-scale development to proceed unhindered, the use of subsurface injection to dispose residual fluids must be successful because there are no other environmentally acceptable methods of disposal.

- Blowdown from wet cooling towers is another liquid waste that will require proper disposal. The methods of disposal eventually implemented will depend on the chemistry of blowdown discharges. Subsurface injection may be necessary when toxic substances (e.g., NH_3) are present in unacceptable concentrations or if the level of TDS is above 4000 ppm.
- According to our best estimates, approximately $2.7 \times 10^6 \text{ m}^3$ of potentially toxic wastes will be produced with 3000 MW of geothermal development by 2010. This cumulative total includes $9.1 \times 10^5 \text{ m}^3$ of solids associated with well drilling, $1.5 \times 10^6 \text{ m}^3$ of solids removed from spent brines, $1.8 \times 10^5 \text{ m}^3$ of solids associated with the removal of scale, and $1.2 \times 10^5 \text{ m}^3$ of solids produced from H_2S abatement systems.
- Chemical analyses will have to be made of solid wastes in order to provide data needed to determine the actual toxicity of future waste streams.
- Special disposal sites are being developed by private and public parties, and so there should not be any constraints related to inadequate disposal.

SECTION 8. SUBSIDENCE AND SEISMICITY

D. Layton and N. Crow

Land subsidence and induced seismicity have been identified as possible consequences of geothermal energy production in the Imperial Valley. Land subsidence is of direct concern because of potential impacts on the valley's irrigation and drainage systems. Seismicity induced by the injection of residual geothermal fluids or perhaps the cooling of reservoirs due to fluid extraction is also of concern. There is already a high amount of natural seismic activity in the valley, and any increased seismicity due to geothermal operations would be unacceptable if it caused property damage.

LAND SUBSIDENCE

Substantial regional subsidence has been documented in the Imperial Valley (Lofgren, 1974, 1978; Crow and Kasameyer, 1978), with fairly large local variations. The basic cause for the subsidence is the presence of regional tectonic forces (Elders 1975; Jackson, 1979; Lofgren, 1978). Local variations are probably related to differential movements on the faults in the valley (see Fig. 8-1).

Vertical land surface elevations in the Imperial Valley have been measured three times since 1971 by the Imperial Valley Subsidence Detection Network, a cooperative effort of federal, state and local agencies. The subsidence and seismicity element of the IVEP partially supported the third leveling. The network consists of two parts: a basic framework of two first-order leveling lines surveyed by the National Geodetic Survey, and supplementary second-order traverses surveyed by local agencies. The levelings were done in the winters of 1971-72, 1973-74, and 1976-77. Data from all three surveys have been reduced by the National Geodetic Survey (Reese, 1977). Substantial changes in land surface elevation were documented, based on a free adjustment of field survey data. In this technique, only one bench mark is assumed to be stable. Reese used bench mark Y58, which is located in a mountainous area off of Interstate-8, about 50 km west of El Centro. The elevation changes that took place during the 5-year period on the first-order lines are shown in Figs. 8-2 and 8-3.

Fig. 8-1. Location of right-lateral faults in the Imperial Valley. The Imperial and Brawley Faults are the most active in the valley (after Elders *et al.*, 1972; Johnson and Hadley, 1976; Meidav and Howard, 1979).

Figure 8-2 depicts the vertical movement on the line that runs east to west. Subsidence generally increases toward a maximum near the center of the Imperial Valley. Subsidence averaged nearly 7 cm for the 5-year period (a rate of about 1.4 cm/yr) at the midpoint of this survey line. The profile of subsidence along the north-south line (Fig. 8-3) indicates that subsidence gradually increases toward the north end of the valley. The greatest vertical movement is near the east side of the Salton Sea, where as much as 20 cm of subsidence has taken place in the 5-year period (a rate of about 4 cm/yr). The rate of subsidence here is about three times larger than in the south end of the valley. Natural subsidence, though, has not been known to cause damage to lands or property in the valley. This is understandable because subsidence is regionally distributed.

Fig. 8-2. Subsidence for a 5-year period on the line of bench marks that runs east to west across the southern end of the Imperial Valley. First order leveling on the bench marks was done over the years 1971-72 and 1976-77.

Fig. 8-3. Subsidence for a 5-year period on the line of bench marks that runs north to south in the central part of the Imperial Valley. First order leveling on the bench marks was done during 1971-72 and 1976-77.

Lofgren (1978) has compared the changes in subsidence for the 5-year period with the generalized topographic contours of the valley in 1927 in order to determine historic trends. Based on the parallel relationship between the valley's old contours and the contours of recent changes in subsidence, Lofgren suggests that present vertical movements are a continuation of long-term tectonic deformation of this region. The average slope of the valley from Calexico, on the U.S.-Mexico border, to the Salton Sea is about 1 m/km, corresponding to a grade of .001. Even if the more rapid rates of subsidence were to continue in the northern end of the valley for the next 40 years, there would not be any appreciable changes in the valley's slope. However, on a more local scale, the movement of active faults can cause vertical displacements of the land surface. Perhaps the most notable example of this phenomenon is a closed depression known as Mesquite Lake, which is to the southeast of Brawley (see Fig. 8-1). Johnson and Hadley (1976) attribute the depression to tensional forces at the adjacent ends of the Brawley and Imperial faults. After the Imperial Valley earthquake in October of 1979, 19 cm of vertical displacement was measured in the vicinity of the Mesquite Lake depression (Real et al., 1979).

The extraction of large volumes of hot water from a geothermal reservoir comprised of one or more deep aquifers could also lead to land subsidence. As geothermal fluids are produced from wells, the pore pressures in a reservoir will decline, and as a consequence, the aquifer(s) may compact. The amount of compaction will depend on the nature of the stresses applied and the physical properties of the aquifer materials. Deformation within a reservoir could eventually be manifested at the surface in the form of decreases in land elevation. The changes in the slope of the land surface that will accompany subsidence could affect the irrigation of agricultural lands in the valley. Most of the crops grown there are irrigated by either furrow or flood irrigation. With these application techniques, the land surface must be properly graded to insure the efficient application of water. Consequently, changes in slope associated with subsidence could directly interfere with present gravity-type irrigation methods. Furthermore, subsurface drains lie beneath the majority of the valley's irrigated fields in order to remove excess salts from the root zones of the crops grown. Since the drains remove saline water through gravity flow, their operation would also be affected by changes in slope. Where these drains do not operate properly, the salinity of the soil rises,

causing reduced crop yields. Runoff from surface irrigation (tail water) combines with subsurface drainage and they are both carried away in drainage ditches that discharge to the New and Alamo Rivers. Drainage ditches would be sensitive to alterations in surface elevation as would the canals that transport irrigation water to fields. Roads and railroads would be less susceptible to subsidence-related damage than the irrigation and drainage systems. Residential and commercial land users could be affected by subsidence, although the low density of housing outside of incorporated areas reduces the potential for significant damage.

The extent of possible damage resulting from subsidence is important for two reasons. First, damage to agricultural land uses would be unacceptable because of the importance of agriculture to the valley's people and economy. Future geothermal development might be jeopardized unless damages could be mitigated or controlled in some way. Second, if damages proved to be insignificant or repairable, then steam condensate could be used as cooling water for power plants without the need for external water supplies.

At the present time Imperial County has adopted a full injection policy that requires that all withdrawn fluids (or an equal volume of another fluid such as agricultural drainage) be injected back to the reservoir. So, for example, if steam condensate is used for evaporative cooling in a wet cooling tower, then an equivalent volume of agricultural waste water must be injected to the reservoir. However, the large scale consumption of waste waters to support the operation of geothermal facilities would increase the Salton Sea's salinity, adversely affecting its aquatic ecosystem (these effects are described in Section 11). A partial injection policy would therefore have the advantage of reducing negative impacts on the sea.

The amounts of damage resulting from subsidence of lands that are above compacting reservoirs will differ from well field to well field. Differences will result from variations in the configurations and slopes of irrigated lands; the layouts of canals, drainage ditches, and subsurface drains; and the morphologies of the subsidence depressions. As a means of studying the various kinds of surface impacts, we did the following: predicted compaction in a reference reservoir that results from the extraction of geothermal fluids to support a 50 MW (net) power plant; calculated potential levels of subsidence using alternative assumptions on

how much of the subsurface compaction is translated to the surface; and analyzed the impacts of the resulting subsidence depressions on agricultural lands. This approach is graphically portrayed in Fig. 8-4.

Fig. 8-4. Diagram of the approach used to assess the potential impacts of subsidence resulting from the extraction of hot water from a reference geothermal reservoir.

Predictions of Subsidence

To simplify the assessment of potential subsidence impacts associated with the operation of a geothermal power plant in the Imperial Valley, we predicted pressure declines, aquifer compaction, and associated subsidence for a reference reservoir having geohydrologic characteristics that are similar, but not identical, to existing reservoirs in the valley. We assumed that the overburden above the reservoir includes a "caprock" of impermeable clays, shales, and mudstones 533 m thick. Covering the impermeable layer is a shallow unit containing silts, clays, and some sands that is 76 m thick. The reservoir has two producing zones, each 610 m thick. These aquifers have a constant thickness, and for calculations of pressure changes, they are assumed to be homogeneous, isotropic, and infinite in areal extent. We also assumed that the aquifers were isothermal and that the upper and lower aquifers were not hydraulically connected. The upper production zone has a permeability of 150 md, while the lower zone has a permeability of 50 md.

An important property of the aquifers that must be estimated to calculate compaction is their compressibility (defined as the fractional change in the bulk volume of porous rock per unit change in uniform pressure). The compressibility of aquifer materials can be estimated in the laboratory by subjecting a rock sample to a uniform stress and measuring the change in volume. The laboratory approach, though, can lead to low values of compressibility because it does not simulate the inelastic response of materials to long term, in situ stresses. Methods for simulating such stresses in the laboratory are now under development (Schatz et al., 1979a).

Decreases in the porosity of sediments with depth, however, are an expression of in situ stresses and can be used to calculate the compressibility of materials in a young sedimentary basin like the Salton Trough. We used a depth-dependent relationship between porosity and compressibility developed by Schatz et al. (1979b) with porosity data from the Salton Sea KGRA to establish upper bound estimates of compressibility for the producing zones of the reference reservoir. The upper bound estimates will lead to conservative predictions of compaction. The compressibility for the upper producing zone was placed at $14.5 \times 10^{-9} \text{ m}^2/\text{N}$ and the lower as $7.25 \times 10^{-9} \text{ m}^2/\text{N}$.

Pressure drawdowns in the reservoir were predicted for two well fields. The first field (well field A) has 20 production wells and 12 injection wells. The production wells have a 13 ha/well spacing (see Fig. 8-5 for the well field array). Half of the production wells are completed through the shallow production zone and half through the deeper zone. Wells only extend through the first 305 m of each zone. The total discharge from the producing wells is 1260 kg/sec, or 63 kg/sec per well. That level of production is sufficient for a 50 MW (net) power plant, assuming the fluids are at about 177°C.

The injection wells are used for the disposal of residual geothermal fluids, management of a reservoir's temperature and pressure, and the control of subsidence. These uses are not necessarily compatible. For instance, to control subsidence, reductions in pore pressure should be minimized, and therefore injection wells should be placed near the producing wells where pressure declines would be greatest. But if they are located too near the well field, the fluids that are injected will eventually lower

Fig. 8-5. Layout of the production and injection wells in well field A. There are 20 producing wells and 12 injection wells. Half of the producing wells are completed to the shallow zone of production and half are completed to the deep zone. Production wells in this configuration (well field A) have a 13 ha/well spacing; in well field B they have a 9 ha/well spacing.

the temperature of fluids reaching the production wells. In our analysis, injection wells are situated about 1800 m (just over a mile) from the nearest production wells (see Fig. 8-5) in groups of three wells. This distance is consistent with current proposals for future well field configurations in the valley (VTN, 1978). Presumably the 1800 m of separation provides for proper temperature and pressure control. We further assumed that the injection wells are only completed to the shallow production zone in the reservoir. Injection to the shallower horizon was chosen because the high porosities and permeabilities of that zone would facilitate the injection of large volumes of fluids. The second well field (well field B) produces the same amount of geothermal fluids and also has 20 production wells and 12 injection wells. The well spacing of the production wells, though, is 9 ha/well instead of 13 ha/well, and the injection wells are located 1500 m (just under a mile) from the nearest producing wells.

For each well field we examined pressure changes associated with a partial injection case (i.e., 85% of the withdrawn fluids are injected) and complete injection of the produced fluids. The partial injection case is important to consider because if it does not lead to unacceptable subsidence, then steam condensate, which makes up approximately 10 to 20% of the fluid flow from wells, could be used as a source of cooling water for flashed-steam plants. With partial injection, 89 kg/sec would be injected through each of the 12 injection wells, compared to 105 kg/sec per well for full injection.

Pressure changes in each aquifer were simulated using a model of unsteady-state flow to partially penetrating wells in a nonleaky, confined aquifer (Walton 1970). We assumed that production wells penetrated half-way into each reservoir. This analytical model was used rather than a more sophisticated numerical model of a geothermal reservoir (see, for example, Lippmann et al., 1977) because we were only interested in obtaining first order predictions of changes in reservoir pressure to carry out the assessment. Furthermore, a numerical reservoir model was not warranted because of a lack of data on actual reservoirs. Numerical models, however, will probably be more suitable for assessment purposes in the future when a more complete set of site-specific reservoir data is available and after actual measurements of pressure changes, compaction, and subsidence have

been made so that such models can be calibrated and verified. Reservoir compaction at different points in a rectangular grid was calculated as the product of the aquifer's thickness, the change in pressure at a point after 30 yrs, and aquifer compressibility. Total reservoir compaction at grid points was set equal to the sum of the compaction values computed for the individual aquifers. An uplift compressibility factor of 20 was used to reduce the amount of aquifer expansion where injection created positive pressures (Schatz et al., 1979b). Table 8-1 lists the values of the parameters used to estimate compaction.

Table 8-1. Parameters used to estimate compaction in the reference reservoir.

Parameter	Upper aquifer	Lower aquifer
Extraction rate, kg/sec/well	63	63
Injection rate, kg/sec/well		
a. partial injection	89	89
b. full injection	105	105
Permeability, md	150	50
Compressibility, m^2/N	14.5×10^{-9}	7.25×10^{-9}
Uplift compressibility factor	20	20
Fluid temperature, $^{\circ}C$	177	177
Fluid viscosity, Cp	0.2	0.2
Fluid density, kg/m^3	1033.6	1033.6

The response of the overburden to compaction in the reservoir is more difficult to predict. The structure, thickness, and composition of overburden will control the amount of compaction that propagates upward. A worst case situation would be that all of the compaction reaches the surface as subsidence. Generally, the thicker the overburden, the lower the amount of compaction that would reach the surface. The aquifers of interest here

are between 610 m and 1220 m below the surface. Since field data dealing with the propagation of compaction through aquifers such as these are unavailable, we assumed as an alternative, that 30%, 10%, and 1% of the reservoir compaction was translated to the surface. This approach does not account for any horizontal displacement in compaction as it propagates through the overburden. Therefore, the subsidence depressions we predict would probably be deeper, and would have steeper slopes than the depressions that actually occur. We also assumed that compaction and subsidence are instantaneous, although there is likely to be some lag in the time between when compaction occurs at depth and its manifestation at the surface (Grimsrud et al., 1978).

Changes in surface elevations associated with the operation of the different well fields and injection rates were displayed on three dimensional surfaces to facilitate the analysis of subsidence impacts. Figure 8-6 is a block diagram depicting the general slope of the valley, which is approximately .001 to the north. Estimates of subsidence are

Fig. 8-6. Block diagram representing the general slope of the Imperial Valley's land surface. Estimates of subsidence are projected onto this surface, which has a .001 slope to the north. Analyses of the resulting changes in slope are made along the cross sections identified by the dashed lines.

projected onto this sloping surface. Two cross sections of subsidence depressions are presented for analysis; an east-west profile and a north-south profile (the dotted lines on the block diagram indicate where the profiles are taken). Figure 8-7 shows the north-south profile of the land surface resulting from the production of fluids from well field A for 30 years, 100% injection, and 30% translation of compaction to subsidence. The maximum amount of subsidence is 2.48 m, and slopes in the bowl vary between .002 and .000. Figure 8-8 presents the cross-section of the land surface after 30 yrs of fluid production and with 30% of the predicted compaction transferred to the surface, and only 85% injection of the withdrawn fluids. The differences in slope and total subsidence between this case and 100% injection are small, but partial injection did lead to more subsidence.

Fig. 8-7. North-south profile of the land surface resulting from the production of fluids from well field A for 30 years, 100% injection, and 30% translation of compaction to the surface.

Fig. 8-8. North-south profile of the land surface resulting from the production of fluids from well field A for 30 years, 85% injection, and 30% translation of compaction to the surface.

The operation of well field B under the same conditions (i.e., 30% transfer of compaction, 85% injection and 30 years of production) results in slightly more subsidence (see Fig. 8-9a) because of the higher pressure drops in the reservoir caused by the denser spacing of wells (i.e., 9 ha/well). The effect of varying the translation factor for compaction is shown in Fig. 8-9b and 8-9c. Declines in the elevation of the land surface around well field B for 10% and 1% translation of compaction are insignificant.

Fig. 8-9. Declines in land surface elevations at well field B after 30 years based on the following percentages of compaction propagating to the surface as subsidence: (a) 30%, (b) 10%, and (c) 1%.

Impacts of Subsidence

The extent of property damages resulting from the production of geothermal fluids from well fields in the Imperial Valley will depend on the sensitivities of existing land uses to vertical and horizontal changes in the topography. Desert lands on East Mesa, for instance, could tolerate more subsidence than agricultural lands in the central portion of the valley that are carefully leveled for surface irrigation. Even agricultural lands could withstand some changes in slope without incurring costly damage. For example, the changes in surface elevation associated with well field B when only 10% and 1% of the compaction reached the surface (Fig. 8-9b and 8-9c), should not interfere with the normal operation of irrigation and drainage systems.

Damage would appear, however, when subsidence occurs in the form of bowl-like depressions. Subsidence bowls in the natural slope of the valley's land surface would have increased slopes on one side of the bowl and reversed or lower slopes on the other. Slope reversals would be the most serious impact to farm lands since irrigation could no longer be delivered to affected fields through established canals. On-farm canals are designed to deliver water to a height of .3 m above the highest point in the field, but as slopes are gradually reversed due to subsidence, some canals could eventually end up at the low end of a field, inoperable. Changes in slope would also affect the drainage of surface and subsurface waste waters. Subsurface drain lines are spaced at 15 m to 61 m intervals, depending on soil properties, and are generally 1.8 m below the surface. The gradients of the subsurface lines are usually the same as the natural slope of the land surface, and lower slopes would inhibit their operation. For surface drainage ditches, the best grades are between .001 and .002 (IID, 1978). Grades higher than .002 increase the potential for erosion because of higher water velocities, while grades below .001 promote the growth of aquatic weeds, which must be controlled to maintain the proper flow of water.

The nature of damages related to induced subsidence in the valley can be illustrated using the subsidence bowl predicted for well field B with partial injection and 30% translation of compaction after 30 years of fluid production. Figure 8-10 shows the east-west and north-south land surface profiles that bisect the well field. The lands most seriously affected have

Fig. 8-10. Cross sections of the subsidence bowl predicted for well field B with 85% injection and 30% translation of compaction after 30 years. Drainage within the bowl is indicated by the arrows.

slopes that are either reversed or under .0005. Lands with slopes at or under .001 would present problems in the irrigation of some crops. The profile along the east-west section across the bowl is symmetric because the slope of the original land surface was assumed to be zero. The direction of surface water flows is indicated by arrows. Slope changes in this direction are not necessarily detrimental since most of the fields in the valley have side falls or slopes in the east-west direction besides the main fall to the north. Figure 8-11 shows the areal extent of affected lands. Damage would be greatest in the 1 km² area bounded by the solid rectangle, where flows would be reversed. Unless mitigation measures were undertaken, these lands would be removed from agricultural production at an economic loss to growers. An additional 2 km², delineated by the dashed lines, would experience slopes below .001. Low slopes would pose irrigation problems for crops like alfalfa, which require steeper slopes for effective irrigation.

Fig. 8-11. Areal extent of lands affected by subsidence associated with the production of fluids from well field B after 30 years of fluid production and 85% injection. Flow would be reversed in the 1 km² area bounded by the solid rectangle. An additional 2 km², delineated by the dashed lines, would have slopes below .001.

Drainage would also be altered so that it flows toward the lowest part of the basin of subsidence. This would pose a serious problem for those lands whose waste water discharges flow in drains that are in the closed drainage basin. Irrigation would have to be suspended on such lands until proper drainage was provided. Canals passing through the subsidence depression would be affected as well. Depending on their orientation with respect to the subsiding land surface, water velocities will either increase or decrease. A more serious consequence would be the rise of water levels within canals as their elevation decreased in relation to surrounding lands. Subsidence in the Salton Sea KGRA would present another difficulty: encroachment of sea water on the geothermal well field. The sea's elevation has been rising in recent years, inundating lands adjacent to the sea. Dikes have provided a measure of protection, but increasing sea levels combined with declining surface elevations could cause problems--especially if a well field was near the shoreline.

Other phenomena associated with land subsidence that could produce damage are earth fissures and induced fault movement. In the Casa Grande-Eloy area Southeast of Phoenix, Arizona, subsidence due to withdrawals of ground water has been accompanied by fissures and cracks in the land surface (McCauley and Gum, 1975; Winikka and Wold, 1976). These fissures have disrupted agricultural operations. When fissures have developed in a field, they have had to be back-filled to prevent erosion and loss of irrigation water. The presence of fissures on irrigated lands in the Imperial Valley could adversely affect subsurface drain lines in addition to surface irrigation and drainage structures. Offset across a pre-existing fault, known as the Picacho fault, in that same area of Arizona has been attributed to withdrawals of ground water (Holzer, 1978). Holzer's theory is that the fault has acted as a semi-impermeable boundary that has inhibited the flow of water moving toward wells on the west side of the fault. As a result, water levels are believed to have dropped across the fault, causing more compaction to occur on one side than the other. Today the Picacho Fault has a scarp that is 15.8 km long and is from .2 to .6 m high (Holzer, 1978). Active faults are prevalent in the Imperial Valley, and if impermeable, they could serve as barriers to fluid movement in geothermal reservoirs. Pressure drops across a fault within a reservoir

could produce differential compaction and associated subsidence. The presence of a scarp along a fault in the irrigated portion of the valley would directly interfere with irrigation and drainage.

Mitigation Measures

There are two sets of measures that can be implemented to alleviate the generic impacts discussed above. The first set involves measures to arrest or control subsidence by maintaining pressure in a reservoir. These measures include changing the rates of production and injection as well as locations of both production and injection wells. The second set of counter measures concerns the repair of surface damages, modifications of irrigation and drainage systems, and adjustments in irrigation. The use of different mitigation methods to prevent or reduce adverse impacts is discussed in Volume II.

