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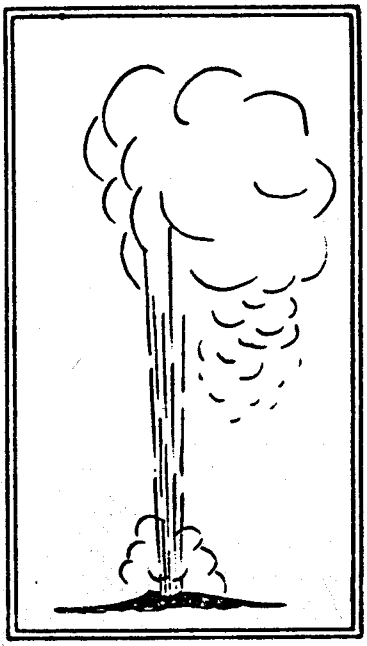
State-of-the-Art of Liquid Waste Disposal for Geothermal Energy Systems: 1979

June 1980



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FOREWORD

This review of the state of the art of geothermal liquid waste disposal has been prepared for the Division of Environmental Control Technology of the Department of Energy. It is a result of the combined efforts of a multidisciplinary team of researchers. Much of the technical information was written by Bill McSpadden. Don Shannon and Gordon Zima supplied information on materials, corrosion and scaling problems. Geology and hydrology input cames from Dick Wallace and Jim Stottlemyre. Laurie Brown reviewed the oil and other industrial experience in liquid waste disposal. Economic criteria and evaluations came from Clem Bloomster, Linda Fassbender, and Kevin Wells. The environmental aspects of geothermal waste disposal were treated by Albin Brandstetter, and Ron Walters and Jon Zuck analyzed the legal and institutional aspects. Jimmy Jacobson and Joe Upton reviewed the document and supplied additional input. W. A. Wahler and Associates provided an independent review of the document. Gunnar Bodvarsson of Oregon State University also participated as a consultant for the project, and Judy Hooper and Cathrynn Novich served as editors.

SUMMARY

This report reviews the state of the art of geothermal liquid waste disposal and evaluates surface and subsurface disposal methods with respect to technical, economic, legal, and environmental factors.

The disposal of geothermal liquid effluents could affect the environment in an adverse manner. Disposal is not only complicated by the wide variability of waste fluid properties (e.g., temperature, pH, and chemical constituency), but also by the large volumetric flows involved. The task of waste disposal is also affected by such site-specific variables as geology and environmental setting and by legal requirements and unknown economic factors.

Three disposal techniques are currently in use at numerous geothermal sites around the world: direct discharge into surface waters; deep-well injection; and ponding for evaporation. Our review shows that effluents are directly discharged into surface waters at Wairakei, New Zealand; Larderello, Italy; and Ahuachapan, El Salvador. Ponding for evaporation is employed at Cerro Prieto, Mexico. Deep-well injection is being practiced at Larderello; Ahuachapan; Otake and Hatchobaru, Japan; and at The Geysers in California. All sites except Ahuachapan (which is injecting only 30% of total plant flow) have reported difficulties with their systems.

This report also reviews disposal techniques used in related industries. The oil industry's efforts at disposal of large quantities of liquid effluents have been quite successful as long as the effluents have been treated prior to injection.

This study has determined that seven liquid disposal methods--four surface and three subsurface--are viable options for use in the geothermal energy industry (see page 8.35). However, additional research and development is needed to reduce the uncertainties and to minimize the adverse environmental impacts of disposal.

EVALUATION OF GEOTHERMAL LIQUID WASTE DISPOSAL TECHNIQUES

	TECHNICAL ASPECTS							LEGAL ASPECTS				ENVIRONMENTAL AND SAFETY ASPECTS								
Disposal Method	Experience with method	Equipment	Importance of geology and underground hydrology	Interaction with processes	Useful by-products	Reliability	Cost	Geothermal laws	Environmental laws	Water rights laws	Land use laws	Occupational Safety	Water pollution	Air pollution	Noise pollution	Toxic substance disposal	Solid waste disposal	Induced seismicity	Land subsidence	Comments
Direct Release to Surface Waters	In use (a)	Readily available	Minimal	Very low	No	High	Low	Yes	Yes	Yes	Minimal	Excellent	Moderate	Yes	Yes	No	No	No	Potential	Low cost, good potential for low-temp., direct-heat applications
Treatment and Release to Surface Water	Minimal	Special materials may be needed	Minimal	Moderate (1)	Possibly	Moderate	Moderate	Yes	Yes	Yes	Minimal	Good	Low	Yes	Low	Potential	Yes	No	Potential	Cost of treatment must be kept low
Closed-cycle Ponding	In use (b)	Special materials (pond Liners) needed	Minimal	Very low	Possibly	High	Low (3)	Yes	Yes	Yes	Yes	Good	Low potential	Yes	Yes (5)	Potential	Some	No	Potential	Needs reliable liners and low-cost land in arid regions
Consumptive Secondary Use	Experimental	Readily available	Minimal	Significant (1)	Yes	High	Low	Yes	Yes	Yes	Yes	Good	No	Low potential	Low	No	No	No	Potential	Shows potential for medium- to low-temperature waters
Injection into Producing Horizon	In use (c)	Special Equipment (pumps) needed	High	Significant (1)	Possibly	Moderate (2)	Moderate (4)	Yes	Yes	No	No	Good	Moderate potential	Low	Low	No	Low	Low potential	Low	Very popular, but potentially has some problems
Injection into Nonproducing Horizon	Experimental	Special equipment (pumps) needed	High	Significant (1)	Possibly	Moderate	Moderate (4)	Yes	Yes	No	No	Good	Moderate potential	Low	Low	No	Low	Low potential	Potential	Used primarily where producing zones are highly fractured
Treatment and Injection	Experimental	Special materials may be needed	Moderate (1)	Significant	Possibly	Moderate to high	Moderate	Yes	Yes	No	No	Good	Low	Yes	Low	Potential	Yes	Low potential	Low	Solid disposal may be a big problem

(a) Wairakei, New Zealand; Ahuachapan, El Salvador; Iceland; Klamath Falls, Oregon
(b) Cerro Prieto, Mexico
(c) Ahuachapan, El Salvador and Larderello, Italy

(1) Temporary backup systems needed
(2) Has shown moderate reliability except in highly permeable zones
(3) Depends on liner and land costs
(4) Depends on permeability of receiving zone (lower permeability increases cost)
(5) Good designs reduce noise output

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1.0 INTRODUCTION

Geothermal energy, the natural heat from the earth, is a potential source of usable energy. Temperatures in the earth increase with depth at a world average of approximately 25°C/km. At the base of the continental crust (25 to 50 km), temperatures can range from 400 to 1200°C. The temperature at the center of the earth is much hotter. Due to various local geological formations and activity, the temperatures and temperature gradients in certain locations can be significantly higher than the world average value. At present, geothermal energy is being exploited at such hot spots as The Geysers, CA; Imperial Valley, CA; Larderello, Italy; and Wairakei, New Zeland.

Geothermal energy is essentially unlimited. Most of it, however, is located too far under the earth's surface to be economically extracted. Even though current drilling technology enables us to reach a depth of 10 km (and possibly 15 km in the foreseeable future), the most economical extraction is limited to nearer-to-surface depths of 1 to 5 km. A recent assessment of geothermal resources in the U.S.(1) indicates that an estimated 95,000 to 150,000 MWe--good for 30 years of geothermal energy--is available using current technology from hydrothermal convection systems. A hydrothermal convection system is one in which hot water or steam is produced in a geothermal anomaly and harnessed with conventional-type machines, such as steam turbines.

A geothermal resource has at least four distinguishing characteristics, namely:

- a relatively low temperature (when compared to temperatures in fossil fuel power plants)
- working fluids that may contain very corrosive elements or compounds
- large volumes of fluids
- a multiplicity of by-products within the primary working fluid that must be regarded as a potential resource even though they complicate the handling of the working fluid.

Geothermal energy was first tapped for electric power generation in 1904 in Italy, but only recently has rapid expansion and development occurred. As of 1978, goethermal electric power generation had reached a combined installed capacity of 2000 MWe in seven nations.[1]

Electric power generation uses goethermal energy at an efficiency rate of 10 to 20 percent; consequently, 80 to 90 percent of the thermal energy is released to the environment or returned to the reservoir. Geothermal fluids are more efficiently used in space heating, industrial processes, and agriculture. As of 1975, nonelectric applications consumed approximately 6600 MWt worldwide, of which 5100 MWt was used in the Soviet Union. The United States has no large-scale nonelectric application of geothermal energy at this time, albeit several small systems are in use and many are being investigated. Were geothermal energy given widespread nonelectric and electric applications, it is estimated that this resource could ultimately satisfy 5 to 10 percent of the country's energy needs. The Department of Energy (DOE) has a current national goal to develop 3000 to 4000 MWe of power and 0.2 Quad/yr of direct use by 1985.

One of the major technical problems that must be solved prior to wide-scale development of geothermal energy concerns the disposal of large amounts of liquid from geothermal energy plants. The geothermal industry will have to dispose of a larger volume of brine at a much greater disposal rate than the oil industry accomplishes at present. The East Texas oil field,[2] the largest known oil field in the U.S., produces about 3.2×10^7 ℓ/C(200,0000 bbl) of oil per day and injects about 8×10^7 ℓ/day (500,000 bbl/day) of brine into approximately 80 wells, at an average pumping rate of 42,000 ℓ/hr/well (260 bbl/hr/well).[2] In comparison, the effluent from one 100-MWe plant using 15 percent flashed steam and requiring 9 kg (20 lb) of steam/kWh, will be about 1×10^8 ℓ/day, or 660,000 bbl/day. In addition, most geothermal sites plan to use one injection well for every two producing wells. Highly productive wells would require an even greater injection capacity of about 320,000 ℓ/hr/well (2000 bbl/hr).

In the past few decades, great strides have been made in developing and applying new technology for the use of geothermal resources, especially as regards low-temperature geothermal energy sources. Even geothermal fluids with dissolved solids content in excess of 300,000 ppm (e.g., from the Salton Sea area of California) can be used to generate electricity. However sufficient and encouraging the technical advances have been, the use of the geothermal resources has not kept pace with our pressing needs for energy. The delay is partially caused by a lack of parallel advancement in the legal and regulatory arenas that control the activities of goethermal developers. Consequently, in order to speed the development of geothermal systems, we need to acquaint ourselves with policy and satutory considerations.

Geothermal development has been reviewed in terms of its environmental impact on air and water quality. Although some concern has been raised about air pollution from H_2S and possible water pollution from liquid wastes, many people consider geothermal energy to be among the cleaner sources of power available. In contrast to forms of energy that involve mining, fuel processing, transportation, and other handling facilities, geothermal developments confine all resource utilization activities to the immediate vicinity of the energy source.

The following liquid waste disposal methods are viewed and evaluated in this report:

<u>Surface Disposal</u>

- direct release to surface waters (fresh or saline)
- treatment and release to surface waters
- closed-cycle ponding and evaporation
- consumptive secondary use

<u>Subsurface Disposal</u>

- injection at producing horizon
- injection at nonproducing horizon
- treatment and injection.

Chapters 3, 4, and 5 describe the three major components of the geothermal system: respectively, the reservoir, the physical plant, and the disposal system (see Figure 1.1). Chapter 6 is a review of the liquid disposal experience for industry; Chapter 7 discusses the legal aspects of geothermal waste disposal; and Chapter 8 evaluates the various waste disposal techniques that were identified above. Finally, Chapter 9 provides a list of research and development areas that need to be studied in order to reduce the adverse environmental effects of disposing of geothermal-liquid effluents.

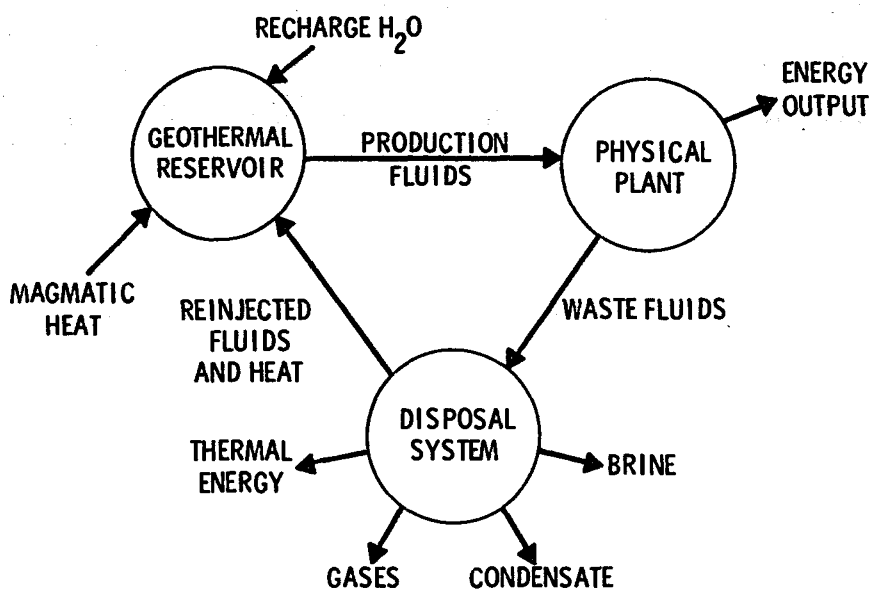

FIGURE 1.1. The General System for Utilization of Geothermal Energy

2.0 CONCLUSIONS AND RECOMMENDATIONS

This study has determined that the seven liquid disposal methods--four surface and three subsurface--are viable options for use in the geothermal-energy industries. However, additional research and development is needed to reduce the uncertainties or to minimize the adverse environmental impacts of disposal.