Monitoring of Land Deformation

Changes in land elevation and subsurface compaction should be monitored periodically to determine whether the long term extraction of geothermal fluids will eventually produce subsidence that results in unacceptable impacts on agriculture. Fortunately, there is already a subsidence detection network in the valley. It was established in the early 1970's when local officials recognized a need to establish baseline data on natural subsidence in the valley before geothermal development was initiated (Crow, 1976). The network includes two sets of bench marks that are surveyed with first order techniques; one set is aligned in a north-south direction and the other in an east-west direction. In addition, there are second order survey lines that are tied to the first order lines by common bench marks. Regulations adopted by Imperial County (1971) require that a permanent bench mark be installed at each geothermal well drilled in the County. This will insure that all areas that are susceptible to subsidence are covered by a full network of bench marks.

For subsidence monitoring to provide early warning of increased subsidence resulting from geothermal energy production, leveling data taken

before and after production started will have to be analyzed. Post production subsidence data will have to be analyzed to determine whether it is significantly different from natural subsidence previously measured at relevant bench marks (see Van Til (1979) for a discussion of statistical techniques for analyzing subsidence data). If increased rates of subsidence at bench marks are detected through data analysis, then appropriate actions can be implemented. One drawback to the use of land leveling to monitor land deformation over a geothermal well field is that it does not provide information on compaction within particular zones in the reservoir (Brandt, 1978). Without an understanding of reservoir compaction, it is not possible to accurately predict the effects of continued fluid extraction. Moreover, subsurface monitoring is needed to determine how overburden responds to the compaction of a reservoir. If overburden does attenuate compaction, then land subsidence may not become a problem.

SEISMICITY

The fault systems of the Imperial Valley are very active, with an extremely high level of seismic activity and measurable amounts of crustal displacement within this century. Perceptible earthquakes (Richter magnitude greater than about 2.5-3) are almost daily occurrences. Swarms of several hundred earthquakes (Richter magnitudes up to 5.0) occurring within a short period of time have been recorded several times since 1975 (Hill et al., 1975; Johnson and Hadley, 1976; Fuis and Schnapp, 1977). More than 12 earthquakes with Richter magnitude greater than 6.0 have occurred in the Salton Trough this century (Elders, 1975). The most active fault zones in the Imperial Valley are the Brawley and Imperial fault zones, which trend southeasterly from the Salton Buttes past Brawley and between El Centro and Holtville across the Mexican border. These faults have been the site of no less than four earthquakes with Richter magnitude greater than 6.0 in this century. The most recent occurred October 15, 1979, and caused extensive damage in the valley. Surface rupture and both horizontal and vertical motion along the Brawley and Imperial faults have been documented (Elders, 1975; Hill et al., 1975; Johnson and Hadley, 1976; Sharp, 1972; Real et al., 1979).

Reviews of seismic patterns in the Imperial Valley by Hill et al. (1975) and Johnson and Hadley (1976) indicate the following characteristics:

- A linear alignment of epicenters in the middle of the valley corresponding to the northern part of the Imperial Fault,
- A second concentration of epicenters in the Brawley area associated with the Brawley Fault,
- An infrequency of earthquakes to the east of the Imperial Fault, and
- Depths of most of the quakes between 5 and 14 km.

There have been concerns that the injection of geothermal fluids into a reservoir could enhance seismic activity. These concerns stem from two separate incidents in Colorado in which subsurface injection was directly linked with seismic events. In one case, earthquakes were triggered by the high pressure injection of water into an oil reservoir in Rangely, Colorado and in the other situation, earthquakes resulted from the injection of waste fluids at the Rocky Mountain Arsenal near Denver (Raleigh, 1972; Raleigh et al., 1975; Hsieh and Bredehoeft, 1979). At Rangely, Colorado, the presence of a threshold pressure for induced seismicity was demonstrated. It was shown that by increasing injection pressure above the threshold, seismic events could be induced. The mechanism for the induced seismicity was concluded to be decreased physical strength of the rock body caused by the injection, and the presence of a substantial seismic stress field (Raleigh et al., 1975). The mechanisms for decreasing rock strength include forcible lubrication of several kinds of fracture planes in the rock, and dilatation--the increase of interstitial pore pressure to a level at which the injection may cause uncontrolled fracturing of the reservoir rock. The potential for leakage of injected fluid to adjacent aquifers was considered the most important problem with induced fracturing. As a result, guidelines have been developed to avoid this type of problem. A standard commonly adopted by states limits injection pressure at the formation face to 0.8 psi per foot of depth. This pressure is below the generally expected fracturing pressure for reservoir rocks.

There is a substantial body of experience, however, to indicate that short-term injection at pressures above the fracture pressure of a reservoir does not induce seismic activity. The widespread practice of hydraulic fracturing to increase productivity of oil or gas reservoirs involves using high-pressure injection to fracture the formation and then to force fluids

into the created fractures to extend them. Pressures above fracture pressure are maintained for periods in the range of hours to a few days. There is no documented instance of induced seismicity caused by this practice.

There are two critical factors in inducing seismicity by injection: fracturing the reservoir rock by prolonged high-pressure injection and the presence of substantial seismic stress. It is impossible to predict in advance the pressure at which fluid injection will fracture reservoir rock. Normally, the pressure required is above the common standard of 0.8 psi per foot of depth, but the Colorado experience indicates that there are cases in which the fracture pressure is substantially lower than the standard. Even though the pressure at which fracturing will occur cannot be predicted, the actual occurrence of fracturing can be recognized from changes in injection pressure. These relationships suggest that a more comprehensive standard that might avoid induced seismicity would specify that prolonged injection to a formation above its fracture pressure is prohibited.

There has been largely undocumented experience with injection of geothermal fluids to the producing reservoirs in the Imperial Valley. In addition to a report by Morse (1978), personal contacts with field personnel by Crow and comments by D.N. Anderson, a former California State Geothermal Officer, indicate that injection is successful there at very low pressures at the formation face. Typical well head injection pressures are about 200 psi. Most of the pressure is required to overcome fluid friction in the well bore, and the incremental pressure exerted at the formation face is on the order of a few pounds to a few tens of pounds per square inch. There is no evidence of induced fracturing of the formation at these pressures. There is, however, evidence of formation plugging. Increased injection pressure at the Magmamax 3 well in the Salton Sea resource area, for example, was considered to be evidence of well damage, and operations were suspended. Attempted repair of the well indicated that the well bore and the reservoir rock adjacent to the well had been plugged by scale from the geothermal brine (Morse, 1978). It was determined that the well was irretrievably plugged, and it is no longer in use. A similar pressure rise

was unofficially reported to have occurred during an injection run at the North Brawley field. This also was interpreted as incipient plugging of the formation. Injection was terminated until better pretreatment of the injected brine was instituted.

High-pressure injection is not the only method of inducing earthquakes. For example, Marks et al. (1978) have linked increased seismicity (Richter magnitudes 3 and below) at The Geysers resource area to the extraction of steam and the injection of condensate. It is conceivable that these microearthquakes are associated with stresses in the reservoir rock resulting from changes in temperature and pressure. Because the geology of the vapor-dominated reservoir of The Geysers is different from that of the water-dominated reservoirs in the Imperial Valley, it is not possible to determine whether microearthquake activity will also accompany geothermal development in the valley.

The uncertainties regarding induced seismicity underscore the importance of monitoring seismicity. However, there is a serious problem in the Imperial Valley in distinguishing any induced seismicity from the naturally high level of seismic activity in the region--which is often associated with the geothermal areas. Fortunately, we have baseline seismic activity data collected by a seismograph network supported in part by the LLNL Imperial Valley Environmental Project. These data indicate (Crow and Kasameyer, 1978) that natural activity occurs at a greater depth than the expected depth of injection, so that focal depth will be an important factor in determining the cause of earthquakes near producing geothermal fields. The data also indicate that earthquakes often occur in swarms of several hundred events in a small area. If it were not known that this were a natural occurrence, it would be reasonable to believe that such a series of events near an injection field might be erroneously associated with extraction and injection. The baseline data indicate a complex situation, and more research and continued monitoring are extremely important.

CONCLUSIONS

- Natural subsidence ranges from less than one cm per year in the southern end of the valley to as high as 4 cm per year at the north end of

the valley near the Salton Sea. Natural subsidence has not caused damage to lands or property because it is regionally distributed.

- It is not possible to accurately predict subsidence above a compacting geothermal reservoir in the valley due to a lack of data on the inelastic response of porous materials in a reservoir to reductions in pore pressure.

- In order to properly analyze land deformation, data should be collected on: (1) compaction within a reservoir as well as confirming beds, (2) expansion in over burden, and (3) changes in land surface elevations. Most of the emphasis to date has been placed on surface monitoring. More emphasis needs to be placed on subsurface measurements because they would provide data on the actual response of reservoir materials to changes in stress. Such data could provide an early warning of future subsidence.

- We made estimates of how much subsidence might occur above a reference reservoir supporting a 50 MW geothermal power plant in order to assess the potential impacts of land deformation on agricultural land uses. For our analyses we assumed that 1%, 10%, and 30% of an upper-bound prediction of compaction for the reference reservoir reached the surface. The only assumption that resulted in impacts was the 30% case. In that situation, a subsidence depression was formed that altered the natural slope of the land surface. Slopes were reversed over part of the bowl, and these reversals would directly interfere with the surface irrigation of affected lands. Sprinkler irrigation, which does not require carefully graded fields, would be an alternative method of irrigation on those lands. A more serious consequence would be the movement of drainage waters to the low point of the depression. This would have to be rectified because irrigation in the valley depends on the continuous removal of surface and subsurface waste waters.

- There is a remote possibility that the injection of spent geothermal fluids in the valley will induce seismic activity. In previous cases where injection triggered earthquakes, fluids were injected at pressures above the fracture pressure of the formations receiving the waste fluids. An injection experiment in Colorado (Raleigh et al., 1975) did show that induced seismicity can be mitigated 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 be reduced because injection will be done at low pressures. However, if harmful seismic events are triggered, then the remedial action would be to either stop injection or lower injection pressures.

- As geothermal energy production proceeds in the Imperial Valley, it will be necessary to monitor earthquakes to determine if seismicity changes with the extraction and injection of geothermal fluids. However, it could be difficult to distinguish between natural and induced events in this seismically active region. Data on the location, frequency, and focal depths of earthquakes near geothermal fields would have to be compared with historic measurements to show if significant changes have taken place. Such comparisons would depend in part on statistical techniques of data analysis; for this reason, continued monitoring by the present seismographic network is essential in order to enlarge the data base needed for these analysis techniques.

SECTION 9. IMPACTS ON AGRICULTURAL RESOURCES

J. Kercher and D. Layton

In order for geothermal development in the Imperial Valley to proceed in an acceptable manner, it must be compatible with irrigated agriculture. Geothermal operations could affect agriculture through the emission of atmospheric pollutants, the consumption of arable lands to support well fields and production facilities, and the inadvertent release of geothermal fluids. Salt drift emitted from cooling towers might also have a negative impact on crops. In this section we examine the extent to which each of these activities could interfere with agriculture in the valley.

EFFECTS OF NONCONDENSABLE GASES ON CROPS

Our assessment of the effects of noncondensable gases 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. This crop is one of the principal field crops in the valley. Beets have also been extensively studied, and much background work in the form of modeling has been carried out. For the second part of the assessment, we used existing pollutant effects data to analyze the impacts of gaseous emissions on other important crops.

Effects on Sugar Beets

Figure 9-1 is a schematic diagram of the modeling procedure used with sugar beets. First, a general crop model GROW1 was developed (Kercher, 1977). Using this as a basic framework, the specific details of sugar beet growth were added or used to modify the general model (Kercher, 1979). Meanwhile, a detailed model of leaf photosynthesis (Kercher, 1978) was developed. The data for parameterization of the sugar beet growth model, BEETGROW2, were taken from Fick (1971) and Hunt (1974). These data were used to parameterize the nominal response of sugar beets grown under no pollutants. The data consisted of parameters estimated by Fick (1971) and Hunt (1974), growth and yield data under field conditions, and weather data taken in the field at

Fig. 9-1. Schematic diagram of the procedure used to assess the impacts of gaseous effluents from geothermal power plants on crops.

U.C. Davis. The nominal behavior of the leaf photosynthesis model under no pollution was taken from the thesis of Hall (1970). These data included the response of photosynthesis to light level and CO_2 level and the value of dark respiration. Data on the temperature dependence of dark respiration were taken from Fick (1971) and data on the temperature dependence of photosynthesis were taken from Nevins and Loomis (1970). These data were also used to parameterize the leaf photosynthesis model. The leaf photosynthesis model was then parameterized for the response to H_2S pollution using data from Shinn (1979). It was found that it was necessary to consider the effects of H_2S as acting in the short term on the enzyme kinetics of photosynthesis while in the longer term, it was necessary to consider chronic effects of H_2S on the production and destruction of the means of the leaf to carry on photosynthesis. The data of Shinn were used to parameterize the short-term model. The photosynthesis model with long-term effects was used in the general growth model to fit the growth data of Thompson et al. (1979). In parameterizing this combination, we used the growth parameters as determined previously but the model was exercised using environmental data from Riverside for the period in which Thompson and Kats conducted their experiments. This was obtained by Climatological Data Reports of NOAA (USNOAA, 1976; USNOAA, 1977). Thompson et al. (1979) give data on growth and yields of sugar beets under various fumigation regimes. This parameterization procedure is described in detail in Kercher (1978, 1979).

The growth model requires data on air temperature, relative humidity, net solar radiation, wind, normal CO_2 levels, and maximum light levels. The IVEP air quality baseline study took such data in fifteen minute averages for various locations around the valley (Gudiksen et al., 1978; Axelrod, 1978). In addition, they monitored various pollutant levels in the valley including H_2S . These data cover the time period from December 1, 1976 to April 30, 1978. For use in BEETGROW2, the fifteen minute averages were converted to hourly averages. Missing data were estimated by averaging the values for the preceding and succeeding day.

To perform the model calculations, we also needed the cultural practices of plant density and crop calendar. To do an accurate water budget, the irrigation schedule is also needed. However, for our purposes of assessing pollutant impact, the exact irrigation schedule was unnecessary. Instead, we simulated the application of enough water to keep the beets well watered.

It was found that an irrigation schedule of one application approximately every 10 days of four to six inches was more than adequate to keep the beets under good moisture conditions. Plant density was assumed to be seven plants/m², which is common commercial practice (Fick, 1971). For the crop calendar, we used the results of Cudney (1967), supplemented with detailed comments by Hagemann (1979). Hagemann stated that the first beets are planted the last week of August with the first harvest occurring the first week of April, the following year. Assuming six to seven days until emergence, we took 10 days after emergence to be September 10 and harvested on April 7. The model initializes at 10 days after emergence following Fick (1971). To calculate the daily course of the sun above the horizon, the latitude is required as an input variable. We used the latitude of Imperial, which is 33° N.

The model was run for each location with the expected time series of H₂S concentrations predicted for 3000 MW level of development. In addition it was run for ambient H₂S only (no geothermal development) and for H₂S at 3000 MW plus the expected increase in CO₂ due to geothermal development. Then it was run at 2, 4, 8, 16, etc., times the H₂S output until damage began to occur. For these cases, it was run with and without the proportionate increases in CO₂. This was done for all 22 locations included in the air quality assessment (see Fig. 5-6).

In Fig. 9-2, we show a simplified schematic diagram of the model used to perform the assessment for the target crop, sugar beets. A detailed discussion of this model can be found in Kercher (1978, 1979). The model contains a canopy submodel to calculate the light intensity profile in the canopy. Light is absorbed by leaves as it travels through the canopy. This extinction is a function of leaf angle, angle of the sun, and cumulative leaf area index. The net radiation profile is also calculated for the canopy using the observed extinction coefficient for sugar beets. The water budget submodel is also calculated using input to soil moisture content from precipitation or irrigation. Transpiration is calculated using a modified Penman's equation (Goldstein and Mankin, 1972). This formula requires stomatal resistance, canopy resistance, net radiation absorbed by the leaf, temperature, and relative humidity. For purposes of this assessment, we used stomatal resistance as a function of soil moisture content (Brown and Rosenberg, 1971). A sulfur submodel estimates sulfur delivered to the leaf.

Fig. 9-2. Schematic diagram of the growth model used to assess effects on sugar beets. The photosynthesis submodel uses information from the sulfur, canopy, and water submodels to calculate photosynthate production.

Air concentrations of H_2S are required as input to this submodel. The photosynthesis submodel calculates photosynthesis at the leaf as a function of CO_2 concentration in air, sulfur at the chloroplast, temperature, and light level with stomatal resistance as an important variable affecting photosynthesis. Stomatal resistance is a function of light level and water stress. In the growth model, we used the photosynthesis submodel which simulates the long-term effects of sulfur absorption. The photosynthesis submodel integrates photosynthate production over the entire canopy and deposits it into a reserve compartment. The photosynthate allocation submodel uses the reserve photosynthate to grow the plant, provide for maintenance respiration, growth respiration, and organ development. Growth occurs by the construction of structural material of leaves, beet, and fibrous roots. Photosynthate is also deposited in a sugar compartment in the beet. The photosynthate allocator is a set of coupled ordinary, non-linear differential equations.

The total, unabated H_2S emissions for the four KGRAs at 3000 MW is equivalent to 9.0 metric tons (mt)/day with 5.4 mt/day from the Salton Sea KGRA, 2.3 from Brawley, 0.9 from Heber, and 0.4 from East Mesa, assuming no H_2S abatement. The projected CO_2 release at 3000 MW is 6700 mt/day proportioned as 2900, 1200, 1800, and 800 mt/day between the KGRAs. In Fig. 9-3 we plot the response of the sugar beet model for Imperial Valley climatic conditions using IVEP meteorological data and IVEP air quality data for the time-series of H_2S and CO_2 . Each curve is for one of the 22 locations in the valley except for location 15. Location 15 was not included because it was over the Salton Sea. The x-axes of the graphs are in multiples of emission rates of H_2S . It is assumed that CO_2 emission rates remain constant. Thus the nominal emission rate of 9.0 mt H_2S /day at 3000 MW is one unit on the x-axis. The y-axis is relative growth of the entire beet plant (tops, beets, and roots). At all the locations there is some net increase in growth at the expected level of H_2S emissions. Station 14 shows the greatest increase (i.e., 35%) at the expected emission rate and also the lowest emission rate at which negative effects begin to cancel out the fertilization effect. This crossover is at 13 times the expected emission rate (EER). The smallest increase in growth at the EER is for location 16 in Mexico (Fig. 9-3d). This value is 0.4%. Location 19 has the greatest

value for this crossover point between growth enhancement and growth suppression. This value is approximately 220 times the EER. From Fig. 9-3 it is apparent that the maximum growth occurs anywhere between 2 and 32 times the EER at the various locations examined. The statistics for the values of growth enhancement at the EER are summarized in Table 9-1. Seven locations (14, 13, 2, 11, 7, 1 and 12) show an increase of 10% or greater at the EER. This is probably a rough cutoff of where commercial operations might discern a change in yield. In column two of Table 9-1, we show the expected increase in ambient concentration of H_2S averaged over the growing season at the EER. Note the wide variation in this value indicating relative proximity to sources, wind conditions, strengths of nearby sources, etc. In looking at Table 9-1 and Fig. 9-3, one can find odd phenomena. For example, location 21 shows slightly greater enhancement than location 4, yet location 21 has a lower expected H_2S increase than location 4. This is due to the odd distribution frequency of pollutant episodes coupled with the non-linear dynamics of the growth model.

We also calculated the impact of increased emissions of H_2S and CO_2 combined, on the growth of sugar beets at five locations (14, 11, 2, 1, and 12). In this case, when we use a multiple of the EER for H_2S , we assume that the CO_2 EER is increased by the same multiple. The total growth of the beet plants at the different locations increased monotonically with increasing emission rates. This means that for any level of development, if the ratios between H_2S and CO_2 emissions are accurate, then only increased yields would be expected. We hasten to point out that these results are only known to be valid in the region of concentrations of the data of Thompson (i.e., .3 ppmv for H_2S and less than 400 ppmv for CO_2) that were used in construction and parameterization of the model. Thus it is entirely possible that CO_2 does not provide protection to the effects of H_2S at concentrations greatly exceeding 0.3 ppmv even if the ratio of H_2S to CO_2 remains constant. At those levels other destructive effects might occur which were not modeled and decreases in productivity might take place. Unfortunately, we cannot predict such effects a priori but must instead wait for further experimental work. On the other hand, this consideration seems unimportant because the IVEP air quality assessment indicates that such elevated levels of H_2S should not occur when pollution controls are implemented.

Fig. 9-3. Response of the total growth of sugar beets for various H_2S emission rates compared to growth with no emissions. Emission rates are in units of the expected emission rate (EER) of H_2S where 1 EER equals 9.0 metric tons/day. Emissions of CO_2 are held constant at 6700 metric tons/day. (a) Locations 14, 13, 2, 11, and 7. (b) Locations 1, 12, 22, 8, 10, and 21. (c) Locations 4, 6, 18, 3, and 5. (d) Locations 17, 9, 19, 20, and 16.

Fig. 9-3. Continued

Table 9-1. Enhanced growth of sugar beets caused by unabated emissions of H_2S from 3000 MW of geothermal energy development in the Imperial Valley.

Location ^a	Forecasted change % increase	Concentration of H_2S , ^b ppbv	Ratio of damage threshold to predicted H_2S concentration
14	35	25	13
13	29	14	21
2	22	12	22
11	19	5.0	60
7	19	5.8	61
1	11	4.7	31
12	10	2.8	120
22	7.0	2.2	75
8	6.6	1.7	98
10	6.4	1.8	92
21	6.1	1.6	110
4	5.1	2.5	85
6	3.3	1.0	110
18	3.1	0.7	180
3	2.9	2.0	120
5	2.4	0.5	140
17	1.6	0.3	180
9	1.2	0.3	200
19	1.1	0.3	220
20	1.1	0.4	83
16	0.4	0.1	160

^a See Fig. 5-6 for numbered locations.

^b Average concentration of H_2S over the growing season.

Effects on Other Crops

Thompson and Kats (1978) and Thompson et al., (1979) report on the results of long-term fumigations of alfalfa, cotton, sugar beets, and lettuce with H_2S and CO_2 mixtures. Alfalfa, sugar beets, and lettuce were fumigated with H_2S at concentrations of 0.0, 0.03, 0.1, and 0.3 ppmv. Alfalfa was grown during the summers of 1975 and 1976. During 1976, it was harvested eight times, approximately every 25-30 days. The late summer cuttings (3 of the 8) showed statistically significant increases in growth of approximately 30% at 0.03 ppmv H_2S . The rest of the cuttings at 0.03 ppmv H_2S and all of the cuttings at 0.1 ppmv showed no statistically significant variation from the control at 0.0 ppmv. Six of the light fumigations at 0.3 ppmv showed significant decreases in yield with the average yield being 79% of the control. The averages at 0.03 and 0.1 were 108% and 93% of the control respectively. Three different experiments were conducted with lettuce, each at a different time during the year. In the first experiment, a significant increase in yield at 0.03 ppmv was found; the change at 0.1 ppmv was not significant. In the second experiment, no significant change was observed at either 0.03 ppmv or 0.1 ppmv. In the third experiment, a significant increase was observed at both 0.03 and 0.1 ppmv. In all experiments, significant reductions in growth and yield were observed at 0.3 ppmv. The average responses at 0.03, 0.1, and 0.3 ppmv were 127%, 103%, and 46% of the control, respectively. Three experiments were done for sugar beets. The average values for total growth were 144%, 133%, and 84% of the control at 0.03, 0.1, and 0.3 ppmv, with CO_2 levels held constant. In the experiment on cotton, reductions in leaves and stems at 0.3 ppmv were not significant. However, a significant increase of 277% in dry weight of flowers and bolls was observed at 0.3 ppmv. Since this is the economically important part of the plant, we can ignore the reductions in leaves and stems to state that the expected increases in H_2S are unlikely to damage cotton production in the valley.

Because detailed models of alfalfa and lettuce were not developed or parameterized, and because the data base is not adequate for detailed predictions, we cannot give accurate estimates of the expected changes in yields for alfalfa and lettuce in the valley. However, if we assume that it is possible to extrapolate thresholds of the dominance of growth suppression mechanisms over the fertilization mechanisms from sugar beets to alfalfa and

lettuce on the basis of the above data, then we can estimate the emission rates at which this crossover threshold should occur for lettuce and alfalfa. This is a rough estimation but a reasonable first approximation until more experimental work is done. In Table 9-2 we use these data to project the ratio of the emission rates to produce damage compared to the expected emission rate at four locations in the valley. These locations are the four worst case locations for this parameter. Table 9-2 shows that alfalfa is more sensitive than lettuce to damage but that the EER at 3000 MW is still below the emission rate for damage thresholds by a factor of 4 for the worst case. If we were to express the relative sensitivity of alfalfa, lettuce, and sugar beets in terms of concentrations necessary to produce damage, they would be in the ratio of 1.0, 1.6, and 3.4 respectively. In a published list of SO_2 sensitivity to injury by acute fumigations of SO_2 , the three crops are 1.0, 1.2, and 1.6. We see that the order is maintained but there are differences in the magnitudes. The values of relative sensitivity to threshold damage we propose here should be regarded as indicative. They are based on experiments which contained much statistical variation due to their nature and require more confirmation if they are to be used in the way suggested here. Our values were derived to be reasonably conservative.

If we do assume that the sensitivity to H_2S is correlated with the sensitivity to SO_2 , then we can use sensitivity tables for SO_2 to derive approximate emission rates for the damage threshold. Thomas and Hendricks (1956) give relative sensitivity of various crops to SO_2 as follows: alfalfa 1.0, barley 1.0, squash 1.2, lettuce 1.2, wheat 1.5, carrot 1.5, tomato 1.5, sugar beets 1.6 among others. Correlating these sensitivities with the ones for alfalfa, lettuce and beets for H_2S , we can develop a set of ratios of the emission rates for the damage threshold to the EER. These ratios are shown in Table 9-3 for these crops for locations 14, 13, 2, and 1. These locations are the ones where projected elevated concentrations are nearest the threshold concentration for sugar beets. We see from Table 9-3 that the minimum safety factor or ratio is 4 with most of them being at least a factor of 10.

Table 9-2. Ratios of the emission rates of H₂S that would cause damage to alfalfa and lettuce to the expected emission rate with 3000 MW of geothermal development.

Location	Crop	
	Alfalfa	Lettuce
Salton Sea KGRA	3.8	6.0
Brawley KGRA	6.1	9.7
Calipatria	6.4	10
Niland	9.0	14

Table 9-3. Ratios of the emission rates of H₂S that would cause crop damage to the emission rates expected with 3000 MW of geothermal development.

Crop	Location			
	Salton Sea KGRA	Brawley KGRA	Calipatria	Niland
Wheat	12	19	20	28
Tomatoes	12	19	20	28
Carrots	12	19	20	28
Rye grass	10	17	18	25
Squash	6	10	10	14
Barley	4	6	6	9

EFFECTS OF H_2S ON HONEY BEES

There are several crops in the Imperial Valley that depend directly on honey bees for pollination. Without bees, million dollar crops like cantaloupe, watermelons, and alfalfa grown for seed could not be grown commercially. It is important, therefore, to assess the potential impact that increased levels of H_2S would have on honey bees.

Fumigation studies conducted by Atkins (1979) have shown that the average lifespan of honey bees (Apis mellifera) will be significantly shortened when continuously exposed to H_2S at concentrations of .10 ppmv and higher. More specifically, at .10 ppmv and .30 ppmv of H_2S , the lifespan of exposed bees was shortened by 32% and 51% over the lifespans of the unexposed, or control bees. At .03 ppmv of H_2S , though, the lifespan of the exposed bees actually increased 33% over that of the control bees. The air quality assessment of 3000 MW of development indicates that even with unabated emissions of H_2S , it is unlikely that ambient H_2S concentrations will reach levels that significantly effect honey bee colonies in the valley. And so with H_2S abatement and lower ambient concentrations of H_2S , it is safe to conclude that no adverse impact will take place. Actually, the experimental data of Atkins (1979) suggest that ambient H_2S levels of .03 ppmv and below would extend the lifespan of bees, and presumably their effectiveness as pollinators.

DRIFT FROM COOLING TOWERS

One aspect of future geothermal operations in the Imperial Valley that has not been rigorously examined is the effect on crops of drift emitted from mechanical-draft cooling towers. At The Geysers geothermal resource area in northern California, boron contained in drift emitted from cooling towers is probably the cause of foliar damage to native trees in the vicinity of some of the geothermal power plants (Malloch et al., 1979). It is difficult to predict whether similar damage will be done to crops grown in the valley because of uncertainties involving the prediction of drift deposition, the chemistry of cooling waters, and the sensitivities of crops to saline aerosols. Of particular importance is information on the response of major

crops in the valley to sodium chloride as well as other substances (e.g., boron) that could be present in drift.

Only a limited amount of research has been conducted on the biotoxicity of drift, and most of the work that has been done to date has focused on the effects of saline drift on plants and trees that are common to the eastern part of the country (see Nietubicz, et al., (1978) for a review of recent drift effects research). Previous studies have also been based on rather humid conditions, which are also characteristic of the eastern United States. For example, McCune et al., (1977) have shown that the level of relative humidity can directly change the toxicity of drift. In an experiment they conducted, a change in relative humidity from 50% to 85% increased the toxicity of drift to the exposed plant by a factor of two. They suggest that the increased foliar damage results from the deliquescence of sodium chloride at around 75% relative humidity, which causes increased penetration of salt. The relative humidity in the valley, by comparison, is very low, averaging 30 to 50% in the early morning and 10 to 20% in the late afternoon, with humidities of 10% common during the hottest part of the day. In 1975 the average relative humidity was 26.5% (Layton and Ermak, 1976). The effect of this low level of humidity on the biotoxicity of drift has yet to be examined.

The chemistry of cooling waters (see Table 6-1) will determine the chemical composition of drift and hence its toxicity. A key unknown about cooling water chemistry is the amount of boron that will be present in steam condensate. Toxic levels of boron in drift could occur if a large fraction of the boron contained in geothermal fluids is carried over in flashed-steam, and concentrations in the condensate are subsequently increased by the effect of evaporation as the condensate is circulated through a cooling tower. In addition, the use of biocides in cooling waters could be a potential problem. Assessment of the impacts of drift on crops would also require predictions of the deposition of drift around a cooling tower. The dispersion of drift is a complex phenomenon and the development of models to simulate drift movement is still in progress (see Chen (1977) and Policastro et al., (1978) for reviews and comparisons of different models). However, existing models can still provide estimates of mass deposition rates and particle size distributions of drift for use in assessing the impacts of drift. Volume II contains an analysis of the technology available for controlling emissions of drift.

LAND REQUIREMENTS FOR GEOTHERMAL DEVELOPMENT

Power plants and related well fields sited within the central part of the valley will remove land from agricultural production. For large-scale development, the amount of land could be significant. To establish a low and a high estimate of the land requirements for 3000 MW level of development, we made a series of assumptions regarding the number of wells needed to support power plants in the different resource areas, acreage requirements for production and injection islands, and the quantity of land needed for individual power plant sites. We based our calculations on the introduction of generating facilities in 100 MW units, each requiring 15 to 20 acres of land. Well fields to supply fluids to power plants contained 48 production wells per 100 MW (net) plant in the Heber resource area, 21 in the Brawley area, and 14 in the Salton Sea area. The decreasing need for wells is a result of the higher conversion efficiencies that correspond to the higher resource temperatures. We assumed that 6 injection wells would be needed for every 10 production wells. Therefore, the total well requirements for the three resource areas were: 77, 34, and 22 wells per 100 MW (net). Land requirements for the production and injection islands ranged from 6 acres per 10 well island to 4 acres per 10 well island. Table 9-4 shows the high and low estimates of the number of acres of land needed for geothermal facilities in the Salton Sea, Brawley, and Heber resource areas. The levels of power production are from Table 4-1. Both estimates represent less than 0.2 percent of the 475,000 acres of land that are currently cultivated in the valley. Each generating facility will remove land from agricultural production for periods up to 30 years.

Production and injection islands will normally be located on the edges of fields to minimize interference with cultivation. Pipelines will follow existing farm access roads, and thus additional farmland should not be needed. Power plants will be sited as close to production wells as possible to reduce heat losses during fluid transmission. As a result, there is only a limited amount of flexibility in avoiding agricultural lands. The biggest opportunity for lowering land requirements is the use of multi-well production and injection islands. If they were not to be used, up to 2 acres of land would be needed for each well. Even though geothermal facilities will

not occupy large amounts of land, this does not eliminate the possibility of local siting problems in areas where several facilities are to be built.

Table 9-4. Estimates of the acres of land required for geothermal facilities located in the irrigated part of the Imperial Valley.

Resource Area	MW of Production ^a	Number of 100 MW units	Number of Wells	Land Requirements	
				High ^b Estimate	Low ^c Estimate (acres)
Salton Sea	1400	14	308	465	333
Brawley	600	6	204	242	172
Heber	700	7	539	463	321
TOTALS	2700	27	1051	1170	826

^a Based on the 3000 MW scenario of development.

^b Assumes 20 acres/power plant and .6 acre/well.

^c Assumes 15 acres/power plant and .4 acre/well.

ACCIDENTAL SPILLS OF GEOTHERMAL FLUIDS ON AGRICULTURAL LANDS

Geothermal facilities will process large quantities of geothermal fluids to produce electricity. It is conceivable that during the operational life-time of a power plant some fluids will be released because of component failure. Sung et al., (1979) have used failure rates for equipment in the nuclear industry to estimate the probability of a major release of fluids. According to their study, there is a .2% chance that a 50 MW power plant operating for 40 years would have a large spill. A maximum release could amount to as much as 5 acre-feet of fluid, assuming that the entire fluid flow of a power plant (e.g., 14,000 gallons per minute) was spilled for 2 hours before it was controlled. If such a release were not properly contained, crops and farmland in the path of the spilled fluids would be directly impacted. The immediate consequence of an accidental release would be the

loss of crops injured by the heat of geothermal fluids. This would be true of any release of high temperature water--regardless of its salinity or chemical composition. Longer term impacts on soils and future plantings of crops would result from the contamination of soil waters.

Geothermal fluids spilled onto farmland will gradually percolate downwards, and mix with soil waters. The growth of subsequent plantings of crops could then be adversely affected by elevated levels of toxic elements in the soil waters. The actual effect on soil water chemistry of a spill of fluids having a known composition is difficult to predict because of the chemical changes that would take place in the fluids as they cool. For example, the formation of precipitates would reduce the concentrations of different elements in the cooled geothermal fluids. In particular, the depletion of toxic elements through precipitation and adsorption processes would lessen the severity of soil water contamination. Sposito et al. (1979) have simulated the chemical speciation of geothermal fluids from the Heber, East Mesa, and Salton Sea resource areas through the use of a computer program, termed GEOCHEM. In their analysis, GEOCHEM predicted the chemical composition of the geothermal fluids after solids were precipitated at 25°C and metals adsorbed by Fe and Mn oxides. Then it was used to calculate the speciation of trace metals caused by mixing the modified fluids with selected soil waters. The effect of cation exchange in the soils was also included in the calculations.

The important conclusions to be drawn from their analyses are as follows:

- Sulfides present in geothermal fluids as well as exchange surfaces in soils can effectively remove trace metals like Ni, Cu, Zn, and Pb, which can be toxic to crops.
- Li and B do not precipitate and thus can reach harmful levels in soil waters if enough geothermal fluid enters soils.

Geothermal fluids entering soils after a spill will add more dissolved solids to the root zones of crops, increasing the salinity stress that already exists on crops. Fluids with a high sodium content can also affect the permeability of soils, and this could make it difficult to supply water to crops (Ayers, 1977). On the basis of salinity and dissolved constituents, the toxicity of geothermal fluids from the valley's geothermal resource areas increases in this order: East Mesa, Heber, Brawley, and Salton Sea. The quantity and quality of released fluids will directly influence efforts to

reclaim affected soils.

Jury and Weeks (1978) have investigated alternative methods of leaching to remove contaminants from soils. They examined the use of sprinklers, full ponding, and partial ponding to leach soil waters. The important variable in reclamation was shown to be the distance of a spill from a subsurface drain line. Only spills in the immediate vicinity of a drain line could be reclaimed in reasonable amounts of time (e.g., weeks or months). Full ponding of affected soils near drain lines proved to be the most effective method of leaching. Partial ponding was more effective in reclaiming spills situated at a distance from a drain, however, large amounts of time (i.e., years) would be necessary. Sprinkler leaching was generally shown to be ineffective. For spills located away from a subsurface drain, they suggest that the installation of a new drain would facilitate the removal of contaminated waters. Furthermore, they promoted the use of CaCl_2 in leaching water to hasten the removal of excess Na^+ in the soils.

CONCLUSIONS

- Simulation of the response of sugar beets to unabated emissions of H_2S and CO_2 from 3000 MW of geothermal development indicates that the growth and economic yield of beets could be enhanced significantly (i.e., greater than 10%) at locations near geothermal facilities. With abatement of H_2S emissions, ambient concentrations of that gas would have a positive, but reduced effect on the growth of sugar beets.

- Based on the results of previous crop-fumigation experiments (Thompson and Kats, 1978; Thompson et al., 1979), we conclude that the yields of alfalfa, cotton, and lettuce will be unaffected by ambient concentrations of H_2S resulting from 3000 MW of geothermal energy production.

- Fumigation studies with honey bees show that the average lifespan of bees would be shortened by continuous exposure to H_2S concentrations of .10 ppmv and above (Atkins, 1979). Ambient concentrations of H_2S are not expected to reach that level in the valley, and so adverse impacts on bees are unlikely.

- As this time it is not possible to accurately predict what the effect of cooling tower drift will be on crops grown in the valley. Experimental work will be necessary to determine the response of crops to various doses of drift derived from cooling towers used with geothermal power plants.

- Geothermal power plant and related facilities associated with the medium scenario of energy production will use at most only about .2% of lands normally irrigated in the valley.

- 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. On the long term, the contamination of soil waters beneath lands affected by a spill could have toxic effects on future plantings of crops. Work by Sposito et al. (1979) indicates that Li and B do not precipitate after geothermal fluids mix with soils waters, and therefore those substances could reach levels that are harmful to crops.

- Based on the chemical composition of geothermal fluids, the toxic effects of accidental releases would be greatest in the Brawly and Salton Sea resource areas.

- If a release of geothermal fluids does result in the contamination of soil waters, the primary method of removing toxic substances would be through leaching. Jury and Weeks (1978) have shown that the most important variable in soil reclamation is the distance of contaminated areas from a subsurface drain line. Contaminated soils must be over or directly adjacent to a drain line in order to use surface ponding to leach contaminants out of the soil column over a period of weeks or months. Additional subsurface drain lines would have to be installed to facilitate leaching in areas between existing drain lines.

SECTION 10. HEALTH AND SAFETY CONCERNS

L. Anspaugh and P. Leitner

The large-scale development of any technology results in some risk to the health of the general public and of the personnel employed in that technology. These risks are generally difficult to predict in advance of development and several unfortunate surprises have occurred through exposure to chemicals in a number of industries. One of the greatest difficulties in performing a predictive assessment is that one can never be absolutely certain that some new pollutant will not be discovered in the process streams, or that a recognized pollutant will not be shown later to be much more dangerous than known previously. Both types of discoveries have been made numerous times in a variety of industries.

In some respects, however, it is far easier to assess the human health risks from geothermal energy than from many other technologies. This is because the total geothermal energy cycle is relatively short and straightforward; for example, there are no large-scale supporting technologies such as are required for the mining and processing of uranium for the nuclear cycle, or as may be required for the development of special materials for some solar technologies. In addition, the expected effluents from geothermal extraction and use are relatively few in number and they are relatively well-known in terms of biological effects. However, because of the expected deployment of geothermal facilities in small increments for electrical power production (about 100 MW per unit) and for direct-heat use, there are many possible configurations of these facilities that are not predictable. In particular, some direct-heat uses may present unusual occupational health and safety problems if they utilize fluids with high salinity or a high content of hydrogen sulfide.

Geothermal energy has been used in a variety of ways for many years, and has been used to generate electricity at many locations throughout the world. The largest geothermal electrical power plant is at The Geysers, California, where the first unit began operation in 1960. This significant amount of experience is very valuable in assessing the possible hazards to health of a large-scale development in Imperial Valley. Residents of communities nearby The Geysers Geothermal Power Plant have registered public

health complaints, mostly related to such annoyance effects as odor from hydrogen sulfide (PG&E, 1978) and noise. Some residents have appeared at hearings held by the California Public Utilities Commission (CPUC, 1975) and voiced complaints of headache, nausea, sinus congestion, etc., that were attributed to the presence of hydrogen sulfide. There have also been occupational illnesses observed at The Geysers that are due to exposure to geothermal effluents or to abatement products (Hahn, 1979b). Both of these aspects will be discussed fully below; they are mentioned here to emphasize that the potential for health-related problems does exist and that vigilance and planning are required if problems are to be avoided in the Imperial Valley.

A Health Effects Element was included in the Imperial Valley Environmental Project (IVEP); much of this work was performed by the California Department of Health Services (CDHS) under contract to the Lawrence Livermore National Laboratory. Several reports have been produced by the Health Effects Element and these provide much of the basis for this Section. Hahn (1979a) surveyed and mapped existing sources of odor pollution in Imperial Valley in order to provide baseline data in advance of large-scale geothermal development. A summary of occupational hazards in the geothermal industry has been published (Hahn, 1979b), and a detailed evaluation is being prepared (Hahn, 1979c). A review of the behavioral toxicology of hydrogen sulfide was written by Vigil (1979), and a preliminary summary of human health implications was prepared by Anspaugh and Hahn (1979).

In addition to these studies funded through the IVEP, there are a number of recent reports of immediate relevance. The National Research Council (USNRC, 1977) has prepared a comprehensive report on hydrogen sulfide including its effects on human health, and the National Institute of Occupational Safety and Health (USNIOOSH, 1977) has published a criteria document for occupational exposure to hydrogen sulfide. USNIOOSH (1978) has also published a health hazard evaluation related to specific occupational health problems at The Geysers, and funded a more general study of occupational health in the geothermal hydrothermal industry (Zerwas et al., 1979). The Pacific Gas and Electric Company (PG&E) has funded a study of public health considerations relative to The Geysers Geothermal Power Plant

(Walton and Simmons, 1978); this report considers not only hydrogen sulfide, but also sulfur dioxide, sulfates, total suspended particulates, ammonia, mercury, arsenic, and boron. Another review of the health effects of hydrogen sulfide has been published by the Illinois Institute of Environmental Quality (IIEQ, 1974).

PUBLIC HEALTH CONSIDERATIONS

As mentioned previously, residents of communities near The Geysers have complained about the odor of hydrogen sulfide and noise and some residents have associated adverse health effects with exposure to hydrogen sulfide. Because the geothermal resources in Imperial Valley are liquid-dominated, the problem of noise will be substantially less than at The Geysers where the resource is vapor-dominated. As shown in Table 5-1, the emission rates of hydrogen sulfide are expected to be substantially less at Imperial Valley sites compared to The Geysers. However, in terms of impacts on health (including annoyance reactions) of the general public, hydrogen sulfide is thought to be the most serious concern. Other chemicals that may be released to the atmosphere also deserve consideration; these include ammonia, mercury, radon, and benzene.

This analysis of impacts upon public health has been made with the assumption that discharges of spent geothermal fluids to surface waters will not be permitted, and that subsurface injection of spent fluids is successful in avoiding contamination of waters used for other beneficial purposes.

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 (USNRC, 1977); it produces immediate collapse with respiratory paralysis at concentrations above 1000 parts per million by volume (ppmv). At concentrations above 200 ppmv, it is still distinctly dangerous and should be considered an imminent threat to life. At concentrations above 500 ppmv strong stimulation of the nervous system is

noted and apnea (transient cessation of respiration) occurs. At concentrations above 300 ppmv, the most serious danger is the production of pulmonary edema (accumulation of fluid), which can occur with exposures of a few hours. While hydrogen sulfide has a characteristic odor, olfactory paralysis occurs at concentrations of 150 to 250 ppmv and this warning becomes unavailable at life-threatening concentrations. At lower concentrations, hydrogen sulfide is still an irritant gas and it produces local inflammation of the moist membranes of the eye and the respiratory tract. The threshold for serious eye injury is 50 to 100 ppmv. The current USNIOSH (1977) recommended standard for occupational exposure is 10 ppmv for a 40-hour week with the requirement of evacuation if the concentration exceeds 50 ppmv.

Hydrogen sulfide exerts its toxic effects through local irritation of moist membranes and systemically when it is absorbed through the lung or the gastrointestinal tract (USNRC, 1977). The systemic toxic effects are believed to be due to the reversible inactivation of cellular cytochrome oxidase by the undissociated form of hydrogen sulfide. (At the physiologic pH, about one-third of the total sulfide exists in the undissociated form.) Humans and animals have a detoxification mechanism that oxidizes hydrogen sulfide to harmless sulfates. Guinea pigs are capable of detoxifying 85% of the single lethal dose of sulfide each hour. Because of its action by reversible inhibition of enzyme systems and because of this efficient detoxifying mechanism, hydrogen sulfide is considered to be a noncumulative poison. USNIOSH (1977) found no reports associating hydrogen sulfide in air with carcinogenesis, mutagenesis, or teratogenesis.

Hydrogen sulfide is ubiquitous in nature (USNRC, 1977). Organic compounds that contain sulfur-bearing amino acids are a source of hydrogen sulfide when acted upon by a large array of bacteria. Other bacteria achieve the reduction of sulfate to hydrogen sulfide through an anaerobic process. Thus, we can anticipate that hydrogen sulfide would be produced in the gastrointestinal tract; and while there is no general agreement of the measurements, human flatus may contain up to 10% of hydrogen sulfide (USNRC, 1977). Because of rapid absorption from the gastrointestinal tract, the human body is probably constantly exposed to low levels of hydrogen sulfide from natural sources.