Subsurface Injection

Present U.S. legal and environmental constraints make subsurface injection the most popular disposal method. Injection into a producing horizon promises to help maintain reservoir pressure and prevent subsidence. Some difficulties with the method have been reported at numerous sites, however. With proper system and equipment design, subsurface injection techniques can be environmentally acceptable, but they will also remain expensive. The oil industry experience indicates that surface treatment of the liquids will be required for most long-term injection programs. Wastes injected into highly fractured zones may not require surface treatment.

Research in support of subsurface disposal must provide information that will permit developers to design their equipment and disposal systems more effectively and at less cost, helping, at the same time, to reduce any adverse environmental impacts. Future research must:

- provide more detailed cost analysis of disposal systems (especially treatment systems)
- identify and evaluate disposal areas for solid wastes generated from liquid waste treatment
- develop tests to determine the compatibilities of the waste fluids and the receiving reservoir
- develop methods to monitor the flow patterns of injected fluids
- develop methods or probes to determine the integrity of the well cement

- develop methods in the reservoir engineering program to predict or identify formations that can accept large quantities of fluids over long periods of time.

Surface Disposal

Surface disposal of geothermal effluents is often favored because of its simplicity and low capital cost. Surface disposal also offers an opportunity to beneficially use the water for domestic, agricultural, or recreational purposes. In spite of these advantages, surface disposal is expected to be used only for low salinity effluents due to strict legal and environmental constraints.

We recommend that research be conducted in the following areas to aid in reducing the potential environmental impacts of surface disposal. We need to:

- complete a more detailed cost analysis of disposal systems, especially treatment systems
- develop a system to remove trace impurities, such as fluorides, arsenic and boron, from waste water
- develop economical and reliable monitors to detect pond leakage
- assess long-term effects of discharging wastes into the ocean.

3.0 GEOTHERMAL-ENERGY RESERVOIRS

When a body of molten magmatic material from beneath the earth's crust intrudes within a few kilometers of the surface and cools slowly over geologic time, there exists a possibility of a useful geothermal-energy resource. These intrusions can often be detected by the presence of hot springs, geysers, and fumaroles, or by changes in geochemical, geophysical, and geological characteristics of the surrounding rocks. One diagram of an intrusion and a geothermal-energy reservoir is shown in Figure 3.1.

The essential characteristics of a useful geothermal-energy reservoir are:

- a heat source within an economically exploitable depth
- a source of fluid to transport the heat to the surface
- a geothermal-energy reservoir region of sufficiently high rock permeability (for fluid flow in the rock)
- a cap rock or seal over the reservoir to sufficiently confine the heat and pressure.

A cap-rock region owes its existence to a self-sealing property of geothermal-energy reservoirs, wherein hot water and steam escape upward from the reservoir and leave mineral deposits, which tend to reduce the rock's permeability, thereby creating a seal over the reservoir. As a direct consequence of this seal, the geothermal-energy reservoir high temperatures and pressures.

Two types of geothermal reservoirs - hydrothermal and geopressured - are presently being considered for development. The hydrothermal reservoirs can be vapor (steam) dominated like The Geysers area in California, or liquid (water) dominated like the geothermal sites in California's Imperial Valley. The temperatures of the water or steam in hydrothermal reservoirs are known to vary up to at least 350^{o}C (662^{o}F). The geopressured reservoirs can have

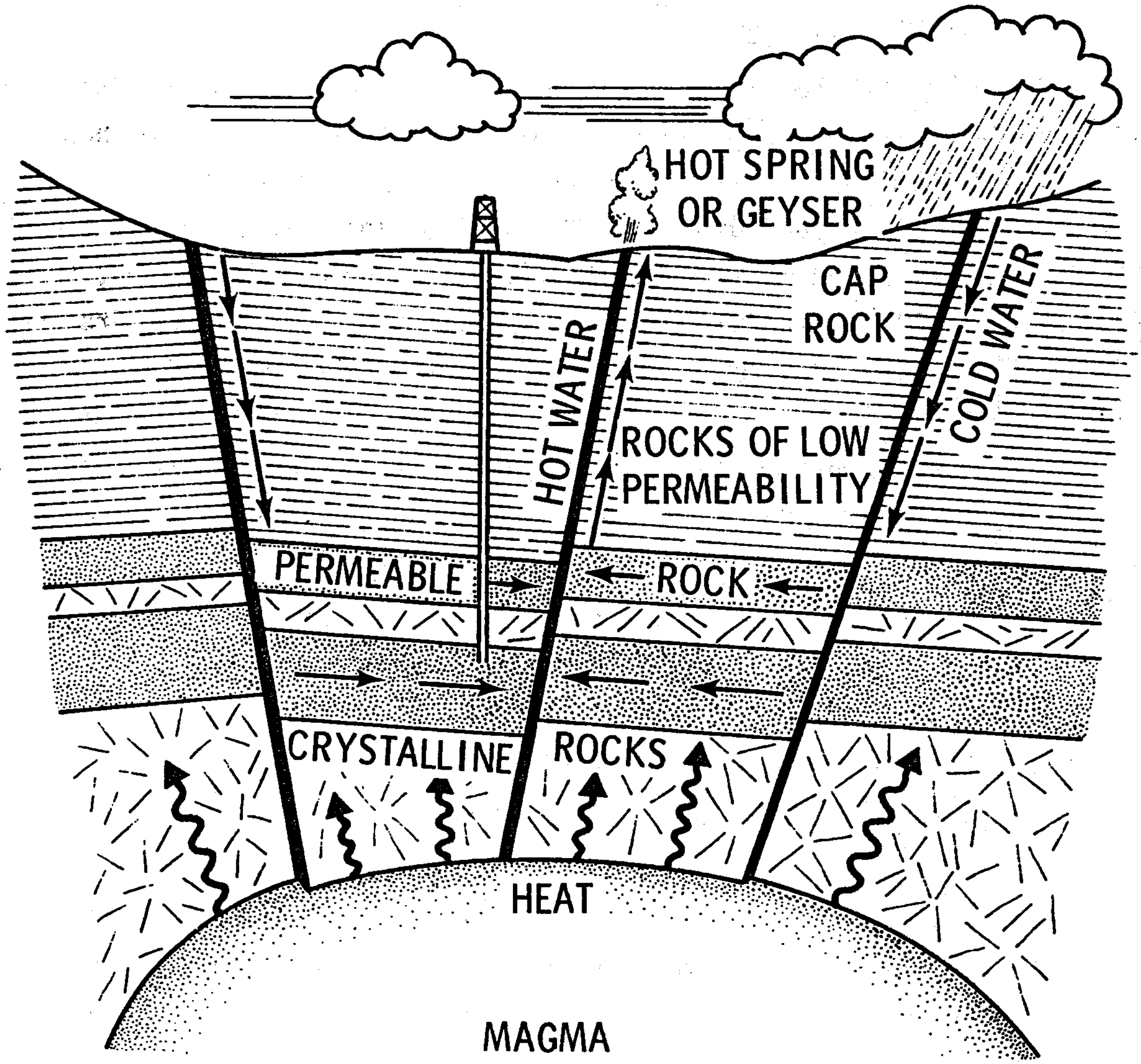

FIGURE 3.1. Model of Geothermal-Energy Reservoir

bottom hole pressures ranging from 800 bars (9000 psi) to more than 1300 bars (15,000 psi) and temperatures from 120°C (248°F) to over 175°C (347°F).[3] Hot dry rock and magma are two other geothermal energy resources that are currently under investigation, but these sources are not expected to be widely used in the near future and will not be considered in this report.

3.1 HYDROTHERMAL RESERVOIRS

A geothermal-energy reservoir depends upon surface water for its water content. Some geologic structures are such that the surface water has to travel many miles before it reaches the reservoir. Water-dominated geothermal reservoirs are the most common, and the least advantageous for electric power production. Vapor-dominated or steam reservoirs, on the other hand, though more rare, are the most ideal for power generation. Steam reservoirs presently produce about 2/3 of all geothermal-energy electric power in the world. The Geysers field in California is one example of a steam reservoir. Here the quantity of charge water provided by surface runoff is not adequate for maintaining a completely liquid system, and hence, the upper parts of the reservoir become filled with steam.

In water-dominated reservoirs that have sufficiently high temperatures, gas injection into the well may be used to start the fluid flow. As the fluid starts to flow, some of the hot water flashes to steam and a geyser-like eruption occurs at the surface. Once the flow is started, it is generally self-sustaining. Large quantities of water and steam are produced under these conditions.

For steam turbine use, the steam must be separated at the surface. The resulting volume ratio of steam to water is a function of the separator pressure and temperature. For example, at a pressure of 4.46 bars (50 psi), a water temperature of 300°C yields 33 percent steam and 67 percent liquid: 200°C yields 11 percent steam and 89 percent liquid.[4] Flashed-steam systems from water-dominated reservoirs produce about 1/3 of the electric power from geothermal energy. Hot-water systems below temperatures of 150°C may prove useful for power production in binary-cycle plants. These plants use a secondary fluid with a lower vapor point than water (such as fluorocarbon) to drive the turbine. Binary plants are under construction or initial startup at Raft River, Idaho and East Mesa, California.

For the power plants listed in Table 3.1 the reservoir temperatures vary from 150 to 300°C. (Temperatures as high as 350°C have been found in New Zealand and in the Salton Sea area of the U.S.) Reservoir producing zones are located as deep as 300 to 3700 m (1000 to 12,000 ft) under the land surface, although most appear in the 1-2000 m range. The rock composition of the reservoirs varies from fractured shale and sandstone to andesitic volcanics. Regardless of the surrounding geological formations, the rock must be sufficiently permeable to allow the flow of fluids into the production wells with a minimum drop in pressure. Permeability, which is measured in darcy - symbol D - refers to the capacity of a porous rock, soil, or sediment to transmit a fluid without damage to the medium. A bed of rock that passes fluids very easily would have a permeability of 100 millidarcy (mD) or greater, while an impervious rock would have a permeability of 2 mD. In relatively homogeneous formations, such as sandstones, premeability is primarily a function of the intergranular porosity of the rock. Under these circumstances, the rock is said to have <u>primary premeability</u>. Whenever permeability is controlled by the fracture and fault properties of the formation the material is characterized as having <u>secondary</u> or <u>bulk permeability</u>.

Characteristics and Classification of Geothermal Fluids

Geothermal-energy reservoirs may be distinguished by the salinity, temperature and acidity of their fluid systems. Salinity is often measured by the total dissolved solids (TDS) and is an indication of the problems that may be encountered due to scaling, corrosion, precipitation, and fluid disposal in general. Equally important is the acidity (measured in pH) of the geothermal fluids. Table 3.2 shows the wide range of temperatures, TDS, and pH that has been measured for geothermal-energy fluids sampled at a representative cross-section of the world's major geothermal development sites. Some of the fluid specimens were taken at the surface from hot springs and others from subsurface reservoirs that were tapped by way of down-hole well sampling.