Exposure to hydrogen sulfide at concentrations below the occupational limit of 10 ppmv does result in at least one consistent pattern, that of annoyance to its odor. Because of the importance of this fact for the geothermal industry, we have reviewed the literature concerning the odor detection threshold. Some values in the older literature, reviewed by Miner (1969), are as high as 0.13 ppmv while other reported values are as low as 0.00047 ppmv (Leonardos et al., 1969). Values for the odor detection threshold from the more recent literature are plotted in Fig. 10-1.

The largest study is that of Adams et al. (1968) who reported results for 998 people in the 20-year age group from four study groups. It is significant that Adams et al. found that the odor detection thresholds were lognormally distributed; their results for the four groups are shown in Fig. 10-1 as straight lines drawn through three points corresponding to $\bar{x}_g/\sigma_g$, $\bar{x}_g$, and $\bar{x}_g\sigma_g$. The highest geometric mean (0.00644 ppmv) was reported for 789 individuals who were tested in a mobile laboratory at seven fairs in Oregon, Washington, and Idaho. The next highest (0.0056 ppmv) was reported for eleven members of a student panel. The geometric mean value of 0.0038 ppmv was found for 84 individuals tested at the California State Fair. The lowest value of 0.00339 ppmv was found for the first trials of a student panel of 114 individuals.

The three points in Fig. 10-1 shown as circles with dots inside represent results for twelve individuals as reported by Fyn-Djui (1961). The single point shown as a darkened square represents the point at which 50% of an unspecified number of observers were able to detect hydrogen sulfide (Cederlof et al., 1966). The circle with a cross through it represents the concentration (0.0047 ppmv) at which all four members of a trained panel were able to detect the odor. (This value should properly be plotted at the 100% point, which is not on the graph.) This value of 0.0047 ppmv is from the work of Leonardos et al. (1969) and is for hydrogen sulfide gas produced by acidifying sodium sulfide. They also reported a value of 0.00047 ppmv for hydrogen sulfide gas from a cylinder, and stated that this discrepancy may be due to impurities in the gas from the cylinder.

The open squares in Fig. 10-1 represent results extracted from a report by Wilby (1969). These results are for an untrained panel of 33 office workers over the age of eighteen who were chosen so as to approximate the age and sex distribution of the U.S. adult population.

Fig. 10-1. Summary of more recent measurements of the odor detection threshold for hydrogen sulfide: $\diamond$ 16 chemists and technicians (Dechant and Sanders, 1967); $\odot$ 12 subjects (Fyn-Djui, 1961); $\blacksquare$ unspecified number of subjects (Cederlöf, et al., 1966); $\times$ 789 twenty-year olds from Oregon, Washington, and Idaho fairs, Δ 11 twenty-year olds on a panel, $\circ$ 84 twenty-year olds from the California State Fair, and ∇ 114 twenty-year olds on a panel (Adams, et al., 1968); $\oplus$ panel of four subjects (Leonardos, et al., 1969); and $\square$ panel of 33 office workers (Wilby, 1969).

The diamonds in Fig. 10-1 represent the values from the study conducted by the California Department of Public Health (Dechant and Sanders, 1967; CDPH, 1962). This study is particularly important because it provided the information upon which the California ambient air quality standard of 0.03 ppmv is based (CARB, 1970). As shown in Fig. 10-1, the results of this study are clearly at variance with the other modern studies. This may be due to a systematic error of measurement, or it may be because the sixteen tested individuals were all chemists or chemical technicians (Dechant and Sanders, 1967) who might be expected to have a different response due to repeated olfactory insults. It is also of interest that the Department of Public Health (CDPH, 1962) recommended that the ambient air quality standard not be set at the odor detection threshold "... since it is unlikely that this concentration would lead to discomfort, sensory irritation or disturb the stability of residential or work communities." They recommended a standard of 0.1 ppmv. This viewpoint was not adopted by the Air Resources Board (CARB, 1970), and the standard was set at 0.03 ppmv. The results in Fig. 10-1 indicate that this standard is too high if the criterion is to be the odor detection threshold.

Representative values of ambient air quality standards established by other political units are shown in Table 10-1. Many of these standards are in the range of 0.003 to 0.009 ppmv, and are more consistent with the results shown in Fig. 10-1. Thus, it would seem prudent to design geothermal power plants so that concentrations of hydrogen sulfide in ambient air are well below the California standard if annoyance complaints are to be avoided.

The issue of whether there may be other health effects produced by very low concentrations of hydrogen sulfide is not fully resolved, and it may not be resolvable until many years have passed. As mentioned above, residents of nearby communities have voiced health complaints of headache, nausea, sinus congestion, abrupt awakening, etc. The concentrations of hydrogen sulfide that have accompanied these complaints were probably about 0.1 ppmv (PG&E, 1978). The data concerning the possible effects of exposure to low concentrations (a few ppmv or less) have been reviewed by several investigators (IIEQ, 1974; USNIOH, 1977; USNRC, 1977; Vigil, 1979; and Walton and Simmons, 1978). Most of the studies that relate these effects

Table 10-1. Representative values of ambient air concentration standards for hydrogen sulfide (Martin and Stern, 1974).

	Long Term		Short Term	
	ppmv	Avg. Time	ppmv	Avg. Time
California			0.030	1 hr
New Mexico			0.003	30 min
New York			0.009	30 min
Pennsylvania	0.005	24 hr	0.1	1 hr
Czechoslovakia	0.005	24 hr	0.005	30 min
Hungary	0.1	24 hr	0.2	30 min
Protected Areas	0.005	24 hr	0.005	30 min
Israel	0.03	24 hr	0.1	30 min
Italy	0.03	24 hr	0.07	30 min
Spain (proposed)	0.0025	24 hr	0.006	30 min
USSR	0.005	24 hr	0.005	30 min
Yugoslavia	0.005	24 hr	0.005	30 min

contain serious flaws such as inadequate documentation of exposure or concomitant exposure to other chemicals such as carbon disulfide. There is a relatively large number of such studies, however, and the complaints include nausea, diarrhea, abdominal cramps, shortness of breath, acute asthmatic attacks, headache, burning eyes, abrupt awakening, loss of sleep, anorexia, coughing, sore throat, and fatigue. Some of these complaints may perhaps result from odor annoyance alone; nausea and headaches have been reported with annoyance odor and it has also been found that annoyance due

to odor is more frequent among people with previous respiratory or cardiovascular diseases and among people with a propensity to neurosis (USNRC, 1977).

The question has also been raised whether there are individuals or groups of individuals who are particularly sensitive to exposure to hydrogen sulfide. The data in Fig. 10-1 indicate that there is a great deal of variability in individual olfactory response, and it is likely that similar variability occurs for other responses to hydrogen sulfide. Poda (1966) found that alcoholics or individuals who have recently consumed alcohol are particularly sensitive, and that individuals with schizoid or paranoid tendencies become markedly worse following exposure. Because of the irritating effect of hydrogen sulfide on moist membranes of the eye and respiratory tract, persons with eye and lung disease would be expected to be sensitive to exposure. There is also some evidence that the very young are more sensitive to hydrogen sulfide exposure (Vigil, 1979).

Thus, it appears that there may be individuals who are quite sensitive to exposure to hydrogen sulfide, and that actual health effects may occur at exposure levels of 0.1 ppmv or even lower. This makes it all the more important to meet the California ambient air quality standard in the Imperial Valley. As discussed above, it would be preferable if lower concentrations could be achieved.

Other Airborne Contaminants

Ammonia is also released in geothermal effluents, and it can be a toxic gas at high concentrations. The federal occupational standard for exposure to ammonia is 50 ppmv (CFR, 1978), and this is also the odor detection threshold (Leonardos et al., 1969). There are no applicable ambient air quality standards for ammonia, and the review by Walton and Simmons (1978) indicates that there is no evidence that any health effects would occur at concentrations of less than 5 ppmv. This is the maximum level that would be expected in the valley (See Section 5).

Mercury is contained in geothermal fluids, and the presence of elevated levels of mercury in soil is considered to be a useful prospecting tool for locating geothermal resources (Klusman and Landress, 1978). On a per megawatt basis, the emissions of mercury from geothermal power plants are

comparable to releases from coal-fired power plants (Robertson et al., 1977). Robertson et al. have measured mercury in ambient air at The Geysers and found background levels of $0.001 \mu\text{g}/\text{m}^3$; elevated ambient levels of $0.068 \mu\text{g}/\text{m}^3$ were found 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 24-hour standard of $0.3 \mu\text{g}/\text{m}^3$ (Martin and Stern, 1974), and the U.S. limit for occupational exposure is $100 \mu\text{g}/\text{m}^3$ (CFR, 1978). As the maximum expected concentration of mercury in the Imperial Valley is about $0.3 \mu\text{g}/\text{m}^3$, it appears that the emission of mercury is not a significant public health concern.

The emission of radon at The Geysers Power Plant has been studied in detail by Anspaugh (1978). The conclusion was reached that there is no discernible effect from radon emission on downwind communities, or upon the general environment of the power plant. Concentrations of radon daughter radionuclides were a factor of 30 below the federal standard for uncontrolled areas. As indicated in Table 5-1, the emission rate of radon from Imperial Valley resources will be substantially less than at The Geysers, and expected concentrations in ambient air are calculated to be more than 100 times less than the federal standard (See Section 5).

The identification of benzene in geothermal fluids from several sites has recently been reported by Nehring and Truesdell (1978). This is of particular concern because benzene has been identified as leukemogenic and the Occupational Safety and Health Administration (USOSHA, 1978) has initiated steps to lower the occupational exposure limit from 10 ppmv to 1 ppmv. This lowering has not yet been implemented because of a ruling by the Fifth Circuit Court of Appeals, and resolution awaits a decision by the U.S. Supreme Court (Carter, 1979).

Only one quantitative measurement of benzene in geothermal fluids of the Imperial Valley is known. This value is based upon measurements taken at two wells at the Republic Geothermal, Inc.'s site at East Mesa (Layton et al., 1979). These measurements indicate benzene to be present in the noncondensable gases in concentrations of 0.015 to 0.065 weight percent. The concentration of 0.065 weight percent would result in the emission of benzene at the rate of about 60 g/MWh.

This is 40% of the emission rate of hydrogen sulfide at the Salton Sea KGRA (Table 5-1), so the expected concentrations of benzene throughout the valley can be roughly approximated by halving the concentration values calculated for hydrogen sulfide. This results in a maximum one-hour concentration of about $100 \mu\text{g}/\text{m}^3$ of benzene, which is equal to 0.03 ppmv. This is about 30 times lower than the value of the proposed new occupational standard that is, however, for an 8-h exposure; so the calculated exposure is roughly 100 times less than the standard.

In summary, it does not appear that other airborne effluents will present public health problems. However, additional measurements of mercury and benzene should be made as development proceeds. The effect of hydrogen sulfide abatement systems in reducing emissions of other pollutants should also be determined.

Food-Chain Transfer

A thorough assessment of public health concerns should include an evaluation of transfer of pollutants through food-chain pathways, both by direct foliar deposition and by uptake through the soil-root pathway. Sources of the pollutants are the releases of volatile elements like mercury with the noncondensable gases, and the deposition of cooling tower drift.

Amounts of elements emitted as cooling tower drift will depend on several factors including the concentration of elements in cooling water and drift rates for a particular tower. The concentration of elements in the cooling water is further dependent upon the source of the water in the tower, e.g., irrigation water, drain water, or steam condensate, and the rates of evaporation and discharge of blowdown. Many of these parameters are unknown at the present time, and the assessment of food-chain transfer has been deferred until more information is available.

Accidents

Several types of accidents could occur at geothermal installations. These include pipe ruptures and well blowouts; several have occurred at The Geysers; Cerro Prieto, Mexico; and Wairakei, New Zealand. The major impact would be the contamination of adjacent land with saline fluids. This would

probably render some land useless for agriculture, and would contaminate other land with toxic elements that could be transferred to food. Any crops grown on land adjacent to a well blowout should be monitored to ensure that unacceptable levels of toxic elements are not present.

Other types of possible major accidents are explosions and/or fires involving secondary working fluids such as isobutane and propane. These are not considered to be significant hazards to the health of the general public because of the small volumes of fluids at any individual power unit.

Noise

Past experience with geothermal operations at The Geysers vapor-dominated resource area in northern California indicates that noise can become a serious environmental issue when residential communities are exposed to high sound levels (Leitner, 1978). Because of the low ambient noise levels in that region, residents have been readily aware of noise from geothermal development, and there have been numerous complaints to local authorities. Occasional large-scale venting of geothermal steam is the loudest source of noise at The Geysers and has been responsible for most of the adverse reaction (Illingworth, 1976).

Table 10-2 summarizes data concerning expected noise emission levels from geothermal industry sources in Imperial Valley. The loudest noise sources will be heavy trucks and earth-moving equipment used primarily in the preparation of sites for wells, power plants, and other facilities. This equipment will operate during daytime only and will be on-site temporarily for construction phases. During operation of the power plant, noise levels at 1/2 mi (800 m) are not expected to exceed 45 dBA. Steam venting will not be a significant source of noise. As a result, maximum sound pressure levels (SPL) at geothermal facilities will be much lower than at The Geysers, where SPL's as high as 125 dBA have been measured at 50 ft (15 m) from large-scale steam-venting operations. The potential for community annoyance, hazards to occupational health and safety, or harm to wildlife is consequently greatly reduced in the liquid-dominated geothermal resource areas of Imperial Valley.

Table 10-2. Sound pressure levels (SPL) expected to be associated with the various phases of geothermal energy development in Imperial Valley.

Development Phase	Expected Range of SPL (dBA)	
	50 ft (15 m)	1/2 mi (800 m)
Drill Site Preparation	85-95	50-60
Well Drilling	75-85	45-55
Well Testing	80-90	45-55
Construction of Power Plant	85-95	50-60
Operation of Power Plant	75-85	40-45

Noise from geothermal activities is specifically controlled by regulations established by Imperial County in Terms, Conditions, Standards, and Application Procedures for Initial Geothermal Development (Imperial County, 1971). The criteria contained in this document set octave-band limits and compliance is judged by measurements made at the boundary of the project area. Two classes of noise standards for drilling and production activities are defined. The Class I standard applies to all drilling and production operations irrespective of their location; the Class II standard applies when these operations are situated near existing industrial, commercial, dense residential, normal residential, or open space areas. The Class I Standard corresponds to an overall A-weighted SPL of 76 dB and applies to areas remote from sensitive receptors. The Class II standard has more stringent sound level values, which decrease according to the sensitivities of the types of land use in the vicinity of geothermal facilities. In addition to the protection provided by existing regulations, the use of buffer zones to separate geothermal operations from sensitive receptors (e.g., residential areas, schools, hospitals, etc.) would further reduce the potential for unacceptable noise. For example, a separation of 0.8 km (0.5 mi) between a noise source and a receptor should result in a reduction of the SPL of 35 to 40 dBA (Bush, 1977). Thus, even in the

absence of improved control technology, noise from the loudest geothermal sources should not exceed 60 dBA at 0.8 km (0.5 mi). At that level the geothermal industry would be able to meet the U.S. Geological Survey (USGS, 1975) Standard of 65 dBA at 0.8 km (0.5 mi) (applicable to geothermal operations on federal lands on East Mesa). The U.S. Department of Housing and Urban Development (USDHUD, 1971) criteria for "Normally Acceptable" conditions at residential sites would also be met at that level. The Class II noise limits, though, may present some difficulties, but only in those cases where the boundary of the project area is close to residential receptors. In that situation, efforts would have to be taken to muffle noise from geothermal operations.

OCCUPATIONAL HEALTH AND SAFETY

A detailed evaluation of the occupational hazards in the geothermal industry is being prepared by Hahn (1979c), and a summary of these results has been published (Hahn, 1979b). This discussion is largely taken from these sources.

Drilling and Blowouts

Occupational hazards from geothermal drilling for hot water and steam are similar and are due to airborne contaminants from the steam/hot water, noise, heat stress, hazardous chemicals and wastes, and drilling during blowout repair (oxygen deficient atmosphere).

Exposure to airborne contaminants in geothermal fluids does occur. The extent and severity of exposures to hydrogen sulfide and the monitoring required to prevent exposure are being debated. Substances in geothermal fluids that can become airborne are hydrogen sulfide, ammonia, mercury, carbon dioxide, hydrocarbons (including benzene), and radon. In the last two years, two workers on or near drilling rigs suffered acute effects from hydrogen sulfide and ammonia at The Geysers (CDLSR, 1979). Attempts to detect hydrogen sulfide at high enough levels to cause such effects have been unsuccessful; however, hydrogen sulfide alarms have sounded when set at 10 ppmv. Another potential source of hydrogen sulfide and ammonia gases is the procedure of opening the drill string on removal to test the drilling

muds. If the mud-return line is not monitored for hydrogen sulfide and is not dry, gas pockets encountered near the time of the drill-string removal could cause a release of mud and gases to the drilling platform. Hydrogen sulfide can also accumulate in the low lying areas of the drilling rig such as under the drill-rig platform and around the blowout preventer in the well pit, both during and after drilling. Also, areas around the mixing tanks and mud pits where most releases of noncondensable gases occur can accumulate hydrogen sulfide.

Occupational exposure to noise in geothermal drilling comes from general equipment (e.g., large diesel engines and compressors) and specific noise sources (e.g., the blooie line used for venting when drilling for steam). The noise exposure for drilling employees can be estimated from environmental noise levels. However, these levels do not reflect noise peaks, such as those from raising the drill string or during blowouts nor do they reflect noise at certain specific points. These levels are about 85 dBA at 15 m from mud drilling typical for the Imperial Valley resources.

The U.S. Department of Labor regulates occupational exposure to noise under provisions of the Occupational Safety and Health Act of 1970. Each state may establish its own occupational safety and health program, including measures to protect workers against the effects of noise exposure, provided that it is as effective as that of the federal government. In order to contribute to the conservation of workers' hearing, the California Occupational Safety and Health Act (CAL-OSHA) sets standards (CAC, 1972) for noise exposure comparable to those of the federal regulations. Table 10-3 shows the current allowable daily exposure without the use of personal hearing protection devices. It is not likely that these levels will be exceeded by drilling operations in the valley.

Heat stress during drilling operations is also a potential hazard, especially during the valley's very hot summer months.

Table 10-3. Standards for occupational noise exposure without personal hearing protection (CAC, 1972).

Total Exposure Time Per Day, Hours	Sound Level dBA
8	90
6	92
4	95
3	97
2	100
1-1/2	102
1	105
1/2	110
1/4 or less	115

Electrical Power Production

Production of electricity from geothermal fluids has various occupational hazards. These hazards are both unique, because of the energy source, and traditional, occurring in all power production. Construction of geothermal power plants has the same specific hazards as that of other types of power plants except for the airborne contaminants from geothermal fluids. Occupational hazards from geothermal power production are airborne contaminants, noise, and hazardous chemicals and waste.

In the early operation of The Geysers power units, for example, workers were exposed to hydrogen sulfide concentrations of up to 20 ppmv in working areas of the power units. Moreover, noise levels were very high in some places and had to be reduced. Workers at power plants in the Imperial Valley would probably not be exposed to unacceptably high levels of hydrogen sulfide or noise. Binary conversion facilities are not expected to emit any

hydrogen sulfide so long as the geothermal fluids are kept under pressure (see Section 3 for a discussion of this process). However, precautions would be necessary to prevent leaks from developing in the system containing the secondary, or binary fluids--especially when they are flammable. Experience gained from the operation of Imperial Magma's 10 MW Power Plant on East Mesa, a binary facility, will provide information on the safety of using and handling organic fluids. The use of hydrogen sulfide abatement equipment with flashed-steam power plants may pose some health and safety problems. At The Geysers, hydrogen sulfide abatement systems use the most hazardous chemicals associated with operation of power plants. One candidate system for controlling hydrogen sulfide emitted from power plants at The Geysers and in the Imperial Valley is the Stretford process. A by-product of this process is sulfur, and it must be handled safely, especially when molten. Operation of a Stretford system on Unit 15 at The Geysers should give some insight as to the kinds of occupational problems that might be encountered in the use and maintenance of this hydrogen sulfide control process.

History of Occupational Disease Occurrence

In California physicians are required to file a Doctor's First Report of Occupational Injury or Illness immediately after the first examination of an employee with an occupational injury or illness. These reports were available for 1974 to mid-1977. The name, employer, and doctor are restricted; however, the remaining data may be used to analyze occupational diseases. Thus, data on occupation, location and date injured, exposure, and nature of the injury or illness are available. All available data for the geothermal industry are given in Table 10-4. Because underreporting is typical, the information in Table 10-4 should not be considered complete. The data are placed in two major categories: reports on hazards directly related to geothermal energy production and those on general hazards occurring in the geothermal industry. Of the 26 reported illnesses, 18 are directly related to geothermal, and 8 are general. Figure 10-2 shows the number of reports plotted vs occurrence in 6-mo periods, with the reports separated into geothermal or general hazards.

Table 10-4. Reports of occupational illnesses, 1974 - mid 1977 (numbers in parentheses are the numbers of reported illnesses).

Operation	Exposures related to geothermal energy		Exposures related to general industrial hazards	
Drilling	H ₂ S, NH ₃	(2)	Hazardous chemicals	(5)
Power production	H ₂ S	(3)	Airborne contaminants	(1)
	H ₂ S and H ₂ S-abatement sludges	(10)	Hazardous chemicals	(2)
	Hazardous chemicals	(3)		
Total number		18		8

Occupational health hazards in industry are presented as analyses of all Doctor's First Reports of Occupational Injury or Illness (Baginsky, 1975). The total number of Doctor's First Reports is listed and categorized by industry and rate of occupational disease (number of reported illnesses/1000 employees). Privately owned utilities are a separate category, while publicly owned utilities are lumped together with local government. To evaluate geothermal energy production, rates of occupational disease for privately owned utilities are compared to a rate established for geothermal energy production. The latter rate was estimated by dividing the

Fig. 10-2. Number of Doctor's 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 the geothermal industry.

number of Doctor's First Reports for geothermal power production by the approximately 50 persons who operated and maintained geothermal power production each year. Because reports from geothermal energy production are few, the rates vary widely. The approximate rates of occupational disease are 20 (illnesses/1000 employees) in 1974 and 1975 and 100 in 1976 when the problem from hydrogen sulfide abatement is separated. When included, the rate jumps to 240. Thus, while the rates in privately owned utilities decreased from 7.7 to 5.7 during 1973-75, the rate for geothermal energy production increased. Although the rates are based upon a small number of reports, the increased rates indicate more attention must be paid to occupational exposure and disease in geothermal energy production.

Direct Heat Use

When the geothermal fluids contain hydrogen sulfide, most occupational hazards will result from exposure due to improper venting. The far less complex, low temperature systems should have fewer occupational health hazards in their development and use. However, if wells that are awaiting power plant completion are temporarily employed for direct use, or if wells into high temperature reservoirs are drilled intentionally for direct use, hazards discussed above may prevail. In addition, some projected uses would require very long pipelines, and the risk of rupture is increased.

CONCLUSIONS AND RECOMMENDATIONS

- In terms of impact upon public health, the emission of hydrogen sulfide is the most significant potential problem due to the annoyance of its odor.

- Systems to abate hydrogen sulfide emissions will be required in order to meet the California ambient air quality standard of 0.03 ppmv. However, as 50% of the people can detect the odor of hydrogen sulfide at concentrations of 0.003 to 0.009 ppmv, just meeting the standard may not eliminate the problem of odor annoyance.