TABLE 3.1. Geothermal Reservoirs for Power Productions

Geothermal Power Plant (1976)	1975 Capacity, MWe	Number of Turbines	System Type(a)	Res. Temp., °C	Res. Area, mi^2	No. of Producing Wells	Ave. Well Depth, ft	Production Bore Dia., in.	Comments
The Geysers, U.S.	502	11	DS	250	180	88	3000	8 5/8	Growth: 1400 MWe by 1985. Generation began in 1960 at 12.5 MWe. Geology: Metamorphosed highly fractured Franciscan shale and sandstone. Meso--oil Disposal: Steam is condensed and reinjected. Noncondensable gases, primarily CO_2 and H_2S, are vented to atmosphere
Larderello, Italy Monte Amiata, Italy	420	15	DS	200	150	467	3300	13 3/8	Growth: Generation began in 1904. Geology: Cavernous limestone and anhydrite with impermeable schistous clays above. Disposal: Condensate gases to natural drainage. High in boron.
Wairakei, New Zealand Kawerau, New Zealand Broadlands, New Zealand	193	7	FS	270	900	61	2500	7 5/8	Growth: 300 MWe projected. Production began in 1958. Geology: Rhyolitic pumice breccia and open jointed welded tuft, in region of volcanism and faulting. Pleistocene. Disposal: Brine is discharged into a large river. Land subsidence is occurring.
Hachimantai, Japan	10	1	?	?	?	?	3000	?	Growth: Production started in 1971. Data lacking.
Hatchobaru, Japan	50	2	FS	?	?	?	?	?	Growth: Under construction, data lacking.
Matsukawa, Japan	20	1	DS	240	•	5	3600	7 5/8	Growth: 60 MWe expected by 1980. Production started in 1966. Geology: Andesitic volcanics. Pleistocene. Disposal: Condensate discharged into natural drainage.
Onikobe, Japan	25	1	DS	280	?	12	3000	?	Growth: Construction started April 1973. Completion due 1975.
Onuma, Japan	10	1	FS	260°	?	3	4500	?	Growth: Operation began in 1973 at 4.8 MWe.
Otake, Japan	13	1	FS	200°	?	5	3000	7 5/8	Growth: Operation began in 1967 at 12 MWe. 60 expected by 1980
Cerro Prieto, Mexico	75	2	FS	300	10	15	4500	7 5/8	Growth: 150 MWe by 1982. Geology: Highly fractured sandstone and shale at The San Jacinto Fault Zone. Late Tertiary. Disposal: Brine follows natural drainage to Gulf of California. Condensed steam supplies potable water.
Pathe, Mexico	3.5	1	FS	150	?	12	1000	?	Growth: Experimental plant started in 1958. No expansion planned.
Namufjall, Iceland	3.0	1	FS	260	20	4	2200	?	Growth: 3 MWe plant in operation since 1969. 60 MWe construction started in 1974.
Krafla, Iceland	60								Geology: Late Quaternary centers of dacitic and rhyolitic volcanism.
Paratunka, USSR	0.75	1	HW	82	?	8	1300	7 5/8	Growth: Binary cycle operation with Freon began in 1964.
Pauzhetka, USSR	5.0	2	FS	170	?	8	1000	?	Growth: Operation began in 1967 at 3 MWe. Expansion to 20 MWe is planned.
Makhachkala, USSR	12	?	FS	160	?		12,000	?	Growth: Under construction.
Ahuachapan, El Salvedor	30	1	FS	230	10	?	1500	?	Growth: 60 MW in 1977. 95 MW total. Generation began in 1975. Geology: Fractured andesitic lavas. Disposal: Surface disposal to the Rio Paz River at present. In the future will use other means.

(a) System type: DS = dry steam, FS = flashed steam, HW = hot water (not flashed).

TABLE 3.2. Characteristics of Geothermal Fluids from Selected Geothermal Sites

Well and Location	Temperature, °C	TDS, ppm	pH	Type
Joseph O'Neil, Sportsman #1 Salton Sea, CA	310 - 340	334,880	4.82 - 6.10	Brine, high temperature
Cesano 1 Well Northern Latium, Italy	204	356,000	8.50	Brine, high temperature
State of California #1 Salton Sea, CA	304	219,500	No record	Brine, high temperature
Sen Kyoko Nobwell Hakone, Japan	100	175,000	1.4	Brine, medium temperature
MHq MHMAX #3 Salton Sea, CA	240	116,100	5.14	Brine, high temperature
Pioneer Development # 3 Salton Sea, CA	Not available	110,000	6.5	Brine,
Reykjanes Spring Reykjanes Peninsula, Iceland	100	52,160	6.2 - 6.99	Brine, medium temperature
Drillhole No. 2 Sousaki, Greece	250	44,550	6.5	Brine, high temperature
M-3 Cerro Prieto, Mexico	292	25,000	6.2	Saline, high temperature
Well #3 Svartsenqi, Iceland	236	27,300	6.15	Saline, high temperature
AH-1 El Salvador	210	22,000	7.4	Saline, high temperature
Nowlin #1 Heber, CA	190	12,900	Ave = 6.72 6.45 - 7.1	Saline, high temperature
Kaseman #2 James River Basin, NM	170	11,300	7.0	Saline, high temperature
Phillips Well 54-3 Roosevelt, UT	Ave = 277 260 - 294	6,442	6.5	Brackish, high temperature
No. 1 Hatchobaru, Japan	300	4,720	8.15	Brackish, high temperature
Bore 67 Wairakei, New Zealand	250	4,400	7.8	Brackish, high temperature
IC-4 Ching Shui Area, Taiwan	190	4,255	8.5	Brackish, high temperature
HGP-A Hawaii	260	2,500		Brackish, high temperature
GW-8 Puqa, India	224	2,000	7.9	Brackish, high temperature
GO-2 Onikobe-Katayama, Japan	294	2,065	6.9	Brackish, high temperature
E 101 Tatum Area, Taiwan	160	1,735	2.1	
Hole G-3 Hveraqerdi, Iceland	216	1,036	9.6	Brackish, high temperature
Well #1 Wabuska, NV	155	1,050	8.76	Brackish, high temperature
Warner #1 & 2 Warner, CA	139	330 - 340	9.5 - 9.6	Fresh, medium temperature
Slant Hole Empire, DH-1 Marysville, MT	110 - 180	176	7.4	Fresh, medium temperature

Following Renner, White, and Williams,[1] we can classify geothermal-energy fluids by temperature:

	Temperature	Type	Application
Class 1:	> 150°C	High temperature	Power generation Industrial applications
Class 2:	90 - 150°C	Medium temperature	Industrial applications Space heating
Class 3:	< 90°C	Low temperature	Space heating Agriculture Balneological baths

Similarly, we may classify fluids by salinity using TDS as a measure of salinity:

Class A:	<1000 ppm	(fresh water)
Class B:	1000 - 10,000 ppm	(brackish water)
Class C:	10,000 - 36,000 ppm	(saline water)
Class D:	>36,000 ppm	(brine)

This system,[5] which is well suited for geothermal-energy fluid classification, is a modified version of one designed by the American Water Works Association (AWWA).[a] Using a combination of the above classifications, we can assign fluids to one of 12 categoires: 1A, 2A, 3A, 1B, 2B, 3B and so forth. Electric-power-producing reservoirs with temperatures of 150°C or greater would fall into the 1A to 1D categories. 1A would be more desirable than 1D because of the lower TDS.

(a) The AWWA system of classification is:

< 500 ppm	drinking water
≤1000 ppm	fresh water
1000 - 3000 ppm	slightly brackish
3000 - 10,000 ppm	moderately brackish
10,000 - 33,000 ppm	highly brackish
33,000 - 36,000 ppm	sea water
36,000 or greater	brine

Figure 3.2 illustrates the classification system using data points from Table 3.2. TDS tends to increase proportionately with temperature, but the scatter band is wide. To further classify fluids, the nearest integer pH number of the fluid can be included in the code. For example, a high-temperature, low-TDS, and neutral-pH fluid would be 1A7; whereas a hot, briney, acidic fluid would be 1D2.

From the standpoint of corrosion, the acidity of the fluids may be more important than their salinity. Geothermal fluids vary from highly acidic to moderately basic. The pH of the samples in Table 3.2 ranges from 1.4 to 9.6 (neutral fluids have a pH of 7.0). The spread is illustrated in Figure 3.3, which also shows no dominant relationship between the temperature and the pH. Corrosion in electrical power plants can be controlled if the pH of geothermal fluids is greater than 7.0. Chemicals may be added to the geothermal energy fluids to raise the pH to the desired values. However, the addition of chemicals affects not only the economics of the operation, but also the disposal of fluids.

The chemical constituents found in geothermal-energy fluids are limited only by the number of elements found in the producing reservoir and by their solubility in water at the existing temperatures. Figure 3.4 lists the 26 elements most commonly found in a variety of fluid samples taken from around the western U.S.[6] The dominant elements are sodium, potassium, calcium, silicon and chlorine. However, other elements such as arsenic, boron and mercury, which tend to be present only in relatively small amounts, may cause significant disposal problems because of their toxicity. Arsenic (As) concentrations in geothermal-energy fluids, for example, have been found to vary 100-fold from 0.1 to 10 mg/ℓ (see Figure 3.4). By comparison, concentrations in fresh water range from 0.003 to 0.050 mg/ℓ. According to the U.S. EPA's Safe Drinking-Water Act, arsenic concentration may not exceed 0.05 mg/ℓ; the California standard is $\leq$0.01 mg/ℓ. (The primary drinking water regulations were established pursuant to section 1412 of the Public Health Service Act as amended by the Safe Drinking-Water Act.) Typical standards are 1 mg/ℓ for food and 0.1 mg/ℓ for beverages. The toxicity of arsenic depends upon the chemical state of the arsenic. In the form of arsenious oxide, a dose of 100 to 300 mg