- Other noncondensable gases -- ammonia, mercury, radon, and benzene -- do not appear to pose public health problems even if emissions are unabated. However, we recommend that emissions of mercury and benzene be monitored. This is particularly true for benzene, as very limited data are currently available.

- Hydrogen sulfide abatement systems may also be effective in removing other noncondensable gases. Measurements should be made to determine this.

- Noise from geothermal operations is not expected to result in public annoyance, if site selection avoids areas that are close to residential areas.

- The possible effects of cooling tower drift and noncondensable gas deposition have not been assessed in terms of transfer to man via food-chain uptake. This is very difficult to predict due to the large number of variables that affect transport. As the early power plants come on-line, measurements should be made of representative elements in soil and crops.

● Table 10-5 summarizes the evaluation of the occupational hazards associated with the geothermal industry. Results are given by subcategories of the technology and by chemical and physical agents. This Table is generalized for all hydrothermal operations. In Imperial Valley, noise would be much less of a problem than indicated.

● Data on the occurrence of occupational diseases show that the rate (dominated by the operation of The Geysers) is very high compared to the overall rate for private utilities. This indicates that more effective industrial hygiene programs are needed to control exposure to hazardous agents. A large fraction of these diseases are dermatoses caused by handling abatement chemicals and sludges. Obviously more care is needed to ensure that abatement systems are well designed and operationally safe.

Table 10-5. Summary of the evaluation of occupational hazards for geothermal energy.^a

	Toxic Compounds	Asphyxiant Compounds	Explosive Compounds	Heat Stress	Noise	Hazardous Materials	General
Drilling	(3)	2	2	2	3	(3)	
Blowouts	3	3		3	3		
Steam field development	2	2	1	2	3	2	2
Power plant operations	(3)			1	3	2	
Power plant maintenance	(3)		1	2	1	(3)	(3)
Power plant emergencies	3	3	3	3	3	3	

^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.

SECTION 11. IMPACTS ON FISH AND WILDLIFE

D. Layton and P. Leitner

The freshwater ecosystems of the valley's rivers and drains and the quasi-marine ecosystem of the Salton Sea all depend on waste waters from irrigation for their existence. Agriculture is also the main source of stress on these ecosystems. Stresses are derived from variations in the quantity and quality of waste waters discharged from irrigated lands, and the influx of pesticides and fertilizers to surface waters. Geothermal operations are likely to introduce additional impacts on the aquatic ecosystems. The principal impacts would result from changes in the Salton Sea's elevation and salinity caused by the use of agricultural waste waters. Inadvertent discharges of geothermal effluents would also cause ecological damage. The potential for substantial habitat loss and other negative impacts to terrestrial ecosystems is greatly reduced because most of the geothermal development will take place on lands already dedicated to irrigated agriculture. The presence of sensitive wildlife habitats, however, will constrain the siting of some facilities. Impacts on the terrestrial ecology of desert areas are also possible, but are presently restricted to geothermal operations on East Mesa.

BIOLOGICAL RESOURCES OF THE IMPERIAL VALLEY

Ecologically, the Imperial Valley is a land of contrasts. It contains these major ecosystems: (1) aquatic ecosystems consisting of the Salton Sea's quasi-marine ecosystem and fresh water ecosystems of the valley's rivers, drains, and canals, and (2) terrestrial ecosystems associated with the desert areas on either side of the agricultural lands and riparian areas along the southern edge of the Salton Sea and along the New and Alamo Rivers. Each of these ecosystems will be affected in some way by large-scale geothermal development in the valley.

The Salton Sea contains a unique, quasi-marine ecosystem. The basic food web of the sea is shown in Fig. 11-1. The orange mouth corvina (Cynoscion xanthulus), croaker (Bairdiella icistia), and sargo (Anisotremus davidsoni) were introduced to the sea in the 1950's by the California Department of Fish and Game to establish a sport fishery. The recreational

value of the sea is based on these fish. A key organism in the food chain is the pileworm, Neanthes succinea. It feeds on detritus derived from phytoplankton and zooplankton. The croaker and sargo consume the pileworm, and these fish are then consumed by the corvina. Without the pileworm, the sport fishes would not survive because they cannot rely directly on plankton as a source of food.

The primary stress on the sea's ecosystem is salinity. Within the last several years the sea's salinity has leveled off at around 38,000 ppm total dissolved solids (TDS). Bioassays have shown that when salinities reach 40,000 ppm TDS, and above, reproduction of sport fishes will be adversely

Fig. 11-1. Basic food web of the Salton Sea. Dashed lines refer to minor diet items (Kercher and Buchanan, 1976).

affected (USDI, 1974). Studies have been made on different measures to control salinities (e.g., diked impoundments); however, it is unlikely that any controls will be implemented because of economic constraints. Other sources of stress include the presence of anaerobic conditions at the bottom of the sea in the summer months due to the decay of organic matter and the discharge of pesticides and agricultural chemicals to the sea (Kim, 1973). The status of the sea's ecosystem during the next decade will be affected by several things: the salinity of Colorado River water imported to the Coachella and Imperial Valleys, the quantities of water flowing to the sea, and the overall response of the food chain to increasing salinities.

The freshwater ecosystems of the valley's drains and rivers could be affected by accidental releases of geothermal fluids and by reductions of stream flow resulting from withdrawals of water for power plant cooling. The California Department of Fish and Game conducted a brief aquatic survey of the valley's agricultural drains in 1975 (Herrgesell, 1975) and found that the aquatic habitat of drains supported a variety of game and non-game fish. In addition, bullfrogs and invertebrates such as crayfish and clams were identified. The trophic dynamics of the ecosystem were not analyzed in that study. Little is presently known about the impact of different stresses (e.g., pesticide residues from irrigation runoff, low dissolved oxygen levels and ammonia from fertilizers) on the aquatic organisms in the drains. The most important non-game fish are Tilapia (Tilapia zillii and mossambica) and Mosquitofish (Gambusia affinis). Tilapia have been introduced into canals and drains in recent years by the Imperial Irrigation District (IID) to assist in the control of weeds. They are stocked in the springtime, and they survive until the winter months when colder water temperatures kill most of the fish. Some fish, though, survive in drains because the drains have higher water temperatures than canals (VTN, 1978). Tilapia are also found in the Salton Sea. Gambusia, which are native to the eastern United States, have been introduced to control mosquitos.

The primary effect of geothermal development on the valley's terrestrial ecology will be the disturbance of habitats. Of particular concern is the possible disruption of habitats that support rare or endangered plants and wildlife. The Yuma Clapper Rail (Rallus longirostris yumanensis), which is classified as an endangered species by the U.S. Fish and Wildlife Service (USFWS, 1978b), has been observed on the deltas of the New and Alamo Rivers,

on lands of the different units of the Salton Sea National Wildlife Refuge, and on the Wister and Finney-Ramer units of the Imperial Wildlife Area (Bennett and Ohmart, 1978). These areas and the important wildlife refuges are identified in Fig. 11-2. The largest populations of rails were found in areas where there were mature stands of cattail, shallow waters that had small fluctuations of water level, and high populations of crayfish, the main source of food for the rails. The presence of high ground near this type of habitat was also associated with the greater densities of rails. At the present time the major threat to marsh land habitats of the Yuma Clapper Rail and other birds is the continued rising of the Salton Sea. The sea has inundated thousands of acres of shoreline in recent years, encroaching on rail habitat on the deltas of the New and Alamo Rivers, shoreline areas of the

Fig. 11-2. Wildlife refuges in the Imperial Valley.

Salton Sea National Wildlife Refuge, and washes adjacent to the Wister Unit of the Imperial Wildlife Area (Bennett and Ohmart, 1978). A stable sea level would reduce destruction of shoreline habitat; however, if the sea's elevation were to remain constant, its salinity would rise, putting added stress on aquatic organisms.

Other areas that support plants and animals of special interest are the desert lands on either side of the valley. Most of the known geothermal resources lie beneath East Mesa, but potential resources are also found at other locations (e.g., lands in the Yuha Basin and lands to the east of the Salton Sea near the boundary of Riverside and Imperial Counties). The vegetation on East Mesa is dominated by creosote bush (Larrea tridentata). One plant that has a special status is the desert buckwheat (Eriogonum deserticola), which is listed as rare by the California Native Plant Society (Powell, 1974). This species grows in sandy washes and on dune systems. No wildlife species that are listed as endangered or threatened by the U.S. Fish and Wildlife Service are found on lands presently leased for geothermal development on East Mesa. Nevertheless, several species of special concern are found in this region. Andrew's dune scarab beetle (Pseudocotalpa andrewsi) has recently been proposed for threatened status (USFWS, 1978a). The Imperial Sand Hills east of the Coachella Canal have been designated as critical habitat for this species, which occurs only in the troughs of loose, drifting sand between dunes (Fig. 11-3). The flat-tailed horned lizard (Phrynosoma mcalli) is presently under status review to ascertain whether or not it should be proposed as threatened or endangered (USFWS, 1977). This species is found on East Mesa and in the desert lands to the west of Imperial Valley. Although it ranges widely in sandy areas throughout the hot desert region of southeastern California, southwestern Arizona, and adjoining parts of Mexico, it has always been considered rare (Turner et al., 1979). Concern over low population densities and increasing human use of its habitat have led to an official review of its status.

Large numbers of ducks, geese, shorebirds, and other waterbirds utilize the Salton Sea and adjacent habitats during the winter and in migration. Geothermal development could affect these species if transmission lines are sited across important flight paths. Major water bird flyways near the Salton Sea were mapped and monitored as part of the Ecosystems element of the IVEP (Leitner and Grant, 1978). Two main flight corridors were identified

Fig. 11-3. Critical habitat of the Andrew's dune scarab beetle (*Pseudocotalpa andrewsi*). The beetle inhabits troughs of loose, drifting sand between dunes in Imperial Sand Hills.

from these observations of bird movements and are shown in Fig. 11-4. Many water fowl traveled between the feeding and resting areas along the southern and eastern shores of the Salton Sea. In addition, snow and Canada geese often moved inland for short distances from the wildlife management areas to feed on nearby agricultural lands; flight altitudes were usually less than 50 yds and therefore these birds could be affected by transmission lines. The second important flight path followed the Alamo River. Cattle egrets roosted in large numbers near the shoreline of the Salton Sea and at Ramer Lake in the Finney-Ramer Unit of the Imperial Wildlife Area. They often used the Alamo River flyway and were frequently seen flying below 50 yds.

Fig. 11-4. Flight paths used by waterbirds. The primary corridor joins the wildlife refuges adjacent to the Salton Sea. A second corridor is along the Alamo River.

IMPACTS OF CHANGES IN THE SALTON SEA

The consumption of agricultural waste waters for power plant cooling or injection to geothermal reservoirs will lower the Salton Sea's elevation and increase its salinity. The magnitude of such changes will be a function of the level of geothermal development and the degree to which alternative supplies like irrigation water and steam condensate are used. At the present time the availability of irrigation water and steam condensate for long term geothermal development is questionable. Irrigation water is dedicated to agricultural users, and will probably remain so for the foreseeable future. Steam condensate from flashed-steam facilities can supply all, or nearly all, the water requirements of those facilities. No external supplies of water would then be needed. If all geothermal facilities could rely exclusively on condensate for their cooling water needs, geothermal development would have no effect on the Salton Sea. However, concern over the possible effects of land 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. In this situation, external sources of water are needed to support geothermal facilities. Thus, it seems that geothermal operators will have to rely on water from rivers and drains if the existing set of constraints continues (see Section 6 for a complete discussion of the different water supplies).

Figure 6-8 of Section 6 depicts the changes in the sea's elevation that are predicted to occur with the medium scenario of energy growth if policies were pursued that promote the extensive use of waste waters from agriculture (i.e., policy combination E). Also shown are elevation changes calculated for existing efficiencies of water use (REF case) and increased water conservation (CON case), assuming no geothermal development and average crop evapotranspiration. The sea's elevation has been rising in recent years, and will continue to do so until inflows of waste water from the Coachella and Imperial Valley's are reduced. The rising sea has inundated shoreline property and riparian habitats. Dikes have been used to protect farmlands adjacent to the sea, but have provided limited protection to wildlife habitats.

The destruction of habitat areas adjacent to the sea is significant because they are used by large numbers of migratory shorebirds and waterfowl. Rising water levels have done the following (Shinn, 1976):

- Inundated stands of cattail and bulrush that provide nesting and feeding cover for many shorebirds.
- Reduced the areas of mud flats used as feeding areas for shorebirds.
- Covered trees that were used as nesting sites and roosts for herons and shorebirds.

The sea has also encroached on habitat of the Yuma Clapper Rail, an endangered species, that is located on the deltas of the New and Alamo Rivers and along the sea's southern shoreline. The highest populations of rails are associated with mature stands of cattail and bulrush with these attributes: stable water depth and large populations of crayfish, the main food item of the rails.

If agricultural waste waters are used to support geothermal development following the medium scenario of energy growth, increases in the sea's surface elevation will be arrested, and then gradually decline. But as Fig. 6-7 indicates, many years will pass before the 1975 elevation is again reached--under average hydrologic conditions. Similar declines could be possible if increased conservation were achieved in irrigation. Even though the reduction of inflows to the sea would stop further habitat destruction, it is not clear that declining levels would be beneficial for long term habitat maintenance. If this is true, then critical habitats will have to be managed to maintain rail populations along with other migratory birds.

The predicted changes in salinity shown in Fig. 6-8 will directly affect the sea's aquatic ecosystem, which includes an important sport fishery composed of orange mouth corvina, sargo, and gulf croaker. Fish toxicity studies indicate that the mortality rate of eggs and larvae of gulf croaker and sargo can be expected to increase significantly with salinities higher than 40,000 ppm TDS (May, 1976; Lasker et al., 1972). Other work (USDI, 1974) suggests that young gulf croaker, sargo, and corvina, in contrast, are able to withstand salinities around 50,000 ppm. A study directed at the effects of salinity on pileworms (Neanthes succinea), an important organism in the sea's food web, demonstrated the ability of the worms to tolerate salinities over 67,000 ppm (Hanson, 1972). Oglesby (1977) showed that reproduction of the pileworms will probably continue with salinities as high as 45,000 to 50,000 ppm TDS.

The eventual response of the sea's aquatic ecosystem to future salt concentrations will be governed by the toxic effects on aquatic organisms,

the role of those organisms in the sea's food chain, and by any adjustments made in the ecosystem. At this point it is not possible to accurately quantify the effects of elevated salinities on the sea's fishery because not enough is known about the lethal and non-lethal impacts of salinity on the life cycles of fish. However, the consequences of future salinity changes can be assessed qualitatively by comparing predicted salinities with toxic thresholds based on the previous toxicity studies. The first threshold occurs when salinity exceeds 40,000 ppm. Above that level fish and pileworm reproduction would be reduced. As Fig. 6-8 indicates, that level would not be attained until after the year 1990 -- assuming existing water use efficiencies (reference case), average crop evapotranspiration, and constant salinity of inflowing irrigation water. With greatly increased water conservation in agriculture, as defined by the CON case and increasing salinities of irrigation water imported from the Colorado River, the 40,000 ppm level would be reached just after 1985. With geothermal development of 100 MW/year after an initial 400 MW production in 1985, and reference water use efficiencies, the initial threshold is reached a couple of years later. The next threshold of toxic effects is in the range between 50,000 and 60,000 ppm where the mortality of adult fish increases. These levels are not reached before the year 2010 under the reference case. With the conservation case, and no development, they are attained between 1995 and 2000, and with geothermal energy production they are attained between 2000 and 2005.

To summarize, increases in salinity will be slow if medium levels of crop evapotranspiration continue with existing efficiencies of irrigation and there is no geothermal development. Toxic effects on the sea's aquatic ecosystem would not occur until after the year 1990 for these conditions. At the same time, though, the sea's surface elevation would continue to rise, destroying valuable riparian habitats used by birds like the Yuma Clapper Rail, an endangered species. If agricultural waste waters are used to support the operation of power plants associated with medium scenario of energy growth, the rate of salinity change will increase, but rises in the sea's elevation would be arrested by 1990, and then decline at about 0.2 ft per year. Declines in the sea's elevation would have near term benefits to riparian habitats; however, a stable sea level would be more beneficial on the long term. The attainment of a stable sea level without some sort of program to control inflows is doubtful.

ACCIDENTAL RELEASES OF GEOTHERMAL FLUIDS

Inadvertent spills of geothermal fluids are likely to happen over the operational lifetime of power plants and related well fields. To have a direct effect on fish residing in the valley's rivers and drains, the geothermal fluids accidentally released from a pipeline or a power plant would have to reach surface waters. The resulting impact would depend on the quantity and chemical composition of fluids mixing with drain or river waters, the flow rate of the receiving stream, and the types of fish coming in contact with the contaminated water. The most hazardous fluids would be the brines of the Salton Sea resource area that have salinities in excess of 200,000 ppm TDS. Experimental results from bioassay studies using Tilapia zillii, a fish that has been introduced into canals and drains for weed control, indicate that such brines would be highly toxic when mixed with drain waters because of the resulting osmotic stress (Ireland, 1978). Extra precautions will be needed to prevent releases of geothermal brines from power plants and well fields in this KGRA. Even if brines did not reach a drain, there is still a potential for future surface water contamination from a spill since the chemically altered brine will eventually be collected by subsurface drain lines and discharged to surface waters (Pimentel *et al.*, 1978). In this situation toxic effects might not be detected for years. The salinities of the geothermal fluids in the other resource areas are substantially lower, but toxic effects could still take place if enough fluids reached a drain during a spill.

FACILITY SITING

Potential impacts to the valley's terrestrial ecology can be minimized through the careful siting of facilities. The power plant sites depicted in Fig. 4-2 avoid sensitive habitats and existing wildlife refuges. The resource area that faces the greatest number of constraints to development is the Salton Sea KGRA. Power plants would be excluded from sensitive habitats along the Salton Sea and the Alamo Rivers and from lands of the Salton Sea National Wildlife Refuge and units of the Imperial Wildlife Area. The establishment of buffer zones around wildlife areas to provide additional protection against intrusive activities (e.g., noise) would further reduce

impacts to wildlife (Shinn, 1976). The cumulative effect of such restrictions will be to make a portion of the geothermal resources in that KGRA inaccessible. Slant drilling can recover some, but not all of the fluid beneath excluded lands.

Transmission lines serving geothermal facilities in the Salton Sea resource area will have to be sited in a manner that takes into account impacts on waterbirds. Lands next to the sea or in the vicinity of the New or Alamo Rivers would be the most critical areas for siting because of the presence of major flight corridors between feeding areas. Transmission lines crossing the Alamo River could interfere with low-altitude flights of cattle egrets and other waterbirds, which are often under a height of 50 yds. Improper siting could increase the possibility for collisions with towers and lines (Leitner and Grant, 1978). Another consideration for corridor selection is the effect that transmission lines would have on the hunting of waterfowl. Lines might cause waterfowl to avoid prime hunting locations, fly at higher altitudes, or use steeper angles of ascent and descent.

The desert ecosystems of the East Mesa resource area will also be affected by geothermal development. The primary source of impact will be the loss of desert habitat. The construction of geothermal facilities on the Mesa involves more land disturbance than similar construction in the irrigated portion of the valley because roads, pipelines, and transmission lines have to be built on previously undisturbed desert lands. None of the lands within the KGRA have been designated as critical habitat for endangered or threatened species of wildlife. However, development of lands to the east of the KGRA would have to avoid the habitat of the dune scarab beetle, which is now proposed as threatened (USFWS, 1978a). The presence of rare plants in the East Mesa area will have to be assessed on a site specific basis to ensure that such plants are not significantly affected by geothermal exploration and development.

CONCLUSIONS

The extensive use of agricultural waste waters for power plant cooling or for injection to geothermal reservoirs will lower the Salton Sea's elevation and increase its salinity. From an ecological stand point, these changes are contradictory. The sea's elevation has been rising in recent

years, inundating riparian habitats. Consumption of waste waters to support geothermal development following the medium scenario of growth would arrest increases in elevation, and mitigate impacts to wetlands. Increases in salinity, on the other hand, will have a negative impact on the reproduction of fish in the sea. Toxic effects on fish reproduction are expected to occur when salinities exceed 40,000 ppm TDS. With the medium scenario of development and normal hydrologic conditions, toxic salinities could appear between 1985 and 1990; without development toxic levels are not attained until the early 1990's.

- The use of steam condensate as the sole source of water to support flashed-steam geothermal facilities would minimize changes in the sea's salinity and elevation due to geothermal development.

- Geothermal fluids entering a drain or a river after an accidental release could have toxic effects on fish. The most hazardous geothermal fluids in this regard would be the brines of the Salton Sea resource area.

- The Salton Sea KGRA contains some of the most sensitive habitats in the valley. To ensure that geothermal development in that KGRA is compatible with wildlife, it may be necessary to establish buffer zones between habitats and geothermal facilities. Transmission lines serving power plants in this resource area could also interfere with the flights of waterbirds. The most critical areas would be where such lines cross the New or Alamo Rivers. Towers and lines should be placed in such a way that they minimize the possibility of collisions.

SECTION 12. SOCIOECONOMICS

C. Hall and Y. Ricker

What are the effects of geothermal development on people, the economy, government, public opinion, and leadership? For a single power plant the effects are not expected to be significant. However, as geothermal development increases, the cumulative impacts will become measurable, but not prohibitively adverse. The greatest potential effects are on the Imperial County economy, the gross output from which could be increased by a factor of three over projected growth without geothermal energy production. The occupation mix will change substantially as the economy diversifies from its current dominance by agriculture. The growth of the county's population will accelerate, and changes will take place in its ethnic composition, age structure, educational attainment, fertility, and migration pattern. The tax base of the county and school districts will improve substantially; however, cities, from which energy development is excluded, will have to bear most of the costs of serving the new population. Impacts on land use, aesthetics, recreation resources, public opinion, and leadership are important but of a lesser magnitude.

Generally, the assessment approach used here is to describe historic conditions and to analyze these for patterns and causal factors. Baseline projections are then made to the year 2020, based on historic trends and anticipated changes not related to geothermal development. These estimate the baseline, "without geothermal development," conditions. The effects of geothermal development are estimated by analyzing projected requirements for labor, land, secondary industries and services, public and private infrastructure, and geothermal industry output in terms of gross product, wages, income multiplier effects, tax revenues, and other variables. The baseline projections are compared with the baseline-plus-geothermal projections to estimate the magnitude of impacts, quantitatively or qualitatively, as appropriate, from geothermal development. The socioeconomic analyses are based on a scenario of geothermal energy production adopted by Rose (1977). In his scenario, energy production begins in 1984, and grows at a rate of 125 MW per yr until 4500 MW of development are attained in 2020. The medium scenario of growth used elsewhere in this assessment (see Section 4) is only slightly lower than the scenario used here.

BACKGROUND CONDITIONS

Agriculture and related industries are the dominant component of the Imperial County economy. In 1975 the agricultural sectors accounted for approximately 70% of the total output of goods and services (Lofting, 1977). Total revenues from agriculture (all crops and livestock) exceeded \$584 million in 1978 (Imperial County, 1978b). The county ranks last in size among the top 100 agricultural counties in the Nation (USBC, 1978a), yet only four other counties have greater agricultural production.