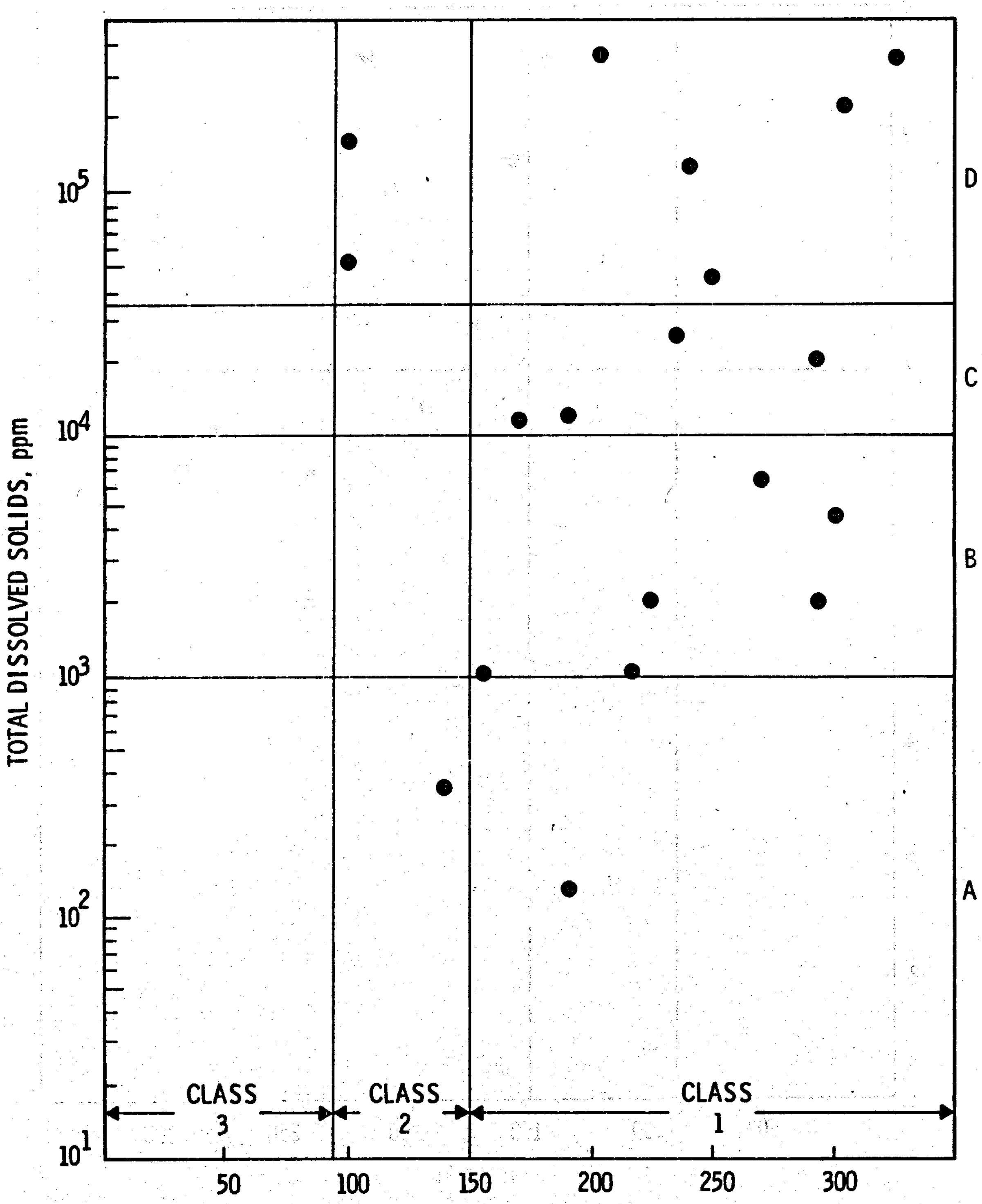

FIGURE 3.2. Classification of Fluids by Temperature and Total Dissolved Solids

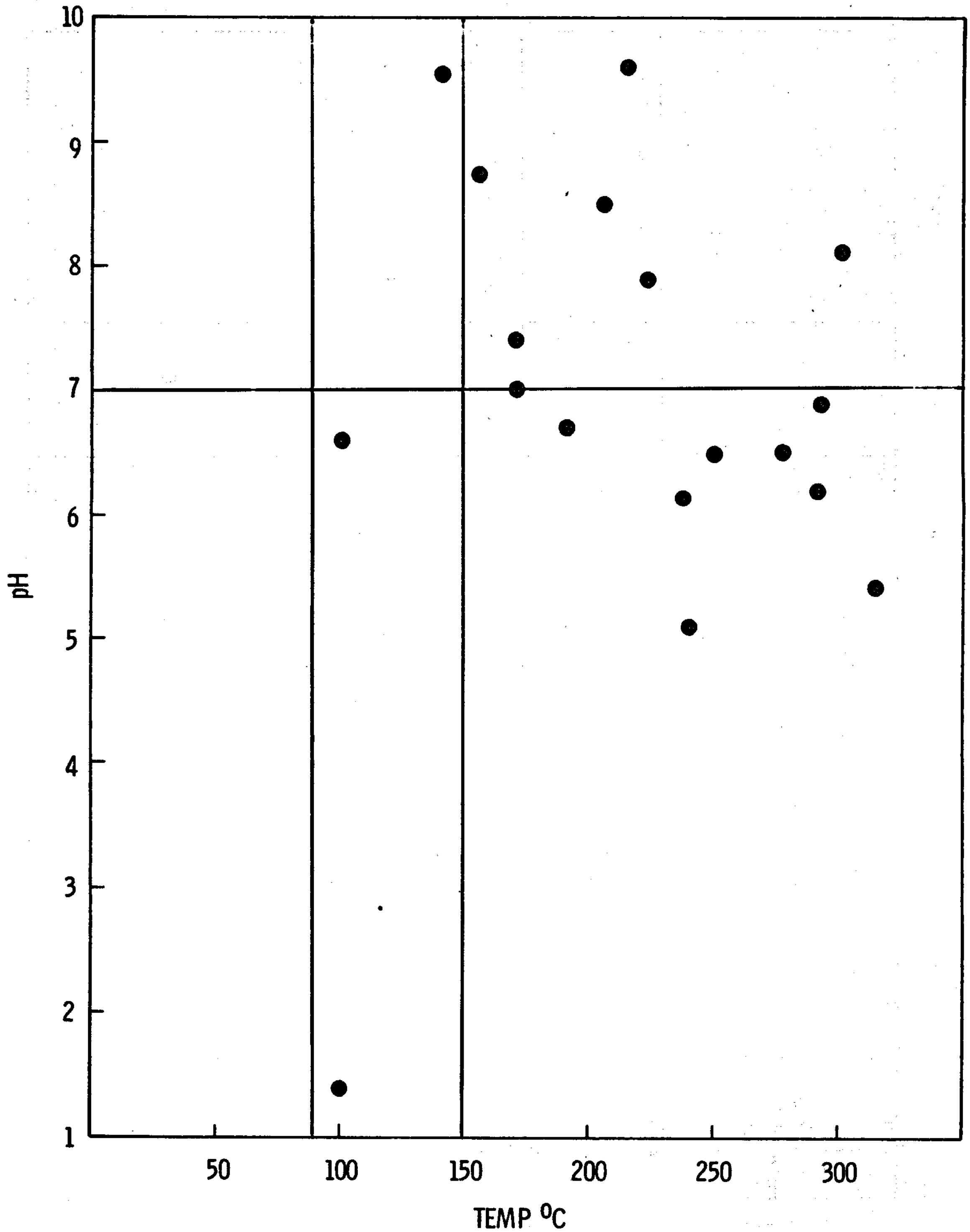

FIGURE 3.3. Classification of Fluids by Temperature and pH

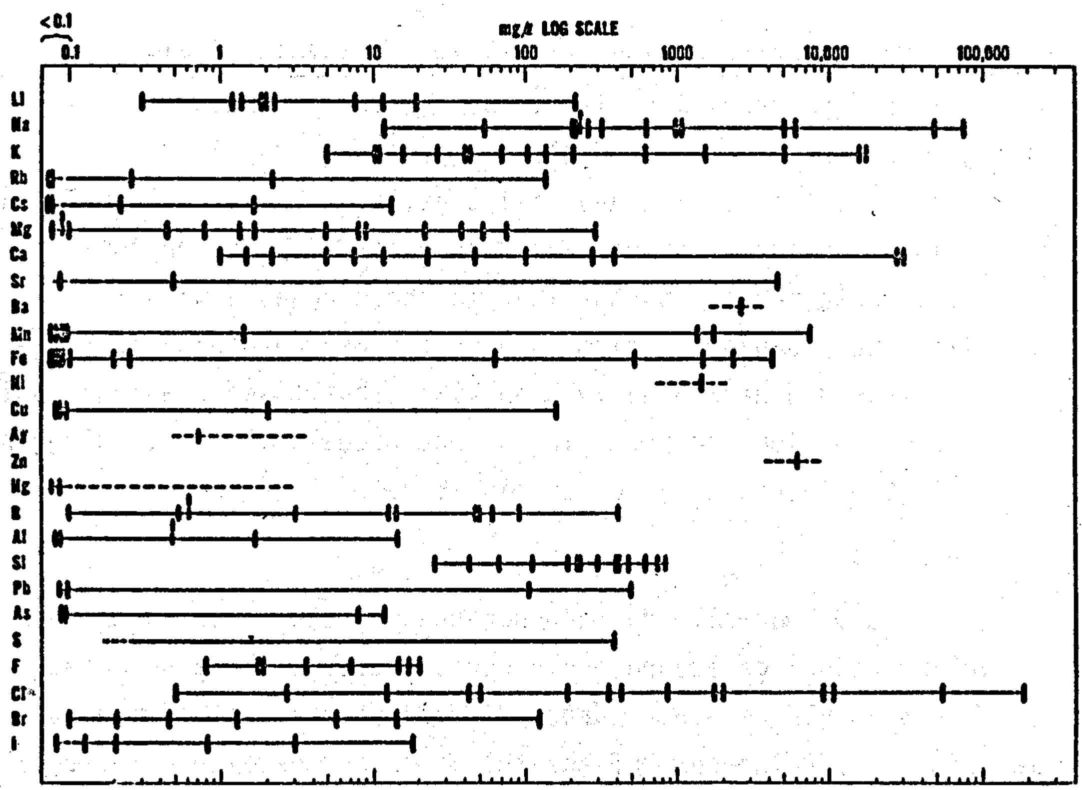

FIGURE 3.4. Concentration Ranges for Elements in Geothermal Waters

is usually fatal to humans. Reportedly, cattle have died in New Zealand after being fed plants grown in geothermal waters contain- ing small amounts of arsenic.[7] Apparently, the plants absorbed and stored the toxic arsenic. Fluids at other geothermal-energy sites, such as Raft River, Idaho, however, are relatively low is dissolved chemicals and are being tested for use in agricultural purposes.[8] Chemical analyses should be undertaken at each site before disposal systems are designed, in order to identify the site specific chemical concentrations in the geothermal-energy fluids.

Chemical constituents may vary during reservoir production as a function of physical changes over time. This phenomenon has been observed in Larderello, Italy, where the water purity increased as fresher recharge-water entered the reservoir. Chemical analysis of the fluids should thus be an ongoing requirement. Data from periodic measurements may indicate a need to modify the chemical treatments and disposal procedures.

While the above classification system may be useful for classifying fluids from geothermal-energy reservoirs, it may not reliably disclose scaling and well-plugging problems. Scaling and plugging are caused primarily by three classes of materials: (a) silica and silicates, (b) calcium carbonate, and (c) metal sulfides, sulfates, oxides and carbonates.[9] One or more of these sources may contribute heavily to the TDS; in these cases a high TDS indicates probable scaling and plugging problems. Some fluids containing mostly sodium or potassium salts would have equally high TDS's, but those readings would be misleading, because sodium and potassium do not necessarily cause plugging and scaling. For further discussion see Section 5.3.

Noncondensable Gases

Geothermal fluids normally contain non-condensable gases which require disposal. The principal gases and their concentrations for a selected set of samples are shown in Figure 3.5. Carbon dioxide is the most common gas and often comprises 70 to 80 percent of the total gas composition. In fact, carbon dioxide from wells at the Imperial Valley, California, and Larderello, Italy have been used for the production of dry ice.

Although a minor constituent of geothermal fluids, hydrogen sulfide presents a difficult disposal problem because of its odor at relatively low concentration levels and toxicity at higher concentrations. It also complicates corrosion problems. At The Geysers, California, hydrogen sulfide constitutes approximately 4.5 percent of the noncondensable gases and 225 ppm of steam. About 30 percent of the hydrogen sulfide is injected into the reservoir with the condensate. Current OSHA standards specify exposure limits of 15 ppm for 15 min of exposure or 10 ppm or 10 hr of exposure. Safety requirements will usually specify that monitors and alarms be installed and that respirator apparatus be available in potentially hazardous areas. Potential problems exist with a number of the other gases, such as hydrogen and mercury, depending on their concentration in the fluids and the methods of disposal.

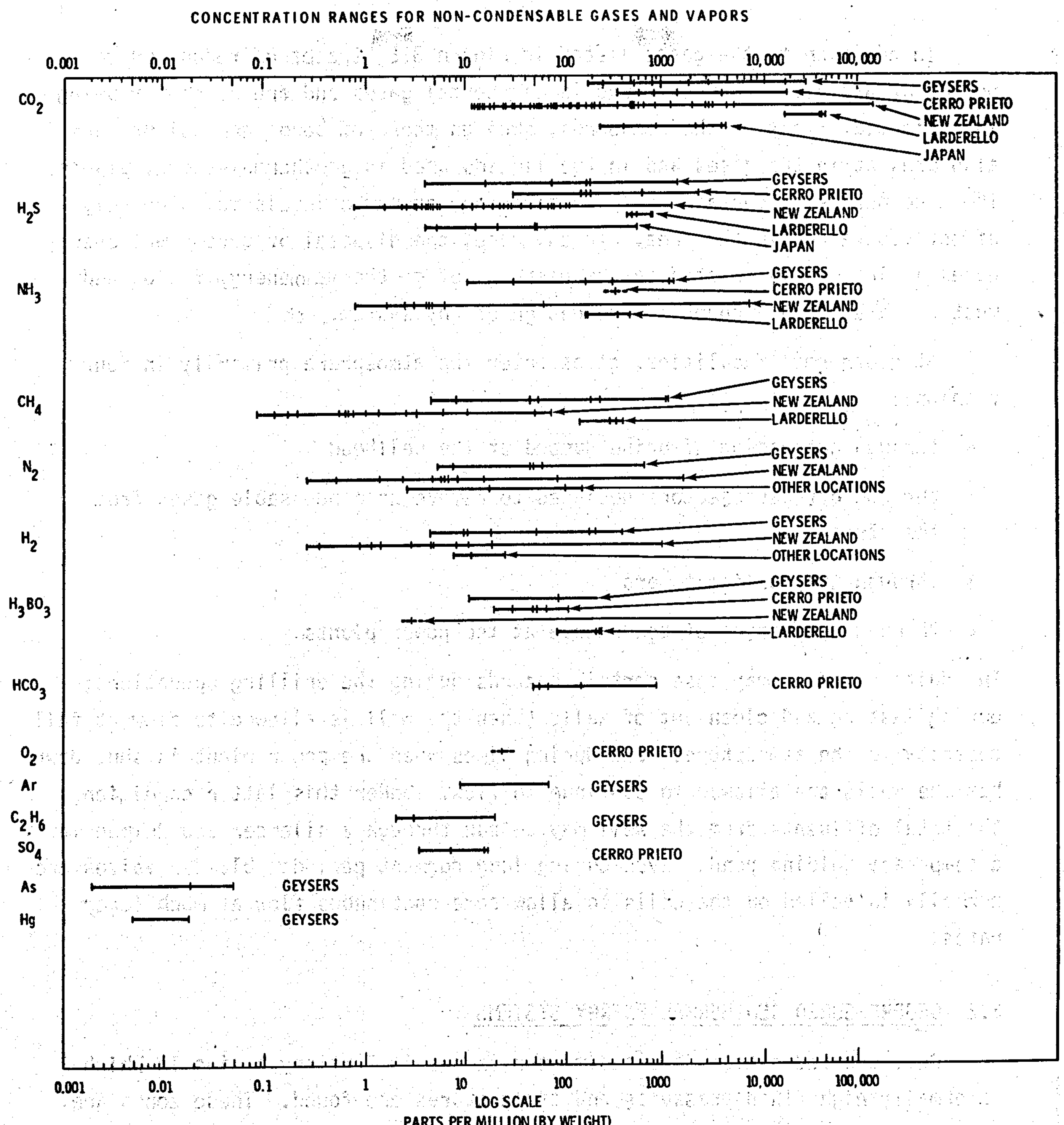

FIGURE 3.5. Samples of Entrained Gases at the Wellhead (In addition, traces of the following may be found: H_3BO_3, HCl, HF, SO_2)

In addition to the gases listed in Figure 3.5, traces of radon and compounds of arsenic have been found in geothermal gases and are currently being investigated. Many of the compounds, such as those of boron and sulfur, are also present in the gases and in the liquids used in geothermal-energy plants. These compounds at certain concentrations and exposure levels may adversely affect vegetation in the area. In any case, the disposal of geothermal-energy gases is integrally related to the disposal of geothermal-energy fluids and must be taken into account in the design of any system.

At geothermal facilities, gases enter the atmosphere primarily in four fashions:

- through outgassing of brine dumped at the wellhead
- through off-gas ejectors designed to remove noncondensable gases from the stream
- through the cooling towers
- through outgassing of condensate at the power plants.

In addition, gases may pose certain hazards during the drilling operations; during testing and clean-out of wells (when the well is allowed to flow at full capacity to the atmosphere); and during times when the power plant is shut down but the wells are allowed to continue to flow. Under this latter condition, the total effluents from the well may be run through a silencer and dumped in a temporary holding pond. Even during long dormant periods, bleeder valves are normally installed on the wells to allow some continuous flow at much lower rates.

3.2 GEOPRESSURED GEOTHERMAL-ENERGY SYSTEMS

Geopressured systems are sedimentary zones in Tertiary basins in which abnormally high fluid pressures and temperatures are found. These zones are found in many places throughout the world. The zones are typically found at depths of 1500 to 3500 m deep, at which point the reservoir pressures exceed the hydrostatic head and, in fact, approach 75 to 90 percent of the lithostatic head.[10] The over-pressure zones occur in layers from a few meters thick to several thousand meters thick, in which the overburden rides on under-compacted clastic sediments (sand and clay or shale). Typically these zones have a porosity 6 to 8 percent greater than would occur at that depth if full compaction took place. Consequently, permeability of these zones tends to be moderate, up to 25 mD. (An interesting feature of these geopressured systems from an energy standpoint, is that the water contains dissolved hydrocarbon gases, in particular, methane.)

Table 3.3 provides estimates of how much energy can be recovered in the Gulf Coast region. The water here is usually slightly alkaline (pH 7.8 to 8.5) and contains total dissolved solids of about 15,000 ppm.

The primary problems in tapping these resources will be the disposal of large volumes of saline water. Surface dumping is a logical choice if the site is near enough to the ocean and subsidence control does not require injection.[12] Injection into a nonproducing reservoir is considered a potential method for disposal if a large enough receiving reservoir can be found. DOE contractors are presently conducting research in Louisiana and Texas to determine the extent of and the feasibility of using the geopressured geothermal-energy reservoirs to produce economical power.

TABLE 3.3. Assessment of "Recoverable Energy" under the Assumed Basic Development Plan, Plan 1. Source: Papadopulos et al., 1975[11]

Reservoir	Available Formation Drawdown, m	Flow rate-Drawdown Ratio, 10^{-5} m^2/s	Well Spacing, km	No. of Wells	Vol. of Water Produced, 10^{10} m^3	Thermal Energy, 10^{18} J	Methane Energy: Volume, 10^{10} std. m^3	Methane Energy: Thermal Equivalent, 10^{18} J	Mechanical Energy, 10^{18} J
AT_1	3,060	4.9	3.1	930	8.80	58.5	96.7	36.5	2.1
ATL_2	2,410	6.2	3.1	2,180	20.64	117.1	173.3	65.4	4.5
BT_1	2,370	6.3	3.9	890	8.43	52.2	80.1	30.2	1.8
BT_2	2,690	5.6	3.5	450	4.20	23.6	32.0	12.1	1.0
CT_1	2,780	5.4	2.6	1,210	11.46	71.5	102.0	38.5	2.6
DT_1	3,250	4.6	2.4	840	7.95	49.6	72.4	27.3	1.9
DT_2	3,090	4.9	3.2	500	4.73	29.3	43.6	16.5	1.1
DT_3	2,580	5.8	3.5	600	5.68	31.9	45.5	17.2	1.3
DTL_4	2,620	5.7	3.7	370	3.50	18.4	25.6	9.7	0.8
DL_5	3,730	4.0	2.9	830	7.86	48.4	62.9	23.7	2.1
DL_6	3,950	3.8	2.5	590	5.59	33.3	46.4	17.5	1.5
ET_1	2,640	5.7	2.4	930	8.80	54.2	77.5	29.2	2.0
ET_2	2,900	5.2	3.2	190	1.80	10.8	16.9	6.4	0.4
ET_3	2,550	5.9	3.2	730	6.91	37.0	53.9	20.4	1.5
ETL_4	2,950	5.1	3.5	280	2.65	13.9	17.8	6.7	0.6
EL_5	3,730	4.0	2.7	1,110	10.51	66.2	84.1	31.7	2.8
EL_6	3,730	4.0	2.6	1,310	12.40	75.1	95.5	36.0	3.3
EL_7	3,680	4.1	2.3	1,180	11.17	59.8	95.0	35.8	2.9
FT_1	2,920	5.1	2.7	310	2.93	18.1	29.9	11.3	0.7
FL_2	3,430	4.4	2.5	750	7.10	40.1	51.8	19.6	1.8
FL_3	4,180	3.6	2.5	980	9.28	52.0	76.1	28.7	2.6
Totals				17,160	162.33	961.0	1,379.2	520.4	39.3

4.0 THE PHYSICAL PLANT

4.1 GEOTHERMAL WELLS AND EQUIPMENT

Geothermal-energy production wells are similar to oil wells with respect to their casing, downhole pipe construction, and wellhead mechanical equipage. This is largely due to the fact that the equipment used to drill, complete, and make safe geothermal-energy wells was originally designed for use in the petroleum industry. The well shown in Figure 4.1 is typical of those used at the Wairakei geothermal-energy field.

The major difference between geothermal-energy wells and oil wells is that oil wells are built with casings in their production zone and geothermal wells generally are not. Additional equipment and special completion techniques are often used for oil wells, because these wells are drilled in soft shale or sand. The lined well shaft is perforated in the production zone; and production tubing is installed and held in place by a production packer. Geothermal-energy wells, on the other hand, when completed in hard rock, often require no casing in the production zone.

Thermal cycling endemic to geothermal-energy wells must be taken into account when designing these energy systems. In changing from full-flow well operation to shutdown, the temperature of the equipment could change by several hundred degrees. As such, the U.S. Geological Survey requires that steel used in the well casing be derated for tensile strength following the American Petroleum Institute (API) guidelines. API data for well casings found in geothermal-energy wells (commonly expressed in English units of measure) are shown in Table 4.1. The casing grades of steel typically used in geothermal-energy wells are J-55, K-55, and N-80.

Wellhead equipment is mounted on a flange that is welded to the surface casing, which normally is cemented to at least one-tenth of the total depth of the well. A thermal expansion spool piece attached to the surface casing allows for free elongation or contraction of the intermediate casing. The spool also accommodates one or more bleeder outlets wherein pressure

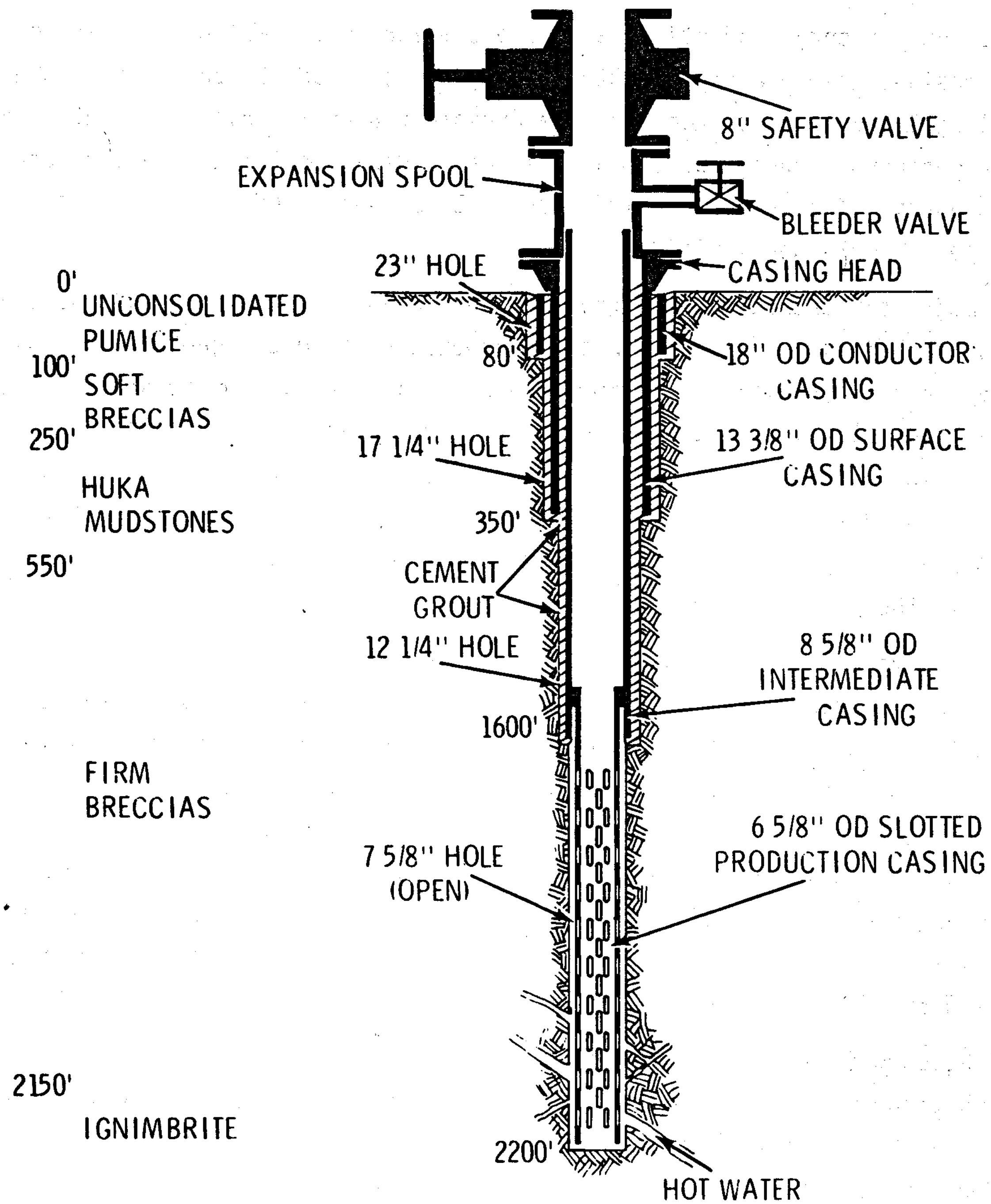

FIGURE 4.1. Typical Casing Profile at Wairakei

TABLE 4.1. American Petroleum Industry (API) Casing List Source: B. C. Craft, et al. (Reference 14)

Outside diameter, in.	Wall thickness, in.	Nominal weight, lb/ft	Available grades[(a)]	Available threads[(b)]
4 1/2	0.205	9.50	F,H,J	S
	0.250	11.60	J	S,L
	0.250	11.60	N,P	L
	0.290	13.50	N,P	L
	0.337	15.10	P	L
5	0.220	11.50	F,J	S
	0.253	13.00	J	S,L
	0.296	15.00	J	S,L
	0.296	15.00	N,P	L
	0.362	18.00	N,P	L
5 1/2	0.228	13.00	F	S
	0.244	14.00	H,J	S
	0.275	15.50	J	S,L
	0.304	17.00	J	S,L
	0.304	17.00	N,P	L
	0.361	20.00	N,P	L
	0.415	23.00	N,P	L
6	0.238	15.00	F	S
	0.288	18.00	H	S
	0.288	18.00	J	S,L
	0.288	18.00	N	L
	0.324	20.00	N	L
	0.380	23.00	N,P	L
	0.434	26.00	P	L
6 5/8	0.245	17.00	F	S
	0.288	20.00	H	S
	0.288	20.00	J	S,L
	0.352	24.00	J	S,L
	0.352	24.00	N,P	L
	0.417	28.00	N,P	L
	0.475	32.00	N,P	L
7	0.231	17.00	F,H	S
	0.272	20.00	H,J	S
	0.317	23.00	J	S,L
	0.317	23.00	N	L
	0.362	26.00	J	S,L
	0.362	26.00	N,P	L
	0.408	29.00	N,P	L
	0.453	32.00	N,P	L
	0.498	35.00	N,P	L
	0.540	38.00	N,P	L
7 5/8	0.250	20.00	F	S
	0.300	24.00	H	S
	0.328	26.40	J	S,L
	0.328	26.40	N	L
	0.375	29.70	N,P	L
	0.430	33.70	N,P	L
	0.500	39.00	N,P	L

(a) Casing grades listed here are those referred to in Sec. 2.2 and Table 2.1 of Reference 4.2.
(b) "S" indicates availability in short threads, "L" in long threads.