The total county population in 1978 was about 90,000 including legal aliens, primarily of Mexican citizenship (CDF, 1978). The county's average annual growth of population has increased dramatically in the early 1970's over that of the 1960-1970 period. About half of the current growth has been due to natural increases; the remainder is from immigration (USBC, 1978a; CDF, 1977; Pick et al., 1977). The relatively large Mexican-American population of the valley's urban areas, as shown in Fig. 12-1, is a reflection of the county's border location. The economic and educational disparities that exist between Mexican-Americans and Anglos in the county (see Figs. 12-2, 12-3, 12-4) will affect the way geothermal development affects local communities.

Employment for 1979 is estimated at about 39,000, with 37% of the work force directly employed in agriculture. The distribution of employees among major industrial groups is depicted in Fig. 12-5. Unemployment has been high in Imperial County, and is estimated to be over 26% for 1979 (CEDD, 1979). Per capita income in 1975 was \$3756, compared with \$5464 for California, and \$4838 for the Nation in that year (USBC, 1978b). The relatively low income level of workers in the county reflects the wage levels and seasonal nature of farm employment. Personal income from farm sources, as a percentage of total personal income, has been decreasing in the county during recent years, but it is still 5 times greater than in California or the rest of the country (USBEA, 1979).

Jurisdiction in Imperial County is divided among the county, seven incorporated cities, and eleven school districts, in addition to a junior college district, the Imperial Irrigation District, and others.

Imperial County had an assessed valuation of nearly \$300 million in 1975-76 (Goldman and Strong, 1977), ranking 33rd among California's 58

Fig. 12-1. Geographical distribution of the Mexican-American population among several of Imperial County's cities. The relatively large percentage of Mexican-Americans is a reflection of the county's border location (Pick et al., 1977).

Fig. 12-2. Income for families and unrelated individuals for Imperial County in 1970 - by ethnic group (Pick et al., 1977).

Fig. 12-3. Education by sex and ethnic group for Imperial County residents 25 years and over in 1970 (Pick *et al.*, 1977).

Fig. 12-4. Ethnic distribution among occupational groups in Imperial County (Pick et al., 1977).

Fig. 12-5. Distribution of employment by major economic sector in Imperial County for 1979 (Employment Development Department, 1979).

counties. Revenues from all sources were about \$35 million. Per capita expenditures in the county were about \$320 in 1976-77 (CDF, 1978), ranking it 43rd among California counties. This compares with a national average of \$153 for the 2700 U.S. counties with less than 100,000 population (USBC, 1978b). Total revenues for all seven cities in 1975-76 was just under \$13 million. El Centro had the largest budget (\$5.1 million) and Holtville the smallest (\$0.1 million). The combined assessed valuation of all cities was \$100 million and ranged from El Centro (\$43 million) to Westmorland (\$0.7 million).

The Imperial Valley has some unique recreational and visual resources, most notably the Salton Sea. In the last decade recreationists have visited the sea in dwindling numbers; in 1967 one million people made visits; but now about half a million visit the area annually (Twiss et al., 1980). Users of the area include hunters, fishermen, boaters, water skiers, and offroad vehicle users.

A public opinion survey (Butler and Pick, 1977) and a study of the leadership of Imperial County demonstrate consistent patterns of favorable attitudes toward geothermal development. About 90% of the citizen respondents and all of the leadership favor development. Nevertheless, those studies indicate that a majority of the citizens and leaders want strict environmental regulation of geothermal operations.

DEMOGRAPHIC CHANGES

Population growth is influenced by mortality, fertility, and migration. The key factors for growth in the Imperial Valley are migration and fertility. Migration is influenced by a number of factors: regional population mobility (retirees moving to the sunbelt; a population shift away from urban areas toward rural areas), natural attractions and climate, living costs, economic growth and job opportunities (spurred by energy development, or other significant development) and international migration (both legal and illegal). Fertility is influenced by age distribution, and the ethnic composition of the population. The precise ethnic balance of the Imperial County population is not known; a variety of definitions of "Mexican-American" exist. Estimates (Pick et al., 1977) of the Mexican-American component in 1970 range from 30.5% (Mexican foreign stock) to 46% (Spanish language or

surname). California ranged from 3.5% to 15.5% according to these definitions. The Employment Development Department (1979) estimates the 1979 proportion of Spanish language or surname to be 62%. In addition, the county population is very young - Imperial County had the fourth lowest median age of all 58 California counties in 1975. The average age of Mexican-Americans in Imperial County is 19; for whites, the average is 33. Over 54% of the Mexican-American population is less than 19 years old and thus is not available for the skilled labor market. The county leads all California counties in fertility. Mexican-American fertility is 50% higher than the remainder of the County population (Pick et al., 1977). Although Mexican-Americans are younger and have a much higher fertility than Anglo Americans, they have increased only 27% in Imperial County in 40 years compared to 114% for California. A very high out-migration can be inferred. This "turnover" and the extreme youthfulness are partly responsible for the low education levels of the Mexican-Americans remaining in the county. Unfortunately, low educational achievement is a handicap in the skilled labor market that dominates the capital intensive geothermal industry.

Several projections of Imperial County population are shown with historic population in Fig. 12-6. The methods and assumptions differ among them and the 2020 range (assuming no geothermal development) is substantial (81,000 to 175,100). A review of the historic population movement and its response to national and international forces shows the difficulty in making population projections. The population range selected for this study, assuming no geothermal development, is between the Department of Finance (high) and a population estimated from a multiple of the projected work force (low); this baseline range is highlighted in Fig. 12-6 and includes a lower projection of Pick, labeled I-75, and the Southern California Association of Governments (SCAG) projections through 2000. For planning purposes, the county has selected the III-70 estimate by Pick for the year 2020 (Imperial County, 1977).

Geothermal development is presumed to have a positive effect on population because it provides direct primary and indirect induced employment. The question is how much. Two of Pick's estimates for population with geothermal development are shown in Fig. 12-6 (III-70 and III-75). The range of population with geothermal development that has been selected for this study (highlighted in Fig. 12-6) is derived from a lower and an upper multiple of work

Fig. 12-6. Historic and projected populations of Imperial County, California.

force projected by Lofting (1977). The lower range multiple of the workforce has existed in the county in the mid-seventies; the upper multiple is derived from Pick's lower population projection (III-75).

Several inferences can be drawn from these projections, regardless of the specific numbers chosen or the actual conditions in the future. If large scale geothermal development takes place, in-migration from other parts of the country is likely to increase and it is likely that the proportion of Mexican-Americans in the county population will decline. If this happens and if the trend toward lower birth rates in Anglo populations of the country continues, there will be a reduction in fertility rates in the county. The age structure should then increase, and with it, education and skill levels. Work force participation and incomes will probably increase as a result.

The subject of illegal aliens is a difficult one. There are no reliable estimates as to their numbers. In this century, up to the late 1970's the majority of illegal aliens were most certainly Mexican. The majority of future illegal aliens will probably continue to come from Mexico. The Mexicali region, just south of the international border, is estimated to contain half a million people (Pick et al., 1977; Border Area Development Study, 1977) and Mexican officials estimate that the population may triple by 1985.

Housing trend data for the 1950-1970 period show that Imperial County has had a relatively large percentage of smaller, more crowded houses than California as a whole. The county still lags behind the state in housing size and has more crowded houses, but the gap has narrowed considerably (1970 census, reported in Pick et al., 1977). Housing costs have risen in the county as elsewhere in the state in the late 1970's. This is probably a major cause of the shortage of lower and middle income housing units reported in the Border Area Development Study (1977). This study reports a housing forecast by SCAG that is shown in Fig. 12-7 along with a population forecast within the selected projection range (see Fig. 12-6). To the extent these two forecasts are accurate, the mean number of people per house should decline slightly, as shown in Fig. 12-7. Population will have increased by 80% from 1950 to 2000, but housing will have increased by 100%. Also, if salaries and wages increase as a result of industrial and occupational diversification as Rose (1977) indicates, more people may be able to afford first homes or larger homes.

Fig. 12-7. Historic and projected housing supply, population, and persons per house.

ECONOMIC IMPACTS

The county is experiencing high unemployment rates and hence economic growth is welcomed. But employment in the capital-intensive geothermal industry is limited and requires advanced education or special skills. One forecast of employment by Lofting (1977) illustrates the potential effect of geothermal development: by 2020, Lofting projects that this new industry will create about 14,000 direct and indirect jobs; this is 30% more than the number of jobs without such development. By 2020, direct geothermal and indirect employment will comprise 23% of the county workforce. These projections agree with those of Rose (1977).

Unfortunately, the educational attainment levels of Mexican-Americans, who make up about half the population, are relatively low. Thus, geothermal development may not have much direct impact on unemployment. But unskilled and semi-skilled labor may find greater employment opportunities in secondary industry and service establishments induced by the geothermal energy production or by non-electric geothermal applications.

A further illustration of the potentially limited effect of geothermal development on employment opportunities for county residents is shown in Fig. 12-8. This figure presents the occupational distributions taken from Fig. 12-4 that show Anglo and Mexican-American participation in occupational categories. Superimposed over this is the projection of increase in demand for various occupational groups (Rose, 1977). In most cases, occupations dominated presently by Anglos will increase substantially. However, groups containing high proportions of the Mexican-American work force will not increase nearly as rapidly, with the exception of the categories of laborers and operators, clerical, and service, none of which is in a high pay scale bracket.

Lofting projects that baseline gross county product will increase by about 50% by 2020; with geothermal development added, the increase may be as much as 200%, eclipsing the potential \$1 million loss in agricultural productivity resulting from the displacement of agricultural lands (Rose, 1977). Geothermal development will contribute about 40% of the gross county product in 2020; with induced growth, the contribution will be about 54% (Rose, 1977).

Fig. 12-8. Projected increases in employment over 1968 levels for several occupational groups, based on the development of 4500 MW of geothermal power by the year 2020. The dark bars show the percent increases over 1968 levels for different occupational categories.

Agriculture and related industries and services, which comprised 70% of the gross county product in 1975, would comprise about 60% in 2020 without geothermal development, according to the Lofting projections, as a result of some diversification. However, with geothermal development, agriculture and related industries and services would contribute about 33% of the gross county product, a result of significant diversification of the county economy. At this point, geothermal and related industries are projected to be a slightly greater contributor to the county economy than agriculture (Lofting, 1977; Rose, 1977). The agricultural sector is projected to grow by 30% by the year 2020; with geothermal development, it may grow by 44%, the difference accounted for by development of secondary uses of geothermal heat for the food and chemical processing industries. According to the Lofting projections, overall county economic growth will be slower than in the past 20 years without geothermal development; with it, the county economy will grow faster than in the past.

The Mexican government has made special efforts to attract industrial growth and to strengthen the Mexicali-border area market for Mexican-made goods. In contrast, the only major diversification effort by officials in the United States is the Calexico Industrial Park sponsored by the City of Calexico and financed with local, state, and federal funds. There are five other private smaller industrial parks in the county.

Certainly a benefit of geothermal development will be economic diversification and economic strength. Employment will be redistributed so that a higher percentage of workers will be in professional, technical, managerial and sales categories, and a reduced percentage will be in unskilled labor categories. The average income of employees will be higher as a result.

THE GOVERNMENTAL FISCAL SYSTEM

Geothermal development will increase both the costs of local governments and their revenues. In general, Imperial County and the eleven school districts will benefit from development (Goldman and Strong, 1977). The seven cities, however, will probably incur more costs than revenues from geothermal development. This distribution of costs and benefits results from the fact that geothermal development is excluded from city boundaries, but residential development is strongly directed within these boundaries so that valuable

agricultural lands are not urbanized. At the same level of development that population and economic effects are discussed (4500 MW), the county assessed valuation will nearly double (in 1975 dollars). The specific effects of development on tax rates, agency revenues, or expenditures will depend on current legislation affecting public agency finance that has seen significant change in the past few years. More such change can be anticipated in the future. However, geothermal development has a generally beneficial effect on local public agencies. These conclusions of Goldman and Strong agree with a fiscal analysis by Rose (1977).

RECREATION AND AESTHETIC RESOURCES

An important recreational resource in the Imperial Valley area is the Salton Sea. Many visitors come to the area to enjoy boating, skiing, swimming, and fishing. It is also a visual attraction. Wildlife refuges near the sea attract hunters, fishermen, bird watchers, and other visitors. Other major recreational resources are the desert dunes areas on either side of the valley, which attract many off road vehicle (ORV) enthusiasts.

The water level of the Salton Sea, and the degree of salinity are both critical factors in the continued recreational use of this area. Shoreline recreation and wildlife have been significantly impacted from the rising level of the sea caused primarily by irrigation runoff. If the water level continues to rise, little riparian habitat will remain and most of the existing marinas will be unusable (Twiss et al., 1980). Increasing salinities in the sea present a threat to the sport fishery, and geothermal development could hasten salinity increases if waste waters are used to support geothermal operations (see Section 6 for predictions of future elevations and salinities).

Twiss reports aerial surveys by the Bureau of Land Management that are used to estimate off road vehicle use in the desert area. Figure 12-9 shows the monthly distribution of vehicles observed, with May and November standing out as high-use months. The major impact from geothermal development to the ORV recreationists and other visitors would be visual. The Bureau of Outdoor Recreation reports that over 70% of those engaging in recreation participate in sight seeing and driving for pleasure. For this reason, power plant siting becomes a critical issue. Twiss et al. (1980) indicate that the

agricultural areas near the Salton Sea are landscapes of hard straight lines, consisting of irrigation ditches, power lines, highways, and tall bulky processing plants. This creates a rectangular pattern that Twiss believes could accommodate increases in bulky structures without major visual disruption.

Power plants sited outside the agricultural area, placed on the desert slopes in the alluvial fan area would be very visible from the valley floor and would not blend with the background. In this area power plants should be consolidated, as a few large units would minimize the negative visual impacts.

Fig. 12-9. Monthly distributions of off-road vehicle use in Imperial County (Twiss et al., 1978).

The wildlife refuges include the Salton Sea National Wildlife Refuge and the Myster Units of the Imperial Wildlife Area, managed by the State of California. Approximately 60,000 people visited the Salton Sea National Wildlife Refuge from July 1975 to June 1976. Hunting is allowed three days a week during hunting season with a maximum of 200 hunters per day at the

Wister Unit and the Salton Sea National Wildlife Refuge combined. In addition to public recreation opportunities, the Wister Unit provides land for the Imperial Valley State Warm Water Fish Hatchery. Hundreds of thousands of waterfowl winter on the Salton Sea, including rare and endangered birds. The level of the sea and the salinity are critical to the wildlife areas.

The additional population resulting from geothermal resource development is not expected to have a significant impact on recreational use. Sites used for recreation are widely dispersed and weekend residents tend to cluster near the sea.

A second recreation-aesthetic study (Rose, 1977) came to essentially the same conclusion. This study had a different focus and a different methodology; however, the researchers found the Niland area, adjacent to the Salton Sea, to have the highest scenic value and the most potential for effects from development. The location of the effects can be seen in Fig. 4-2, taken from the scenario of development by Ermak (1977).

LEADERSHIP AND PUBLIC OPINION

The power structure in Imperial County is monolithic (Butler et al., 1980). That is, decisions affecting the community are made by a rather small group of people. The key members of this influential group are not necessarily the people the general public perceives as the community leaders. Since agriculture is the most important activity in Imperial County, it is not surprising that most of the key influential people are involved in some way with agriculture.

All of the influential leaders in the county are in favor of geothermal development. About 20% add qualifying comments such as, "As long as it doesn't harm agriculture", or, "if oil companies are closely regulated" (Butler et al., 1980).

The county leaders expect many positive impacts from geothermal resource development. For instance, the top leaders agree that geothermal development will bring new tax revenues to Imperial County. About 90% of the leaders, and 75% of the public polled by Butler et al. (1980), believe that new businesses will be attracted to Imperial County. Other expected positive impacts are: increased jobs in the county, a more diversified economic base, and alleviation of fuel shortages.

The major negative impact expressed was water use. To the statement, "Geothermal development will take water away from agriculture", 33.3% of the top leaders among Butler's respondents agreed or strongly agreed. However, only 5.6% of second level leaders and 4.8% of the public agreed with the statement. The other negative impact seen as more probable by top leaders (33.3%) than the public (13.0%) is increase in noise level. Other impacts perceived as negative are: environmental costs, unusual odor, aesthetics, and increased taxes due to increased demands on city and county government (Butler and Pick, 1977).

CONCLUSIONS

- The county's population is estimated to increase by an average of 30% more with geothermal development than under projected conditions without geothermal development at 2020, assuming development of 4500 MW of electric power. A majority of the increase will probably be from people of Anglo-origin. As a result, cultural and recreational interests are likely to be different in future immigrant groups, creating demands for different public services, cultural, shopping, entertainment, and recreation facilities.

- Housing supplies will grow slightly faster than population, reducing the average number of persons per house. If a substantial disparity develops between the educated, skilled, higher income employed and the non-work force participants (less well educated, unskilled, unemployed, often with other elements of isolation such as language, culture, and age), then social friction may develop. This could be intensified if legal and illegal aliens displace resident workers and if employment opportunities for the less skilled do not develop.

- Development of 4500 MW of geothermal electric power could have substantial effects on the county economy, the gross output from which could be increased by a factor of three over a "baseline" growth by 2020. The economy will be more diversified and grow faster with geothermal development, which could create 14,000 direct and induced jobs and add \$1.5-2.0 billion to the annual gross county output, eclipsing the estimated losses of \$1 million in agriculture due to the displacement of agricultural lands by geothermal facilities.

● Geothermal development will probably have little effect on the high unemployment in the county unless: public and private retraining efforts are successful, the educational levels and age structure of Mexican-Americans increase, and jobs for un- and semi-skilled are provided, possibly through growth of non-electric geothermal industries.

● Geothermal development will generate more revenues than costs for county government and the eleven school districts. But the cities, from which geothermal development is excluded, will bear most of the costs of population, commercial, and industrial growth. Cities will only benefit from secondary-growth tax sources that will be insufficient to cover all the costs. Some form of redistribution of a portion of the county tax revenues to offset costs to cities of serving geothermally induced population may be necessary.

● The current power structure, dominated by agricultural interests, is not threatened by geothermal development because the interests of the two are currently parallel. However, geothermal industry leaders will become a force in the overall leadership structure of the county, supported by their growing economic base. There is currently no significant opposition to geothermal development, either among the leadership or the public. This will probably erode somewhat as the education levels increase, but not to inhibitive levels unless there is a serious accident causing injury or long-term environmental damage.

SECTION 13. CONCLUSIONS AND RECOMMENDATIONS

The geothermal resources of the Imperial Valley of California have the potential of producing up to 6760 MW for 30 years (Muffler, 1979). This represents almost a third of the nation's total identified resources for hot water ($>150^{\circ}\text{C}$) 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, which focused on a scenario of 3000 MW of ultimate development, indicates that future geothermal developments will generally be compatible with agriculture. However, there is a possibility that mitigation measures will 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. Furthermore, the consumption of agricultural waste waters to support large-scale development will have to be minimized to mitigate increases in the Salton Sea's salinity. In this section we briefly review the important impacts that were addressed in the assessment and identify methods to mitigate impacts. In addition, we recommend a series of future measurements and studies that should be considered as geothermal development proceeds.

MAJOR IMPACTS AND ENVIRONMENTAL CONTROLS

Large-scale geothermal energy production should 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 1% of the lands normally irrigated will be needed by geothermal facilities. Negative impacts of a site-specific nature could occur resulting from land subsidence, cooling tower drift, and accidental spills of geothermal fluids. Table 13-1

identifies the types of impacts that might happen and the mitigating measures that could be implemented to eliminate or minimize the possible effects on agriculture. Subsidence is undoubtedly the most serious threat to agricultural lands. Nevertheless, there are remedial measures that could be introduced to limit adverse impacts.

Table 13-1. Site-specific impacts to agriculture and possible methods of mitigation.

Source of Impact	Possible Impacts(s)	Alternative Mitigating Measures
A. Land Subsidence	Disruption of irrigation and drainage systems	<ol style="list-style-type: none"> 1. Alter rates of geothermal fluid extraction and injection. 2. Change locations of wells 3. Repair surface damages 4. Implement sprinkler irrigation
B. Cooling tower drift	Foliar damage to crops and trace metal uptake	<ol style="list-style-type: none"> 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
C. Accidental spills	Thermal stress to crops and contamination of soil waters	<ol style="list-style-type: none"> 1. Construct berms to contain spills 2. Use pressure activated alarms to warn of inadvertent releases 3. Reclaim affected soils by leaching

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 avert odors because most people can smell hydrogen sulfide at concentrations below the standard. The seriousness of future odor problems will depend a great deal on the number of people exposed to concentrations of hydrogen sulfide that are above their personal tolerance units. 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 evolve 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.

The extensive use of agricultural waste waters to support geothermal operations will accelerate increases in 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, the partial injection of withdrawn geothermal fluids will have to be allowed. Currently, the full injection of withdrawn fluids (spent geothermal fluids plus condensate) is necessary because of a county policy (Imperial County, 1977) designed to control potential subsidence. Until the use of partial injection is shown to be possible without increasing subsidence, external sources of water will be required for geothermal power production. Aside from the potential impacts on the Salton Sea's aquatic ecosystem produced by increases in salinity, the only other major important impacts to fish and wildlife would be associated with habitat alterations and accidental spills of geothermal fluids. Both sources of impact, however, can be mitigated. The careful siting of geothermal facilities, for example, can prevent significant impacts to sensitive habitats. This will be particularly important in the Salton Sea resource area where wetland habitats support large numbers of migratory birds. Accidental spills can be mitigated through the use of containment berms, warning devices, and contingency plans.

For geothermal development to proceed unhindered in the valley, liquid and solid wastes containing toxic substances will have to be disposed in ways that do not result in adverse impacts to water quality, fish and wildlife, and human health. The largest volume of waste will be thousands of acre-feet of spent geothermal fluids produced from power plants. The only environmentally safe method of disposing 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 detrimentally affected. The solids that are suspended in residual geothermal fluids will have to be separated to prevent the clogging of injection wells. Solids removed from geothermal fluids together with other wastes including solids derived from well drilling, scale removal, and hydrogen sulfide abatement will probably be placed in one or more special land disposal sites.

The positive impacts of future 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 country's economy will become more diverse, and the gross output of goods and services will rise.

FUTURE MEASUREMENTS AND STUDIES

Our assessment of future environmental, socioeconomic, and human health effects was based on the best available information on baseline conditions in the valley, the chemical composition of geothermal fluids, the technical characteristics of geothermal technologies, and the effects of pollutants. As geothermal development proceeds, though, there will be a need to compare actual impacts with the predicted impacts. This activity will be particularly important for impacts that are difficult to quantify (e.g., subsidence) because of uncertainties regarding physical processes and the actual ways in which geothermal power plants and well fields will be constructed and operated. To verify predicted impacts and to detect other impacts as they occur, post operational environmental monitoring and effects studies will be necessary.