TABLE 4.1. (contd)

Outside diameter, in.	Wall thickness, in.	Nominal weight, lb/ft	Available grades[(a)]	Available threads[(b)]
8 5/8	0.264	24.00	F,J	S
	0.304	28.00	H	S
	0.352	32.00	H	S
	0.352	32.00	J	S,L
	0.400	36.00	J	S,L
	0.400	36.00	N	L
	0.450	40.00	N,P	L
	0.500	44.00	N,P	L
	0.557	49.00	N,P	L
9 5/8	0.281	29.30	F	S
	0.312	32.30	H	S
	0.352	36.00	H	S
	0.352	36.00	J	S,L
	0.395	40.00	J	S,L
	0.395	40.00	N	L
	0.435	43.50	N,P	L
	0.472	47.00	N,P	L
	0.545	53.50	N,P	L
10 3/4	0.279	32.75	F,H	S
	0.350	40.50	H,J	S
	0.400	45.50	J	S
	0.450	51.00	J,N,P	S
	0.495	55.50	N,P	S
	0.545	60.70	P	S
	0.595	65.70	P	S
11 3/4	0.300	38.00	F	S
	0.333	42.00	H	S
	0.375	47.00	J	S
	0.435	54.00	J	S
	0.489	60.00	J,N	S
13 5/8	0.330	48.00	F,H	S
	0.380	54.50	J	S
	0.430	61.00	J	S
	0.480	68.00	J	S
	0.514	72.00	N	S
16	0.312	55.00	F	S
	0.375	65.00	H	S
	0.438	75.00	J	S
	0.495	84.00	J	S
20	0.438	94.00	F,H	S

(a) Casing grades listed here are those referred to in Sec. 2.2 and Table 2.1 of Reference 4.2.
(b) "S" indicates availability in short threads, "L" in long threads.

measurements can be made and small volumes of steam or water can be removed to provide some flow from the well. The flow from the well is generally maintained in order to reduce thermal cycling of the well casing and cement, and to reduce the start-up time on the well when higher flows are required.

A safety valve mounted directly above the expansion spool can be operated either manually or by remote control. Sometimes a working valve identical to the safety valve is located above the safety valve, although, more commonly, a by-pass spool is affixed above the safety valve (see Figure 4.2). The by-pass line and the main line both require valves that are essentially identical to the safety valve.

The bypass line, as shown in Figure 4.2, is used to provide an alternate path for the flow when the power plant is not operating or when the well is under test. It is desirable to keep some flow in the well at all times to prevent sand and gravel accumulation. Discharges from the by-pass line can be exceedingly noisy, especially within a 50 m radius. Sometimes they can be heard up to a kilometer away. Consequently, a silencer should be used on the end of the by-pass line. The twin cyclone silencers shown in Figure 4.3 are commonly used and have been found to reduce the noise level to less than 100 db within 30 m of the silencers.[15]

The silencers in Figure 4.3 are approximately 2 m in diameter and 4 to 5 m tall. They dissipate energy and allow steam to separate from the water by cyclone action, which vents the steam upward from the top of the silencer. The water is discharged into a weirbox and then into the remainder of the disposal system. Noncondensable gases and steam will continue to be discharged as long as the silencers are in operation. Under certain atmospheric conditions, the steam itself may present a disposal concern; at Wairakei, for example, steam often drifts across a highway, reducing visibility to essentially zero.

The twin cyclone silencer (Figure 4.3) is relatively expensive to install and does incur maintenance costs because of wear and tear caused by geothermal fluid. The submerged outlet silencer is the most effective and least expensive of all the types of silencers that have been used around the world.

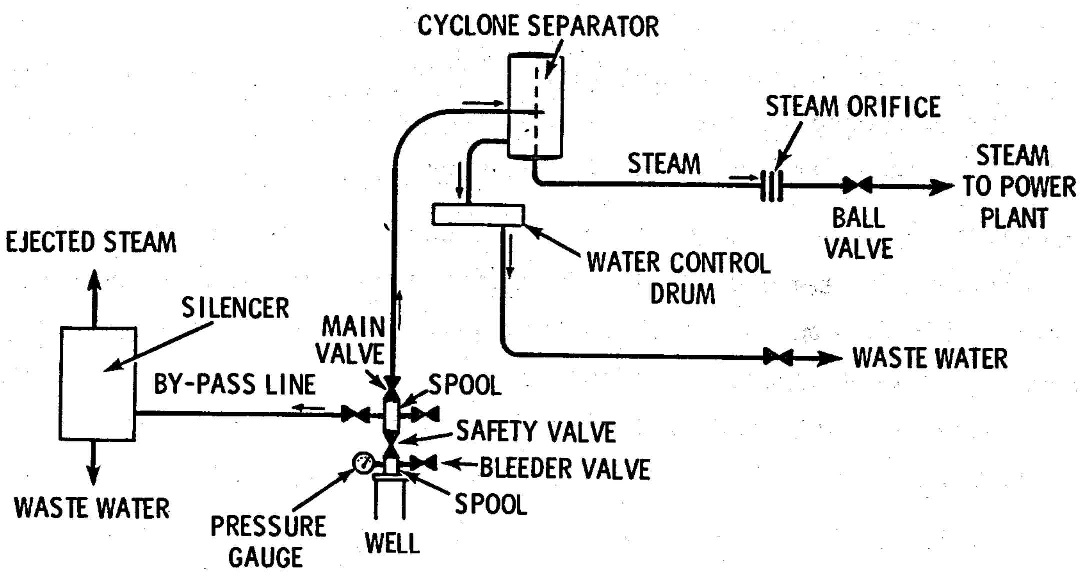

FIGURE 4.2. Diagram of the Wellhead and Associated Equipment

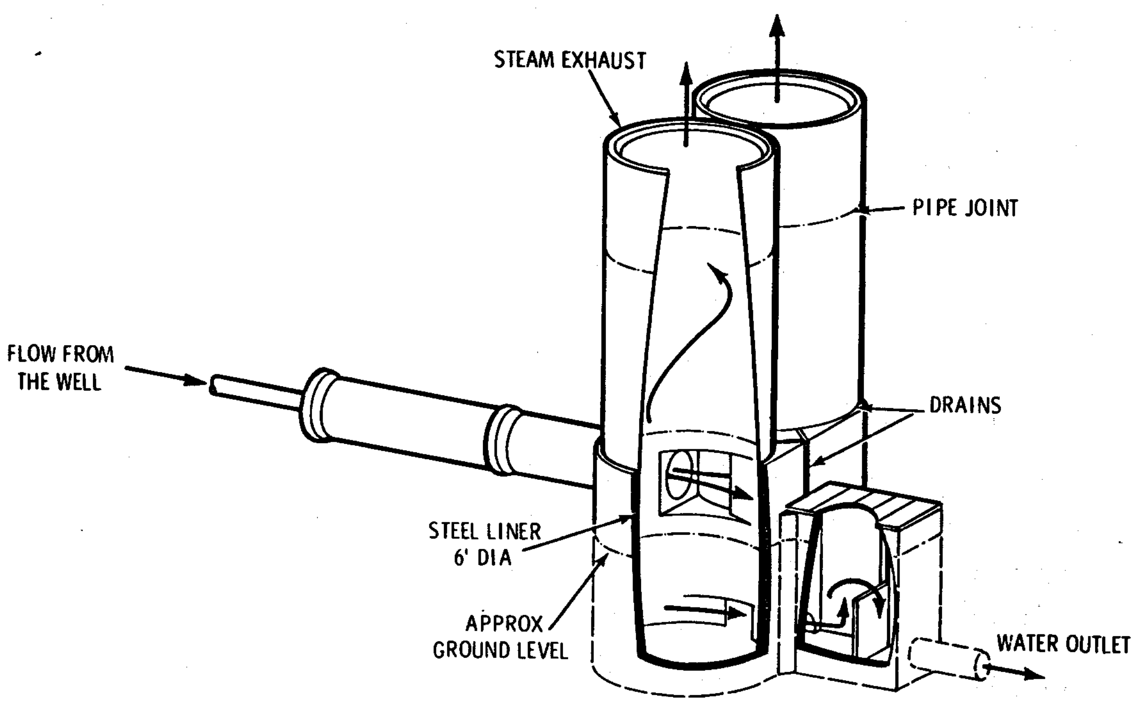

FIGURE 4.3. Twin Cyclone Silencer

If a body of water or a river is available, the open ended by-pass line simply discharges the total wellbore flow into the water body at least one meter beneath the water surface. The discharge line must be firmly anchored to prevent whipping action, and the water depth must be sufficient to quench the steam. At Wairakei, a submerged silencer discharges into a cooling pond through a perforated steel pipe anchored horizontally into the pond and submerged approximately 1 m. In this case, it is important that the surface area of the cooling pond be adequate for dissipating the energy for extended periods of time. Dench[15] found that a cooling pond of approximately 1200 m^2 (1/4 acre) is required to handle the discharge of 16.5 kg/sec (130 klb/hr), based on an average cooling rate of 31.5 kW/m^2 (which assumes a boiling water surface for the pond).

During normal operations of the power plant, the silencers are not in use and the fluids from the wellbore go directly to the cyclone separator (see Figures 4.2 and 4.4). The separator removes high-quality steam from the water at a minimum pressure drop and passes the steam into the power plant's collection system. Steam yields from a water dominated reservoir are approximately

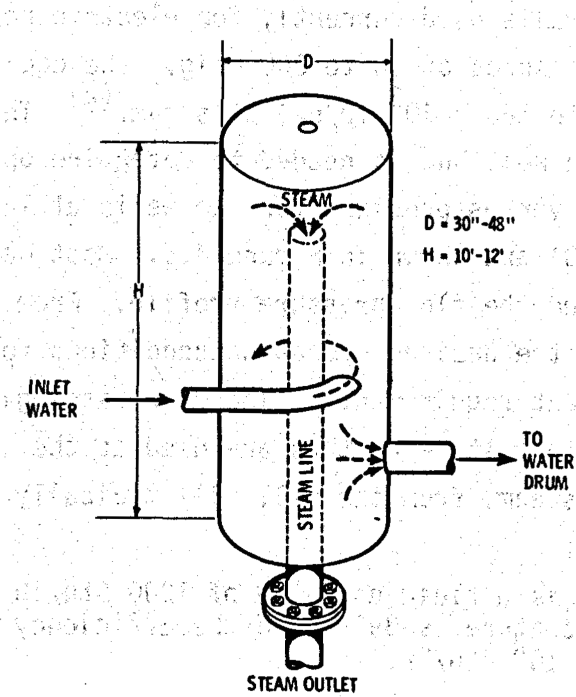

FIGURE 4.4. Cyclone Separator

10 to 20 percent by weight of the fluids coming from the well- bore. The separator can obtain dry steam (about 0.5% mass wetness ratio) at pressure drops of 1 to 10 psig with flow rates from the wellbore up to 126 kg/ sec (one million lb/hr).[16] The separator is approximately 1 m in diameter and 4 m in height. Cyclone separators are effective and operate with low maintenance because of their simplicity, i.e., they do not contain interior baffles or funnels, which could erode or corrode. By removing the steam from the bottom of the separator, mechanical tie-down and vibration problems are greatly reduced.

The main distribution system lines are typically 0.5 to 1.5 m in diameter and are covered with a heavy insulating material. Special design of the distribution system is required to counteract the contraction and expansion that takes place because of thermal cycling.

The water line coming from the cyclone separator goes immediately into a water drum or collection tank that operates under pressure. The discharge line from the water drum contains safety valves and control valves stationed in front of the connection to the waste discharge system.

Geothermal-energy wells used currently for electric power will produce 2 to 8 MWe per well at pressures of 50 to 300 psig. The equivalent flow rates are 5 to 20 kg/sec (40 to 160 x 10^3 lb/hr) of steam.[a] The flow pressure profile differs for each well but is needed to determine optimum operating conditions. Flow rates versus pressure for two wells at The Geysers (Magma No. 1 and Thermal No. 10) are shown in Figure 4.5. Most wells are tested periodically to determine the flow-pressure profile. From these profiles the operators can determine the desired operating conditions for each well with respect to the power plant requirements. The flow rates given above are for steam flow to the turbine. If separators are used at the wellhead, then the total flow (water plus steam) from the well will typically be 4 to 5 times

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(a) The assumption here is a fluid enthalpy of 1200 Btu/lb (typical of The Geysers). The temperature is 390°F and the efficiency is 14%. Note that 1 MW = 3.413 x 10^6 Btu/hr.

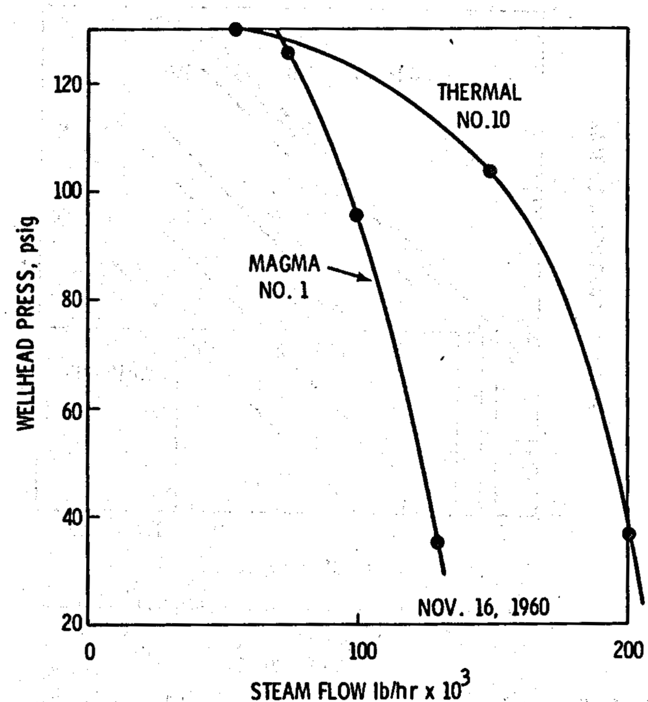


FIGURE 4.5. Pressure-Flow Data from The Geysers
Source: E. F. English (Reference 17)

the flow rates above for water dominated reservoirs. Pressure build-up flow profiles will be required for injection wells. These profiles will be used to optimize the injection flows to each well.

The effects of temperature and flow rate on electric power production have been summarized by Nathenson and Muffler in Figure 4.6. Differences in flow rates between vapor dominated systems and hot water or flashed systems directly affects the design of the disposal system. Also, the lower the water temperature, the greater the volume of fluids that will have to be disposed of for a fixed-size plant.

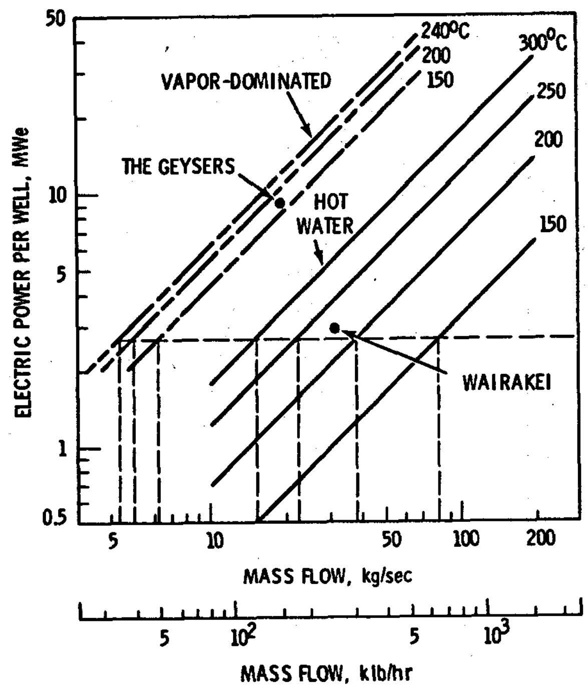


FIGURE 4.6. Electric Power Per Well as a Function of Mass Flow for Various Temperatures of Hot-Water and Vapor-Dominated Systems
Source: M. Nathenson (Reference 18)

4.2 ELECTRIC POWER PLANTS

Flashed or Vapor-Dominated Dry-Steam Systems

The general features of electric power producing plants will be described with the emphasis on those features that affect liquid disposal. The main features of both flashed-steam and dry-steam electric power plants are shown in Figure 4.7. The system may be divided arbitrarily into three major parts: 1) the turbine, generator, and electric system; 2) the steam condensing system and hot-well water reservoir; and 3) the cooling tower and cold-well reservoir. The steam arrives at the power plant at near the wellhead temperature and pressure, less small losses incurred in the steam separator for water-dominated reservoirs and in the transmission and distribution system for both water- and vapor-dominated reservoirs. For vapor-dominated fields, such as

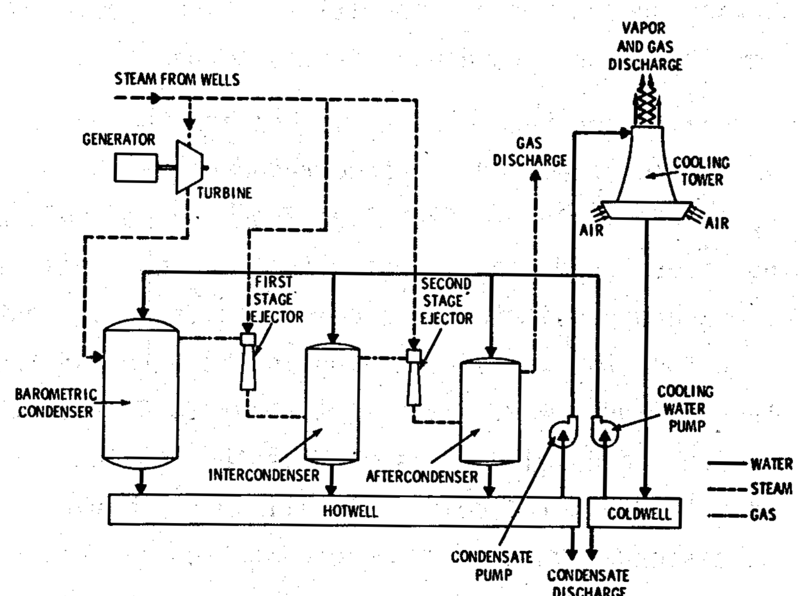


FIGURE 4.7. Electric Power Plant for Flashed-Steam and Dry-Steam Systems

Larderello and The Geysers, the steam is slightly superheated. For water-dominated systems, such as Wairakei, Otake, or Cerro Prieto, the steam arrives at saturation temperature and pressure. For most plants, about 96 percent of the steam flows directly to the turbine and is used to produce electric power and the other 3 to 4 percent is used in the condensers to drive the gas ejectors that remove the noncondensible gases. In plants with high percentages of noncondensable gases, turbo compressors may be used to remove the gas, because they are more efficient for high-volume flow.

The exhaust steam from the turbine flows into a barometric condenser where it is cooled below the vapor point and condenses. A barometric condenser is a large drum in which cold water is injected directly into the turbine exhaust steam. The cold water is obtained from the cold well at the bottom of the cooling tower. The hot water condensate from the condenser is then collected in the hot-well reservoir and pumped to the cooling tower as shown in Figure 4.7. This process differs from that of most fossil fuel plants, where the steam condensate is isolated from the cold water so that it can be returned to the boiler without picking up additional impurities. Since geothermal plants do not have boilers, the barometric condenser proves to be economical.

The hot well is normally located immediately beneath the condensers and may consist of a simple, concrete-lined, covered reservoir in which water temperatures may be 50 to 65°C. An overflow line from the hot well provides a means of discharging excess condensate. Water from the hot well is pumped to the cooling tower, where approximately three-fourths of it is lost to the atmosphere as vapor. Most of the gases remaining in the water of the hot well will be released in the cooling tower. Water (at about 26°C) from the cooling tower flows back to the cold well and is used as the cooling water for the condenser. Any excess water from the cold well will join the overflow from the hot well and enter the disposal system. As opposed to fossil fuel plants, no make-up water is required for the cooling tower. Geothermal power plants inherently provide more water than is needed and, unless 100% injection is required, will have a net excess of water.

Any remaining steam and the noncondensable gases are collected in the top of the barometric condenser and removed by a compressor or ejector as shown in Figure 4.7. If these noncondensable gases meet the discharge standards, they may be discharged through an elevated line and be atmospherically mixed. The gases can be dangerous, both from the toxic standpoint, primarily due to the hydrogen sulfide, and from an explosive standpoint, because of the methane, hydrogen and oxygen mixture. Problems can be alleviated by elevating the gas discharge line to sufficient heights to provide good atmospheric mixing and dispersion. However, most of the geothermal gases are heavier than air and care must be taken that potentially dangerous concentrations do not build up in basements, pits, or low-lying areas. Cerro Prieto has experienced these difficulties and is currently discharging the gases at the waste disposal pond.

<u>The Binary Cycle Power Plant: Liquid Dominated</u>

An alternative power plant that is currently receiving considerable study is the binary cycle plant, in which the geothermal-energy fluids are isolated from the turbine and condenser system as shown in Figure 4.8. This system will

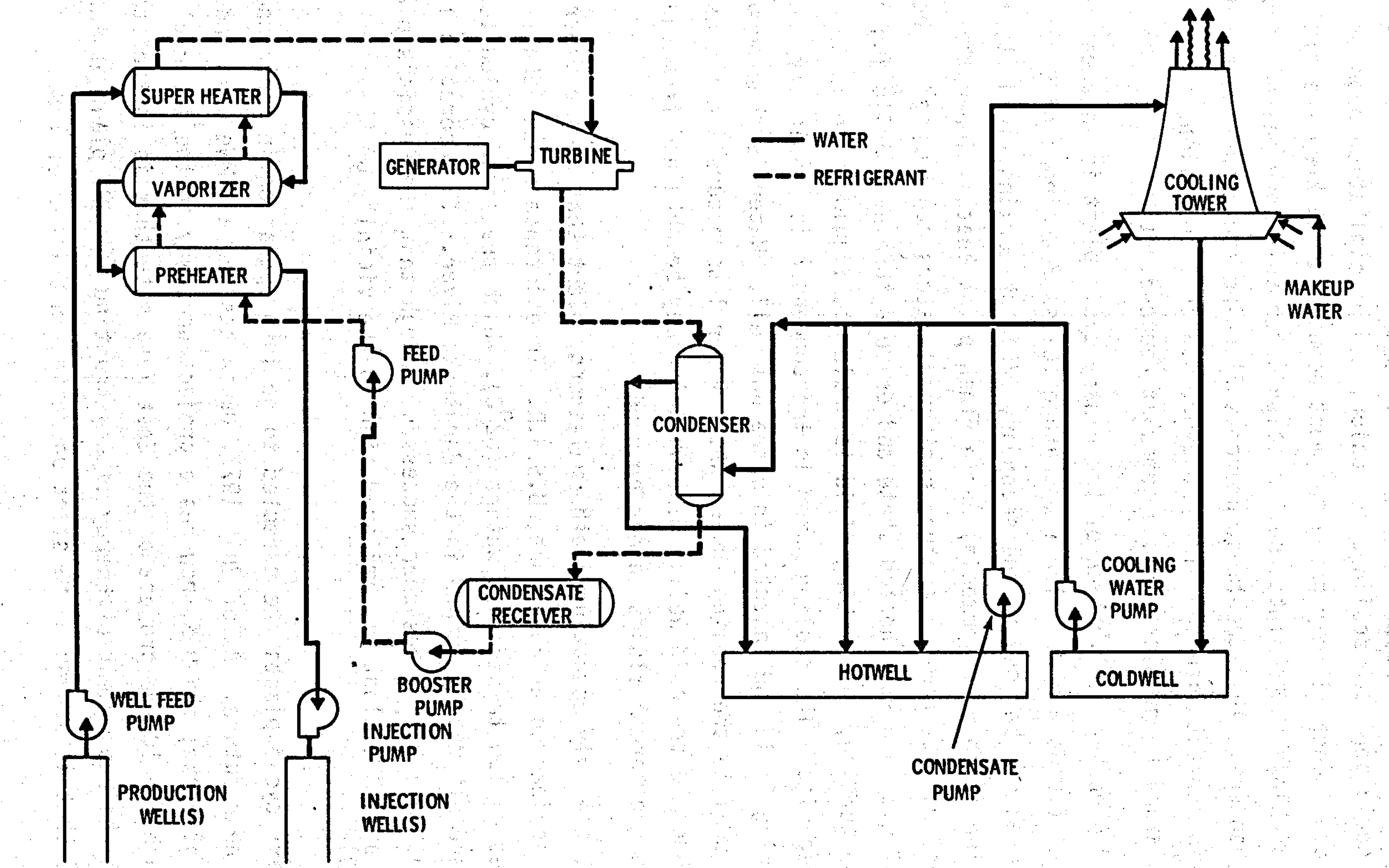


FIGURE 4.8. Sub-Critical Binary Fluid Cycle Power Plant

probably be applied at sites where the geothermal fluids have a high chemical content and could generate scaling, corrosion, and precipitation problems. Under these conditions, it may prove the most economical to keep the fluids pressurized and inject them into the formation after they have passed through the heat exchangers. This treatment prevents flashing and keeps the fluids from coming in contact with the air. However, scaling, corrosion, and precipitation will still be problems though somewhat reduced.