Chemical characterizations of geothermal fluids will be necessary to determine if the concentrations of different substances vary through time, and thus change the nature of potential environmental impacts. To support future air quality analyses, measurements should be made of hydrogen sulfide, ammonia, mercury, carbon dioxide, methane, radon, and non-methane hydrocarbons. In terms of public health, estimated 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 will be 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 because its presence in drift emitted from a cooling tower using condensate could damage crops.

Baseline measurements of various environmental parameters will be needed periodically to preserve the validity of baseline measurements made as part of the IVEP as well as other organizations. The important measurements are summarized here:

- To update the 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 KGRAs.

- 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 later comparisons of a seismic activity happening 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 studies along with field studies could be implemented to determine the sensitivity of crops to differnt doses of saline drift. Other post-operational studies should address land subsidence, health and safety aspects of geothermal operations, and accidental spills of geothermal fluids.

LIST OF ACRONYMS USED IN REFERENCES

CAC	California Administrative Code
CARB	California Air Resources Board
CDF	California Department of Finance
CDPH	California Department of Public Health
CDWR	California Department of Water Resources
CDLSR	California Department of Labor Statistics and Research
CEDD	California Employment Development Department
CEC	California Energy Commission
CFR	Code of Federal Regulations
CPUC	California Public Utilities Commission
CRBC	Colorado River Board of California
CRWQCB	California Regional Water Quality Control Board
CSWMB	California Solid Waste Management Board
CSWRCB	California State Water Resources Control Board
IID	Imperial Irrigation District
IEEQ	Illinois Institute for Environmental Quality
PG&E	Pacific Gas and Electric Company
RGI	Republic Geothermal, Inc.
USBEA	U.S. Bureau of Economic Analysis
USBC	U.S. Bureau of the Census
USBR	U.S. Bureau of Reclamation
USDI	U.S. Department of the Interior
USDS	U.S. Department of State
USFWS	U.S. Fish and Wildlife Service
USNIOOSH	U.S. National Institute for Occupational Safety and Health
USNOAA	U.S. National Oceanic and Atmospheric Administration
USNRC	U.S. National Research Council
USOSHA	U.S. Occupational Safety and Health Administration

SECTION 14. REFERENCES

- Adams, D.F., F.A. Young and R.A. Luhr, 1968. "Evaluation of an Odor Perception Threshold Test Facility," Tappi 51 (3), 62A-67A.
- Amsden, A.A., 1966. The Particle-In-Cell Method for the Calculation of the Dynamics of Compressible Fluids, Los Alamos Scientific Laboratory, Los Alamos, New Mexico, LA-3466.
- Anspaugh, L.R., 1978. Final Report on the Investigation of the Impact of the Release of ^{222}Rn , its Daughters, and Precursors at The Geysers Geothermal Field and Surrounding Area, Lawrence Livermore Laboratory, Livermore, Calif.
- Anspaugh, L.R. and J.L. Hahn, 1979. "Human Health Implications of Geothermal Energy," in: Proc. Park City Environmental Health Conference, Park City, Utah, April 4-7, 1979, in press.
- Atkins, E.L., 1979. Analysis of the Apicultural Industry in Relation to Geothermal Development and Agriculture in the Imperial Valley, Lawrence Livermore Laboratory, Livermore, Calif., UCRL-15026.
- Austin, A.L. and A.W. Lundberg, 1975. "Electric Power Generation from Geothermal Hot Water Deposits," Mechanical Eng. 97 (12) 18-25.
- Austin, A.L., A.W. Lundberg, L.B. Owen, and G.E. Tardiff, 1977. The LLL Geothermal Energy Program Status Report, January 1976 - January 1977, Lawrence Livermore Laboratory, Livermore, Calif., UCRL-50046-76.
- Austin, T.C., 1979. California Air Resources Board, letter to D.L. Carey, Republic Geothermal Inc., December 11, 1979.
- Axelrod, M.C., 1978. "An Exploratory Data Analysis of Photochemical Oxidants in the Imperial Valley, California," in: Electronics Engineering Department Quarterly Report No. 3-1978, Lawrence Livermore Laboratory, Livermore, Calif., UCRL-50025-78-3, pp. 25-34.

Ayers, R.S., 1977. "Quality of Water for Irrigation," J. Irrig. Drain. Div., Proc. Am. Soc. Civ. Eng. 103 (IR2), 135-154.

Baginsky, E., 1975. Occupational Disease in California 1975, California Dept. of Health Services, San Francisco, Calif.

Barnes, H.L. and J.D. Rimstidt, 1975. "Chemistry of Silica Scale Formation," in: Second Workshop on Materials Problems Associated with the Development of Geothermal Energy Systems, May 16-18, 1975, El Centro, Calif. Geothermal Resources Council, Davis, Calif., pp. 1-13.

Bechtel, 1976. Conceptual Design of Commerical 50 MWe (net) Geothermal Power Plants at Heber and Niland, California, Final Report, Bechtel Corporation, San Francisco, Calif., SAN-1124-1.

Bennett, W.W. and R.D. Ohmart, 1978. Habitat Requirements and Population Characteristics of the Clapper Rail (*Rallus longirostris yumanensis*) in the Imperial Valley of California, Arizona State Univ., Tempe, Ariz., UCRL-13813.

Border Area Development Study, 1977. Planning and Land Use in Imperial County. Cross-Border Links with Mexicali's Development, Office of the Lieutenant Governor, State of California, Sacramento, Calif.

Brandt, H., 1978. "Appendix A. Recommendations for Subsidence Evaluation of Geothermal Reservoirs," in: Identification of Environmental Control Technologies in the Imperial Valley of California, D.F. Snoeberger and J.H. Hill, Lawrence Livermore, Laboratory, Livermore, Calif., UCRL-52548.

Brown, K.W., and N.J. Rosenberg, 1970. "Effect of Windbreaks and Soil Water Potential on Stomatal Diffusion Resistance and Photosynthetic Rate of Sugar Beets (*Beta vulgaris*)," Agron. J. 62, 4-8.

Bush, R.C., 1977. "Plant and Equipment Noise Treatment," presented at the Pacific Coast Electrical Association Engineering and Operation Conference, Los Angeles, Calif., March 17-18, 1977.

Butler, E.W. and J.B. Pick, 1977. Opinion About Geothermal Development in Imperial County, California; 1976, Final Report, Dry-Lands Research Institute, University of California, Riverside, Calif., DLRI Report No. 17.

Butler, E.W., C.H. Hall, and J.B. Pick, 1980. A Study of the Influential Leaders, Power Structure, Community Decisions, and Geothermal Energy Development in Imperial County, California. Dry-Lands Research Institute, University of California, Riverside, Calif., UCRL-13911.

California Administrative Code (CAC), 1972. 8 CAC 5095-5099, State of California, Sacramento.

California Administrative Code (CAC), 1979. 22 CAC 66016-66898, State of California, Sacramento.

California Air Resources Board (CARB), 1970. "Appraisal of the Ambient Air Quality Standard for Hydrogen Sulfide," in: Ambient Air Quality Standards, California Air Resources Board, pp. 69-75.

California Dept. Finance (CDF), 1977. Population Projections for California Counties 1976-2020 with Age/Sex Detail to 2000, Series E-150, California Department of Finance, Sacramento, Calif., Report 77-P-3.

California Dept. Finance (CDF), 1978. California Statistical Abstract 1978, State of California, Sacramento, Calif.

California Dept. Public Health (CDPH), 1962. "Basis for Ambient Air Quality Standards for Hydrogen Sulfide," in Technical Report of California Standards for Ambient Air Quality and Motor Vehicle Exhaust, Supplement No. 2, Additional Ambient Air Quality Standards, State of California, Department of Public Health, Berkeley, Calif., pp. 11-16.

California Div. Labor Statistics and Research (CDLSR), 1979. Doctor's First Report of Occupational Injury or Illness, (1973-1979), California Div. Labor Stat. Res., San Francisco, Calif.

California Employment Development Department (CEDD), 1979. Annual Planning Information, Imperial County 1979-1980, Southern California Employment Data and Research, Employment Development Department, Los Angeles, Calif.

California Energy Commission (CEC), 1979. Energy Choices for California... Looking Ahead, California Energy Commission, Sacramento, Calif.

California Public Utilities Commission (CPUC), 1975. Transcripts of Hearings on Geysers Power Units, Open Files, CPUC, San Francisco, Calif.

California Regional Water Quality Control Board (CRWQCB), 1975. Water Quality Control Plan Report, West Colorado River, Basin, California Regional Water Quality Control Board, Colorado River Basin Region, Palm Desert, Calif.

California State Water Resources Control Board (CSWRCB), 1975. Water Quality Control Policy on the Use and Disposal of Inland Waters Used for Power Plant Cooling, California State Water Resources Control Board, Sacramento, Calif.

California State Water Resources Control Board (CSWRCB), 1977. Regulations Concerning Waste Discharge Requirement, National Pollutant Discharge Elimination System, California State Water Resources Control Board, Sacramento, Calif.

Carter, L.J., 1979. "Dispute over Cancer Risk Quantification," Science 203, 1324-1325.

Cederlof, R., M.L. Edfors, L. Friberg and T. Lindvall, 1966. "On the Determination of Odor Thresholds in Air Pollution Control -- An Experimental Field Study on Flue Gases from Sulfate Cellulose Plants," J. Air Pollut. Control Assoc. 16, 92-94.

Chen, N.C.J., 1977. Review of Cooling Tower Drift Deposition Models. Oak Ridge National Laboratory, Oak Ridge, Tenn., ORNL/TM-5357.

Code of Federal Regulations (CFR), 1978. 29 CFR 1910.1000. Washington, D.C., Occupational Health and Safety Administration, Dept. of Labor.

Colorado River Board of California (CRBC), 1969. California's Stake in the Colorado River, Colorado River Board of California, Los Angeles, Calif.

Crow, N.B., 1976. "Subsidence and Seismicity," in: Imperial Valley Environmental Project: Progress Report, P.L. Phelps, and L.R. Anspaugh, Eds., Lawrence Livermore Laboratory, Livermore, Calif., UCRL-50044-76-1, pp. 84-100.

Crow, N.B. and P.W. Kasameyer, 1978. "Monitoring Natural Subsidence and Seismicity in the Imperial Valley as a Basis for Evaluating Potential Impacts of Geothermal Production," Geotherm. Resour. Counc. Trans. 2, 125-128.

Cudney, D.W., 1967. Imperial County Field Crops Calendar, University of California Agricultural Extension Service, Imperial County, El Centro, Calif., Circular 113.

Dechant, R.F. and G.R. Sanders, 1967. Hydrogen Sulfide Odor Threshold Study, Air and Industrial Hygiene Laboratory, California Dept. Public Health, Berkeley, Calif., unpublished report.

DiPippo, R., 1978. Geothermal Power Plants of the United States: A Technical Survey of Existing and Planned Installations, Division of Engineering, Brown Univ., Providence, RI, C00-4051-20.

Elders, W.A., R.W. Rex, T. Meidav, P.T. Robinson, and S. Biehler, 1972. "Crustal Spreading in Southern California," Science 178, 15-24.

Elders, W.A., 1975. "Regional Geology of the Salton Trough," in: Geothermal Development of the Salton Trough, California, T.D. Palmer, J.H. Howard, and D.P. Lande, Eds., Lawrence Livermore Laboratory, Livermore, Calif., UCRL-51775, pp. 1-12.

Ermak, D.L., 1977. Potential Growth of Electric Power Production from Imperial Valley Geothermal Resources, Lawrence Livermore Laboratory, Livermore, Calif., UCRL-52252.

- Ermak, D.L., 1978. "A Scenario for Geothermal Electric Power Development in Imperial Valley," Energy 3, 203-217.
- Ermak, D.L. and P.L. Phelps, 1978. An Environmental Overview of Geothermal Development: The Geysers-Calistoga KGRA, Vol. 1: Issues and Recommendations, Lawrence Livermore Laboratory, Livermore, Calif., UCRL-52496 Vol. 1.
- Ermak, D.L. and R.A. Nyholm, 1978. Multiple Source Dispersion Model, Lawrence Livermore Laboratory, Livermore, Calif., UCRL-52592.
- Ermak, D.L., R.A. Nyholm, and R. Lange, 1978. ATMAS: A Three-Dimensional Atmospheric Transport Model to Treat Multiple Area Sources, Lawrence Livermore Laboratory, Livermore, Calif., UCRL-52603.
- Ermak, D.L., R.A. Nyholm, and P.H. Gudiksen, 1979. Imperial Valley Environmental Project: Air Quality Assessment, Lawrence Livermore Laboratory, Livermore, Calif., UCRL-52699.
- Fay, H.P., C.A. Brown, M.S. Yao, and R.A. Molina, 1976. "Advanced Techniques Minimize Wet-Dry Tower Costs and Water Consumption," Combustion 48, 23.
- Fick, G.W., 1971. Analysis and Simulation of the Growth of Sugar Beet (Beta vulgaris L.). Ph.D. dissertation, University Microfilms, Ann Arbor, Michigan.
- Fuis, G. and M. Schnapp, 1977. "The November-December 1976 Earthquake Swarms in Northern Imperial Valley, California Seismicity on the Brawley Fault and Related Structures," (Abstract). Trans. Am. Geophys. Union (EOS) 58, 1188.
- Fyn-Djui, D., 1961 "Basic Data for the Determination of Limit of Allowable Concentration of Hydrogen Sulfide in Atmospheric Air," in: USSR Literature on Air Pollution and Related Occupational Diseases, Vol. 5. B.S. Levine, Ed., US Public Health Service, Washington, D.C. pp. 66-73. (English Translation of Gig. Sanit. 24 (10) 12-17, 1959).
- Garrett, R.E., 1978. Uses of Warmed Water in Agriculture, Lawrence Livermore Laboratory, Livermore, Calif., UCRL-13930.

Goldman, G. and D. Strong, 1977. Governmental Costs and Revenues Associated with Geothermal Energy Development in Imperial County, Div. Agricultural Sciences, University of California, Davis, Calif., UCRL-13800.

Goldsmith, M., 1976. Geothermal Development and the Salton Sea, Environmental Quality Laboratory, California Institute of Technology, Pasadena, Calif., EQL Memorandum No. 17.

Goldstein, R.A. and J.B. Mankin, 1972. "PROSPER: A Model of Atmosphere-Soil-Plant Water Flow," in: Proc. 1972 Summer Computer Simulation Conference, Simulation Councils, Inc., La Jolla, Calif., pp. 1176-1181.

Grimsrud, G.P., B.L. Turner, and P.A. Frame, 1978. Areas of Ground Subsidence Due to Geofluid Withdrawal, Systems Control Inc., Palo Alto, Calif., LBL-8618.

Gudiksen, P.H., M.C. Axelrod, D.L. Ermak, D.C. Lamson, and R. Lange, 1978. "A Methodology for Assessing the Potential Impact on Air Quality Resulting From Geothermal Resource Development in the Imperial Valley," in: Proc. Int. Clean Air Conf., Clean Air Soc. Australia and New Zealand, Brisbane, Australia, May 15-18, E.T. White, P. Hetherington, and B.R. Thiele, Eds., Ann Arbor Science Publishers, Ann Arbor, Mich., pp.719-734.

Gudiksen, P.H., D.L. Ermak, K.C. Lamson, M.C. Axelrod and R.A. Nyholm, 1979a. The Potential Air Quality Impact of Geothermal Power Production in the Imperial Valley, Lawrence Livermore Laboratory, Livermore, Calif., UCRL-52797.

Gudiksen, P.H., K.C. Lamson, M.C. Axelrod, V. Fowler and R.A. Nyholm, 1979b. Imperial Valley Environmental Project: Baseline Air Quality and Meteorological Data, Lawrence Livermore Laboratory, Livermore, Calif., UCID-18212.

Hagemann, R., 1979. Office of the Agricultural Commissioner, Imperial County, El Centro, Calif., personal communication.

Hahn, J.L., 1979a. Location of Odor Sources and the Affected Population in Imperial County, California, California Department of Health Services, Berkeley, Calif., in press.

Hahn, J.L., 1979b. "Occupational Hazards Associated with Geothermal Energy," Geotherm. Resour. Counc. Trans. 3 283-286.

Hahn, J.L., 1979c. Evaluation of Occupational Hazards in the Geothermal Energy Industry, California Department of Health Services, Berkeley, Calif., in preparation.

Hall, A.E., 1970. Photosynthetic Capabilities of Healthy and Beet Yellow Virus Infected Sugar Beets (Beta vulgaris L.), Ph.D. dissertation, University Microfilms, Ann Arbor, Michigan.

Hanson, J.A., 1972. "Tolerance of High Salinity by the Pileworm Neanthes succinea, from the Salton Sea, California," Calif. Fish Game 58, 152-154.

Harrar, J.E., C.H. Otto, S.B. Deutscher, R.W. Ryon, and G.E. Tardiff, 1979. Studies of Brine Chemistry, Precipitation of Solids, and Scale Formation at the Salton Sea Geothermal Field, Lawrence Livermore Laboratory, Livermore Calif., UCRL-52640.

Hendrickson, P.L., 1977. An Overview of Economic, Legal, and Water Availability Factors Affecting the Demand for Dry and Wet/Dry Cooling for Thermal Power Plants, Battelle Pacific Northwest Laboratories, Richland, Wash., BNWL-2268.

Herrgesell, P.L., 1975. A Report on Aquatic Resources Associated with Agricultural Drains in the Palo Verde Irrigation District, Coachella Valley County Water District and Imperial Irrigation District, Environmental Services Branch, California Department of Fish and Game, Long Beach, Calif.

Hill, D.P., P. Mowinckel, and L.G. Peake, 1975. "Earthquakes, Active Faults, and Geothermal Areas in the Imperial Valley, California," Science 188, 1306-1308.

Hill, J.H. and C.J. Morris, 1976. "Sampling a Two-Phase Geothermal Brine Flow for Chemical Analysis," in: Sampling Geothermal Effluents, Proc. 1st Workshop, Oct. 20-21, 1975, Las Vegas, Nevada, Environmental Protection Agency, Las Vegas, Nevada, EPA-600/9-76-011, pp. 181-203.

Holzer, T.L., 1978. Results and Interpretation of Exploratory Drilling Near the Picacho Fault, South-Central Arizona, U.S. Geological Survey Preliminary Report, Menlo Park, Calif., Open-File Report 78-1016.

Hsieh, P.A. and J.D. Bredehoeft, 1979. A Reservoir Analysis of the Denver Earthquakes: A Case of Induced Seismicity, U.S. Geological Survey, Reston, Va., unpublished manuscript.

Hundley, N., 1975. Water and the West, University of California Press, Berkeley, Calif.

Hunt, W.F., 1974. Respiratory Control and its Prediction by a Dynamic Model of Sugar Beet Growth, Ph.D. dissertation, University Microfilms, Ann Arbor, Michigan.

Illingworth, R.R., 1976. "Factors Contributing to Annoyance by Geothermal Steam Well Venting Noise at The Geysers," in: Geothermal Environmental Seminar -- '76, F.L. Tucker and M.D. Anderson, Eds., Lake County, Calif., October 27-29, 1976, pp. 75-83.

Illinois Institute for Environmental Quality (IIEQ), 1974. Hydrogen Sulfide Health Effects and Recommended Air Quality Standard, Illinois Inst. Environmental Quality, Chicago, Ill. IIEQ Doc No. 74-24.

Imperial County, 1971. Terms, Conditions, Standards, and Application Procedures for Initial Geothermal Development; Imperial County, Department of Public Works, Imperial County, El Centro, Calif.

Imperial County, 1973. "Imperial County Ultimate Land Use Plan," "Open Space Element," and "Conservation Element," Imperial County General Plan, Imperial County, El Centro, Calif.

Imperial County, 1977, "Geothermal Element," Imperial County General Plan, Imperial County, El Centro, Calif.

Imperial County, 1978a. Imperial County Plan to Attain National Ambient Air Quality Standards for Oxidants, Adopted October 31, 1978, Imperial County, El Centro, Calif.

Imperial County, 1978b. Imperial County Agriculture, 1978, Office of Agricultural Commissioner, Imperial County, El Centro, Calif.

Imperial Irrigation District (IID), 1978. Water Report 1978, Imperial Irrigation District, Imperial, Calif.

Ireland, R.R., 1978. "Acute Toxicity of Geothermal Effluents to Fry of Tilapia zillii," presented at the American Fisheries Society 108th Annual Meeting, August 20-25, 1978, Univ. Rhode Island, Kingston, R.I.

Jackson, D.D., 1979. University of California, Los Angeles, Calif., written communication.

Johnson, C.E. and D.M. Hadley, 1976. "Tectonic Implications of the Brawley Earthquake Swarms, Imperial Valley, Calif., January, 1975," Bull. Seismol. Soc. Am. 66, 1155-1158.

Joyce, L. and R.A. Fontes, 1978. "Air Quality as the Limiting Factor on Development of The Geysers Geothermal Resources," Geotherm. Resour. Counc. Trans. 2, 345-349.

Jury, W.A. and L.V. Weeks, 1978. "Solute Travel-Time Estimates for Tile-Drained Fields: III. Removal of a Brine Spill from Soil by Leaching," Soil Sci. Soc. Am. J. 42, 679-684.

Kercher, J.R. and M. Buchanan, 1976. "Biological Resources," in: A Description of Imperial Valley, California for the Assessment of Impacts of Geothermal Energy Development, D. Layton and D. Ermak, Eds., Lawrence Livermore Laboratory, Livermore, Calif., UCRL-52121.

- Kercher, J.R., 1977. GROW1: A Crop Growth Model for Assessing Impacts of Gaseous Pollutants from Geothermal Technologies, Lawrence Livermore Laboratory, Livermore, Calif., UCRL-52247.
- Kercher, J.R., 1978. A Model of Leaf Photosynthesis and the Effects of Simple Gaseous Compounds (H_2S and SO_2), Lawrence Livermore Laboratory, Livermore, Calif., UCRL-52643.
- Kercher, J.R., 1979. A Model of Plant Growth for Assessing Effects of Simple Gaseous Sulfur Compounds on Sugar Beets, (*Beta vulgaris*), Lawrence Livermore Laboratory, Livermore, Calif., in preparation.
- Kim, J., 1973. "Ecosystem of the Salton Sea," in: Man-Made Lakes: Their Problems and Environmental Effects, W.C. Ackerman, G.F. White and E.B. Worthington, Eds., Am. Geophys. Union Geophysical Monograph 17, pp. 601-605.
- Klusman, R.W. and R.A. Landress, 1978. "Secondary Controls on Mercury in Soils of Geothermal Areas," J. Geochem. Explor. 9, 75-91.
- Lange, R., 1978. "ADPIC - A Three-Dimensional Particle-In-Cell Model for the Dispersal of Atmospheric Pollutants and its Comparison to Regional Tracer Studies," Appl. Meteor. 17, 320-329.
- Lasker, R., R.H. Tenaza, and L.L. Chamberlain, 1972. "The Response of Salton Sea Fish Eggs and Larvae to Salinity Stress," Calif. Fish Game 58 58-66.
- Layton, D.W. and D.L. Ermak, Eds., 1976. A Description of Imperial Valley, California, for the Assessment of Impacts of Geothermal Energy Development, Lawrence Livermore Laboratory, Livermore, Calif., UCRL-52121.
- Layton, D.W., 1978a. Water for Long Term Geothermal Energy Production in the Imperial Valley, Lawrence Livermore Laboratory, Livermore, Calif., UCRL-52576.
- Layton, D.W., 1978b. "Water Supply Dilemmas of Geothermal Development in the Imperial Valley of California," Water Res. Bull. 14, 133-143.

Layton, D.W., D.J. Powers, P. Leitner, N.B. Crow, P.H. Gudiksen, and Y.E. Ricker, 1979. Environmental Summary Document for the Republic Geothermal, Inc. Application for a Geothermal Loan Guaranty Project; 64 MW Well Field and 48 MW (Net) Geothermal Power Plant, Lawrence Livermore Laboratory, Livermore, Calif., UCID-18095.

Layton, D.W. and K.D. Pimentel, 1980. Geothermal Power Production: Impact Assessments and Environmental Monitoring, Lawrence Livermore Laboratory, Livermore, Calif. Preprint UCRL-83681, to be published in 1980 Proc. 26th Annual Technical Meeting, Institute for Environmental Sciences, Philadelphia, Pennsylvania, May 11-14, 1980.

Leitner, P., 1978. An Environmental Overview of Geothermal Development: The Geysers-Calistoga KGRA, Vol. 3: Noise, Lawrence Livermore Laboratory, Livermore, Calif., UCRL-52496 Vol. 3.

Leitner, P. and G.S. Grant, 1978. Observations on Water Bird Flight Patterns at Salton Sea, California, October 1976 - February 1977, St. Mary's College, Moraga, Calif., UCRL-13818.

Leonardos, G., D. Kendall, and N. Barnard, 1969. "Odor Threshold Determinations of 53 Odorant Chemicals," J. Air Pollut. Control Assoc. 19 91-95.

Lippmann, M.J., C.F. Tsang, and P.A. Witherspoon, 1977. Analysis of the Response of Geothermal Reservoirs Under Injection and Production Procedures, Prepared for the 1977 47th Annual California Regional Meeting of the Society of Petroleum Engineers of AIME, held in Bakersfield, Calif., April 13-15, 1977. Society of Petroleum Engineers, Dallas, Tex., Paper no. SPE 6537.

Livernois, J., 1979. "'78 Imperial County Ag Income Sets Record," Imperial Valley Press, 77 (299), 1-2.

Loeltz, O.J., B. Ireland, J.H. Robison, and F.H. Olmstead, 1975. Geohydrologic Reconnaissance of the Imperial Valley, California, U.S. Geological Survey Professional Paper 486-K.

Lofgren, B.E., 1974. "Measuring Ground Movement in Geothermal Areas of the Imperial Valley, California," in: Proceedings of the Conference on Research for the Development of Geothermal Energy Resources, Sept. 23-25, 1974. Pasadena, California, Jet Propulsion Laboratory. Pasadena, California, NSF-RA-N-74-159.

Lofgren, B.E., 1978. Measuring Crustal Deformation in the Imperial Valley, California, U.S. Geological Survey, Sacramento, Calif., Open File Report 78-910.

Lofting, E.M., 1977. A Multisector Analysis of the Impact of Geothermal Development on the Economy of Imperial County, California, Dry-Lands Research Institute, University of Calif., Riverside.

Malloch, B.L., M.K. Eaton, and N.L. Crane, 1979. Assessment of Vegetation Stress and Damage Near The Geysers Power Plant Units, Dept. of Engineering Research, Pacific Gas and Electric Company, Report 420-79-3.

Marks, S.M., R.S. Ludwin, K.B. Louie, and C.G. Bufe, 1978. Seismic Monitoring at The Geysers Geothermal Field, California, U.S. Geological Survey, Menlo Park, Calif., Open-File Report 78-798.

Martin, W. and A.C. Stern, 1974. The World's Air Quality Management Standards, U.S. Environmental Protection Agency, Washington, D.C., EPA-650/9-75-001.

May, R.C., 1976. "Effects of Salton Sea Water on the Eggs and Larvae of Bairdiella icistia (Pisces: sciaenidae)," Calif. Fish Game 62 119-131

McCauley, C. and R. Gum, 1975. "Land Subsidence: An Economic Analysis," Water Res. Bull. 11, 148-154.

McCune, D.C., D.H. Silberman, R.H. Mandl, L.H. Weinstein, P.C. Freudenthal, and P.A. Giardian, 1977. "Studies on the Effects of Saline Aerosols of Cooling Tower Origin on Plants," J. Air Pollut. Control Assoc. 27, 319-324.

Meidav, T. and J.H. Howard, 1979. "An Update of Tectonics and Geothermal Resource Magnitude of the Salton Sea Geothermal Resource," Geotherm. Resour. Counc. Trans. 3 445-448.

Miner, S., 1969. Preliminary Air Pollution Survey of Hydrogen Sulfide. A Literature Review, National Air Pollution Control Administration, Raleigh, N.C. APTD 69-37.

Morrison, R., P. Saint, and D. Weaver, 1977. "Surface Disposal of Geothermal Brines," Geotherm. Resour. Counc. Trans. 1, 229-230.

Morse, J.G., 1978. "A Case Study of A Salton Sea Geothermal Brine Disposal Well," in: Proc. 2nd Invitational Well-Testing Symposium, Oct. 25-27, 1978, Berkeley, California Lawrence Berkeley Laboratory, Berkeley, California, LBL-8883, pp. 26-28.

Muffler, L.J.P. and D.E. White, 1969. "Active Metamorphism of Upper Cenozoic Sediments in the Salton Sea Geothermal Field and the Salton Trough, Southeastern California," Geol. Soc. Am. Bull. 80, 157-182.

Muffler, L.J.P., Ed., 1979. Assessment of Geothermal Resources of the United States -- 1978. U.S. Geological Survey, Arlington, Va., Circular 790.

Nehring, N.L. and A.H. Truesdell, 1978. "Hydrocarbon Gases in Some Volcanic and Geothermal Systems," Geotherm. Resour. Counc. Trans. 2, 483-486.

Nevens, D.J. and R.S. Loomis, 1970. "A Method for Determining Net Photosynthesis and Transpiration of Plant Leaves," Crop Sci. 10, 3-6.

Nietubicz, R.S. and R.L. Green, Eds., 1978. Cooling Tower Environment -- 1978. Proc. Symposium on Environmental Effects of Cooling Tower Emissions, The Center of Adult Education, Univ. Maryland, College Park, Md., May 2-4, 1978. Water Resources Research Center, Univ. Maryland, College Park, Maryland.

Nyholm, R.A. and L.R. Anspaugh, Eds., 1977. Imperial Valley Environmental Project: Quarterly Data Report, Lawrence Livermore Laboratory, Livermore, Calif., UCID-17444-1.

Oglesby, L.C., 1977. Reproduction and Survival of the Pileworm Nereis Succinea in Higher Salton Sea Salinities, Pomona College, Claremont, Calif., UCRL-13848.

Pacific Gas and Electric Co. (PG&E), 1975. Amended Environmental Data Statement. Geysers Unit 13. Pacific Gas and Electric Co., San Francisco, Calif.

Pacific Gas and Electric Co. (PG&E), 1978. Notice of Intention, Geysers Unit 17, Pacific Gas and Electric Co., San Francisco, Calif.

Palmer, T.D., J.H. Howard, and D.P. Lande, 1975. Geothermal Development of the Salton Trough, California and Mexico, Lawrence Livermore Laboratory, Livermore, Calif., UCRL-51775.

Phelps, P.L. and L.R. Anspaugh, Eds., 1976. Imperial Valley Environmental Project: Progress Report, Lawrence Livermore Laboratory, Livermore, Calif., UCRL-50044-76-1.

Pick, J.B., T.H. Jung, and E. Butler, 1977. Population Analysis Relative to Geothermal Energy Development, Imperial County, California, Dry-Lands Research Institute, Riverside, Calif., DLRI Report No. 16.

Pimentel, K.D., R.R. Ireland, and G.A. Tompkins, 1978. "Chemical Finger-prints to Assess the Effects of Geothermal Development on Water Quality in Imperial Valley," Geotherm. Resour. Counc. Trans. 2, 527-530.

Pimentel, K.D., 1980. Lawrence Livermore Laboratory, Livermore, Calif., personal communication.

Pines, H.S. and M.A. Green, 1976. The Use of Program GEOTHM to Design and Optimize Geothermal Power Plant Cycles, Lawrence Berkeley Laboratory, Berkeley, Calif., LBL-4454.

Poda, G.A., 1966. "Hydrogen Sulfide Can be Handled Safely," Arch. Environ. Health 12 795-800.

Policastro, A., W. Dunn, M. Breig, and J. Ziebarth, 1978. "Technical Report, Comparison of Ten Drift Deposition Models to Field Data Acquired in the Chalk Point Dye Tracer Experiment," in: Cooling Tower Environment - 1978, Supplement. Proc. Symp., Univ. Maryland on Environmental Effects of Cooling Tower Emissions May 2-4, 1978. Nietubiez, R.S., and R.L. Green, Eds., Water Resources Research Center, Univ. Maryland, pp. 76-84.

Powell, W.R., 1974. Inventory of Rare and Endangered Vascular Plants of California, California Native Plant Society, Berkeley, Calif., Special Publication No. 1.

Purtich, R.R. and M.B. Rogozen, 1977. "Water Supply," in: Study of Alternative Locations of Coal-Fired Electric Generating Plants to Supply Energy from Western Coal to the Department of Water Resources, Inst. Geophys. and Planetary Phys., Univ. California, Los Angeles, pp. 6-1 - 6-208.

Quong, R., K.G. Knauss, N.D. Stout, and L.B. Owen, 1979. "An Effective H₂S Abatement Process Using Geothermal Brine Effluents," Geotherm. Resour. Counc. Trans. 3, 557-559.

Raleigh, D.B., 1972. "Earthquakes and Fluid Injection," in: Underground Waste Management and Environmental Implications, Am. Assoc. Petrol. Geologists, Memoir 18, 273-279.

Raleigh, D.B., J.H. Healy, and J.D. Bredehoeft, 1975. "An Experiment in Earthquake Control at Rangely, Colorado," Science 191, 1230-1237.

Real, C.R., R.D. McJunkin, and E. Leivas, 1979. "Effects of Imperial Valley Earthquake 15 October 1979, Imperial County, California," Calif. Geol. Dec., 259-265.

Reese, S.M., 1977. Preliminary Results of the 1976-1977 Imperial Valley Leveling Surveys, National Geodetic Survey, Rockville, Md.

Republic Geothermal, Inc. (RGI), 1978. East Mesa Geothermal Project Plans of Operation, 48 MW (net) Power Plant. Federal Geothermal Leases CA 966 and CA 1903 Imperial County, California, Republic Geothermal, Inc., Santa Fe Springs, Calif.

Robertson, D.E., E.A. Crecelius, J.S. Fruchter, and J.D. Ludwick, 1977. "Mercury Emissions from Geothermal Power Plants," Science 196, 1094-1097.

Robertson, D.E., J.S. Fruchter, J.D. Ludwick, C.L. Wilkerson, E.A. Crecelius, and J.C. Evans, 1978. "Chemical Characterization of Gases and Volatile Heavy Metals in Geothermal Effluents," Geotherm. Resour. Counc. Trans. 2, 579-582.

Rose, A., 1977. The Economic Impact of Geothermal Energy Development, Dry-Lands Research Institute, University of California, Riverside, Calif.

Rosen, L.C. and C.R. Molenkamp, 1978. An Environmental Overview of Geothermal Development: The Geysers-Calistoga KGRA, Vol. 2: Air Quality, Lawrence Livermore Laboratory, Livermore, Calif., UCRL-52496 Vol. 2.

Sanyal, S.L., 1978. "Appendix B. Injection of Liquid Wastes." in: Identification of Environmental Control Technologies for Geothermal Development in the Imperial Valley of California, D.F. Snoeberger and J.H. Hill, Lawrence Livermore Laboratory, Livermore, Calif., UCRL-52548, pp. 20-22.

Schatz, J.F., A. Abou-Sayed, and M. Carroll, 1979a. "Compaction of Geothermal Reservoir Rock," Geotherm. Resour. Counc. Trans. 3, 633-636.

Schatz, J.F., P.W. Kasameyer, and J.A. Cheney, 1979b. Method of Using in situ Porosity Measurements on Geothermal Reservoir Compaction, Lawrence Livermore Laboratory, Livermore, Ca. Preprint, UCRL-81506.

Sharp, R.V., 1972. "Tectonic Setting of the Salton Trough," in: The Borrego Mountain Earthquake of April 9, 1968, U.S. Geological Survey Professional Paper 787, pp. 3-15.

Shinn, J.H., Ed., 1976. Potential Effects of Geothermal Energy Conversion on Imperial Valley Ecosystems, Lawrence Livermore Laboratory, Livermore, Calif., UCRL-52196.

Shinn, J.H., 1979. Lawrence Livermore Laboratory, Livermore, Calif., personal communication.

Sklarew, R.C., A.J. Fabrik, and J.E. Prager, 1971. A Particle-In-Cell Method for Numerical Solutions of the Atmospheric Diffusion Equation, and Applications to Air Pollution Problems, Systems, Science and Software, La Jolla, Calif., 3SR-844.

Snoeberger, D.F. and J.H. Hill, 1978. Identification of Environmental Control Technologies for Geothermal Development in the Imperial Valley of California, Lawrence Livermore Laboratory, Livermore, Calif., UCRL-52548.

Sposito, G., A. Page, S. Mattigod, M. Frink, W. Toben, and R. Norris, 1979. Trace Metal Speciation in Saline Waters Affected by Geothermal Brines, Lawrence Livermore Laboratory, Livermore, Calif., UCRL-15072.

Sprung, J.L., 1977. "Tropospheric Oxidation of H_2S ," in Advances in Environmental Science and Technology Vol. 7, J.N. Pitts, and R.L. Metcalf, Eds. pp. 263-275.

Stephens, F.B., J.H. Hill, and P.L. Phelps, 1980. State-of-the-Art Hydrogen Sulfide Control for Geothermal Energy Systems: 1979. U.S. Department of Energy, Washington, D.C., DOE/EV-0068.

Sung, R., W. Murphy, J. Reitzel, L. Leventhal, W. Goodwin, and L. Freidman, 1979. Surface Containment for Geothermal Brines, TRW Inc., Redondo Beach, Calif.

Thomas, M.D. and R.H. Hendricks, 1956. "Effect of Air Pollution on Plants," in: Air Pollution Handbook, P.L. Magill, F.R. Holden, and C. Ackley, Eds., McGraw-Hill, New York, pp. 9.1-9.44.

- Thompson, C.R. and G. Kats, 1978. "Effects of Continuous Hydrogen Sulfide Fumigation on Crop and Forest Plants," Environ. Sci. Technol. **12**, 550-553.
- Thompson, C.R., G. Kats, and R.W. Lennox, 1979. "Effects of Fumigating Crops with Hydrogen Sulfide or Sulfur Dioxide," Calif. Agriculture **33** (3), 9-10.
- Turner, F.B., P.A. Medica, and H.O. Hill, 1979. The Status of the Flat-Tailed Horned Lizard (Phrynosoma mcallii) at Nine Sites in Imperial and Riverside Counties, California, Laboratory of Nuclear Medicine and Radiation Biology. University of California, Los Angeles, Calif.
- Twiss, R.H., G. Bingham, J.E. Burke, C.H. Hall, and J. Sidner, 1980. Potential Impacts of Geothermal Energy Development on Outdoor Recreational Use of the Salton Sea, Institute for Urban and Regional Development, Berkeley, Calif., UCRL-13897.
- U.S. Bureau of Economic Analysis (USBEA), 1979. Personal Income and Earnings by Major Source US, States, and Counties. Regional Economics Division, U.S. Bureau of Economic Analysis, Washington, D.C.
- U.S. Bureau of Reclamation (USBR), 1973. Colorado River International Salinity Control Project, U.S. Bureau of Reclamation, Washington, D.C.
- U.S. Bureau of Reclamation (USBR), 1977. Geothermal Resource Investigation; East Mesa Test Site, Imperial Valley, California. Status Report April 1977. U.S. Bureau of Reclamation, Boulder City, Nevada.
- U.S. Bureau of the Census (USBC), 1978a. 1974 Census of Agriculture, Volume IV Special Reports, Part 2. Ranking Counties and States, U.S. Bureau of the Census, Washington, D.C.
- U.S. Bureau of the Census (USBC), 1978b. Statistical Abstract of the United States: 1978, U.S. Bureau of the Census, Washington, D.C.

U.S. Dept. of Energy (USD OE), 1979. Draft Environmental Impact Statement. Geothermal Demonstration Program, 50 MWe Power Plant, Baca Ranch, Sandoval and Rio Arriba Counties, New Mexico, Department of Energy, Washington, D.C., DOE EIS-0049-D.

U.S. Dept. of Housing and Urban Development (USD HUD), 1971. Noise Abatement and Control: Departmental Policy, Implementation Responsibilities, and Standards, Departmental Circular 1390.2.

U.S. Dept. of State (USDS), 1951. U.S. Department of State, International Boundary and Water Commission, United States and Mexico, United States Section, Minute No. 197.

U.S. Dept. of the Interior (USDI), 1974. Salton Sea Project, California, Federal-State Feasibility Report, U.S. Dept. of the Interior, Boulder City, Nevada.

U.S. Fish and Wildlife Service (USFWS), 1977. "Ten Species of Reptiles; Status Review," Fed. Regist. 42, 57492.

U.S. Fish and Wildlife Service (USFWS), 1978a. "Proposed Endangered or Threatened Status and Critical Habitat for 10 Beetles," Fed. Regist. 43, 35636-35643.

U.S. Fish and Wildlife Service (USFWS), 1978b. "List of Endangered and Threatened Wildlife and Plants, Republication," Fed. Regist. 43, 58030-58048.

U.S. Geological Survey (USGS), 1975. Geothermal Resources Operational Order No. 4. General Environmental Protection Requirements, Office of the Area Geothermal Supervisor, U.S. Geological Survey, Menlo Park, Calif.

U.S. National Institute for Occupational Safety and Health (USNIOSH), 1977. Criteria for a Recommended Standard ... Occupational Exposure to Hydrogen Sulfide, U.S. Dept. of Health, Education, and Welfare, NIOSH, Washington, D.C.

U.S. National Institute for Occupational Safety and Health (USNIOOSH), 1978. Health Hazard Evaluation Determination Report 77-121-490, Pacific Gas and Electric Company Geysers Power Plant, Healdsburg, California, NIOSH, Cincinnati, Ohio, HE-77-121-490.

U.S. National Oceanic and Atmospheric Administration (USNOAA), 1976. Climatological Data. California. 81 Nos. 3 through 12. National Oceanic and Atmospheric Administration, Asheville, N.C.

U.S. National Oceanic and Atmospheric Administration (USNOAA), 1977. Climatological Data. California, 82 Nos. 1 through 4. National Oceanic and Atmospheric Administration, Asheville, N.C.

U.S. National Research Council (USNRC), 1977. Hydrogen Sulfide, Committee on Medical and Biologic Effects of Environmental Pollutants, National Research Council, National Academy of Sciences, Washington, D.C.

U.S. Occupational Safety and Health Administration (USOSHA), 1978. "Occupational Safety and Health Standards. Occupational Exposure to Benzene," U.S. Dept. of Labor, Occupational Safety and Health Administration, Fed. Regist. 43, 5918-5970.

Van de Kamp, P.C., 1973. "Holocene Continental Sedimentation in the Salton Basin, California -- a Reconnaissance," Geol. Soc. Am. Bull. 84, 827-848.

Van Note, R.H., J.L. Featherstone, and B.S. Pawlowski, 1978. "A Cost-Effective Treatment System for the Stabilization of Spent Geothermal Brines," in: Second Well-Testing Symposium, Lawrence Berkeley Laboratory, Berkeley, Calif., LBL-8883, pp. 29-33.

Van Til, C.J., 1979. Guidelines Manual for Surface Monitoring of Geothermal Areas, Lawrence Berkeley Laboratory, Berkeley, Calif., LBL-8617.

Vigil, P.J., 1979. A State-of-the-Art Review of the Behavioral Toxicology of Hydrogen Sulfide, Reference Dynamics, Santa Rosa, Calif., UCRL-15093.

VTN Consolidated, Inc., 1978. Draft Environmental Impact Report. Heber Geothermal Demonstration Project. VTN Consolidated, Inc., Irvine, Calif.

Walter, R.A., C.M. Bloomster, and S.E. Wise, 1975. Thermodynamic Modeling of Geothermal Power Plants. Battelle Pacific Northwest Laboratories, Richland, Wash., BNWL-1911.

Walton, A.H. and W.S. Simmons, 1978. Public Health Considerations Relative to The Geysers Power Plant, Flow Resources Corporation, San Rafael, Calif., TR-14500(R).

Walton, W.C., 1970. Groundwater Resource Evaluation, McGraw-Hill, New York.

Welch, J.E., F.H. Harlow, J.P. Shannon, and B.J. Daly, 1965. The MAC Method. Los Alamos Scientific Laboratory, Los Alamos, New Mexico, LA-3425.

WESTEC Services, Inc., 1979a. North Brawley Ten Megawatt Geothermal Demonstration Facility. Final Environmental Impact Report. WESTEC Services, Inc., San Diego, Calif.

WESTEC Services, Inc., 1979b. Imperial Valley Action Plan. Proposed Transmission Corridors. Final Phase I Report. WESTEC Services, Inc., San Diego, Calif.

White, D.F. and D.L. Williams, Eds., 1975. Assessment of Geothermal Resources of the United States -- 1975. U.S. Geological Survey Circular 726.

Wilby, F.V., 1969. "Variation in Recognition Odor Threshold of a Panel," J. Air Pollut. Control Assoc. 19, 96-100.

Winikka, C.C. and P.D. Wold, 1976. "Land Subsidence in Central Arizona," in: Land Subsidence Symposium, Proc. 2nd International Symp. on Land Subsidence, Anaheim, Calif. 13-17 December 1976. IAHS-AISH Pub. No. 121, pp. 95-103.

Zerwas, M.A., C.R. Witmer, R.E. Freeman, A. Salazar, and K. Semran, 1979. Occupational Health Assessment of the Geothermal Hydrothermal Convection Industry, SRI International, Menlo Park, Calif.

APPENDIX A Selected Conversion Factors

To convert from	to	multiply by
1. Area		
feet ²	acre	2.3×10^{-5}
acre	meter ²	4047
meter ²	hectare	1.0×10^{-4}
hectare	kilometer ²	1.0×10^{-2}
2. Volume		
gallon	acre-feet	3.1×10^{-6}
gallon	liter	3.785
liter	meter ³	1.0×10^{-3}
acre-feet	meter ³	1233
3. Mass		
pound	gram	453.6
milligram	gram	1.0×10^{-3}
gram	kilogram	1.0×10^{-3}
4. Length		
inch	centimeter	2.54
feet	mile	1.89×10^{-4}
feet	meter	0.3048
mile	meter	1609
meter	kilometer	1.0×10^{-3}