A second probable application of the binary cycle plant is in areas where the geothermal fluids are at a low temperature (Class 3 and part of Class 2). Low temperatures can be used if the secondary fluid or working fluid (typically isobutane, fluorocarbon, or ammonia) has a flash point that is lower than the temperature of water. Low-temperature geothermal waters can be used to heat the working fluid to a superheated state and drive a turbine. Following ejection from the turbine, the working fluid is cooled to liquid state in the condenser and recycled. The cooling water in the condenser is physically isolated from the working fluid and injected into the hot well. Water is then pumped from the hot well to the cooling tower, where vapor loss occurs and the excess water flows back to the cold well. Make-up water may be obtained from surface waters if the geothermal fluids cannot be used.

To date, the only operating geothermal-energy plant that uses a binary cycle system is loacted at Paratunka, U.S.S.R. In existence since 1964, this plant operates on low temperature waters (82^oC), which are later cycled to greenhouses and ultimately dumped in the Paratunka River. The operation is presently shut down but it has been successful enough that the Russians plan to construct a 25 MWe plant of similar design in the vicinity of the prototype.[19]

New binary cycle plants are expected to go into operation in other countries in the near future. As of July 1977, Japan has had a 1 MWe unit under construction at Otake; the U.S. now has a project underway in the Imperial Valley; Magma has a 10 MWe project at the East Mesa site that is in the start-up phase, and the Department of Energy is constructing a 5 MWe plant at Raft River, Idaho, that is scheduled to start operating in October of 1980.

From a waste disposal standpoint, binary cycle plants present fewer problems than other types of geothermal plants if pressurized fluids are injected into the producing horizon. Injection will return most of the unused thermal energy to the reservoir, prevent the release of noncondensible gases, and reduce the corrosion problem by keeping oxygen from the fluids. However, because of their low conversion efficiency, binary cycle plants operating at low temperatures do require proportionately large volumes of fluids.

4.3 NONELECTRIC GEOTHERMAL-ENERGY APPLICATIONS

Most of the literature and recent development associated with the geothermal industry has been devoted to the generation of electric power, but many significant geothermal-energy applications exist in the nonelectric power sector. Up to 1975, nonelectric applications have consumed approximately 6600 MWt, compared with 9500 MWt (or 1480 MWe) for power generation.

Russia has consumed 5100 MWt from geothermal sources, most of which was spent in agriculture to produce over one million tons of vegetables each year. Russia also applies geothermal energy technology to space heating and refrigeration. Both Hungary and Iceland use geothermal-energy fluids to heat homes and commercial buildings. New Zealand utilizes geothermal energy in industry: the pulp and paper mills near the Kawerau electric power plant use over 100 MWt per year for process heating. These countries and others have also utilized geothermal fluids for recreational and health purposes, such as health spas and swimming pools. The nonelectric uses of geothermal energy - space heating and refrigeration, industrial processing, agriculture, and recreational and health purposes - will probably exceed the applications in electric power generation. Nonelectric applications of geothermal energy have the potential for greater thermal efficiency of 30-50% versus 10-20%. Lindal[20] has charted nonelectric-application capabilities in terms of temperature in Figure 4.9.

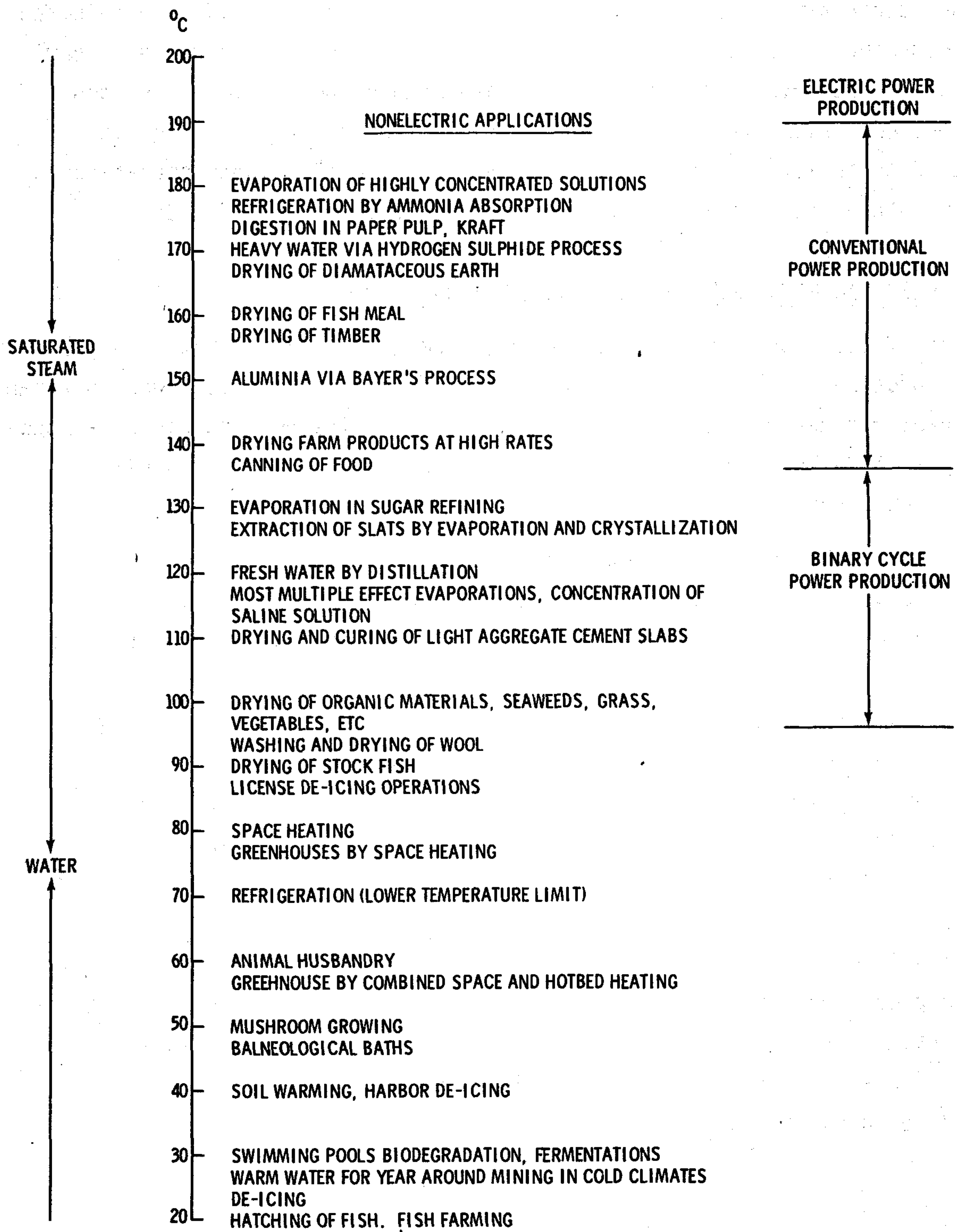


FIGURE 4.9. Geothermal Applications as a Function of Temperature
Source: B. Lindal (Reference 20)

Space Heating and Refrigeration

One of the most obvious and principal applications of geothermal fluids is in the direct heating of homes and buildings, where fluids at temperatures as low as 50°C can be useful. In many cases, the geothermal fluids are relatively noncorrosive and can be piped directly through district heating systems and then used for domestic or agricultural purposes. Iceland[21,22] is now using this method to heat residences for about 127,000 inhabitants in its major cities.

In the U.S., distribution systems for home heating have been developed in Klamath Falls, Oregon and Boise, Idaho. At Klamath Falls, over 350 wells supply heat for numerous houses and over 20 commercial buildings.[23] The entire college campus at Klamath Falls is heated from geothermal fluids.

From the waste disposal standpoint, the primary problems with heating and refrigeration systems will be in the removal and dumping of noncondensable gases, and the dumping or injection of the water after its work cycle is completed. In some power plants, the gases may be exhausted to the atmosphere through a vent line extending above the building heights. However, gas removal equipment may not be economically justifiable, and gases may be allowed to remain in the fluids and become a disposal problem at the system exit. Volumes of water and gas to be disposed of are dependent upon the fluid enthalpy, weather conditions, system characteristics, and the like. Estimates of volume should therefore be made on a site-by-site, application-specific basis.

Additional Industrial Processes

Table 4.2 shows a few of the wide variety of industrial processes that could use geothermal energy for heating, drying, distillation, refrigeration, or chemical processing.[20] Lindal has tried to establish an effective method for evaluating potential applications of geothermal energy.[20] His proposed index is the ratio of the pounds of steam required to produce a unit dollar value of the end products noted in Table 4.2.

TABLE 4.2. The Specific Consumption of Steam and the Steam Used per Dollar Value in Some Established Processes Source: B. Lindal (Reference 20)

Product and Process	Steam Requirements, lb Steam/lb	Product Value, ¢/lb	Steam per Unit Product Value, lb Steam/ $ Value
Heavy water by hydrogen sulphide process	10,000	3,000	333
Ascorbic acid	250	250	100
Viscose rayon	70[a]	75	93
Lactose	40	14	286
Acetic acid from wood via Suida process	35	10	350
Ethyl alcohol from sulphite liquor	22	7	314
Ethyl alcohol from wood waste	19	7	271
Ethyl glycol via chlorohydrin	13	13	100
Casein	13	56	23
Ethylene oxide	11	15	73
Basic Mg carbonate	9	11	82
35% hydrogen peroxide	9	18	50
85% hydrogen peroxide from 35% H_2O_2	4 3/4	--	--
Solid caustic soda via diaphragm cells	8	3	266
Acetic acid from wood via solvent extraction	7 1/2	10	75
Alumina via Bayers process	7[b]	3	234
Ethyl alcohol from molasses	7	7	100
Beet sugar	5 3/4	10	58
Sodium chlorate	5 1/2	9	61
Kraft pulp	4 1/5	6	70
Dissolving pulp	4 1/5	--	--
Sulphite pulp	3 1/2	6	58
Aluminum sulphate	3 1/2	2	175
Synthetic ethyl alcohol	3	7	43
Calcium hypochloride, high test	3 1/3	3	111
Acetic acid from wood via Othmer process	2 3/4	10	28
Ammonium chloride	2 3/4	6	46
Boric acid	2 1/4	5	45
Soda ash via Solvay process	2	1 1/2	133
Cotton seed oil	2	10	20
Natural sodium suophate	1 4/5	1 1/2	120
Cane sugar refining	1 2/3	10	17
Ammonium nitrate	1 1/2	3 1/2	43
Ammonium sulphate	1/6	1 1/2	11
Fresh water from sea water by distillation	1/12	1/60	500

(a) Shreve (1956) quotes 150 lb steam per pound.
(b) Has declined in recent years in most cases.

method for evaluating potential applications of geothermal energy.[20] His proposed index is the ratio of the pounds of steam required to produce a unit dollar value of the end products noted in Table 4.2.

Agriculture

Agricultural use of geothermal fluids is not new, but the incentive for greater development increases as the cost of fossil fuel increases. Potential applications for agriculture are extensive, particularly in the less industrialized countries. It has been estimated that 5 acres of heated soil would produce vegetables year-round for a population of 20,000.[24] Geothermal fluid temperatures of 30°C and 50 to 60°C are appropriate for soil heating and hothouses, respectively. The tremendous potential for agricultural use is best indicated by field experiments that were conducted to measure the effect of soil warming in 1969 near Corvallis, Oregon. The yield of corn increased by 45 percent, tomatoes by 50 percent, soybeans by 66 percent, and beans by 39 percent.[24] The improvement in yields will be location dependent because of local climatic conditions. Geothermal energy might also be used for fruits and vegetables at argricultural processing plants.

5.0 WASTE DISPOSAL SYSTEMS

It is difficult to appreciate the magnitude of the waste disposal problem in regard to the range of contaminants without considering a few trial cases. Assuming that examples from existing power plants will be more meaningful, we have compiled data in Table 5.1 from five of the larger plants (covering both vapor- and liquid-dominated systems) and calculated estimates of waste volumes.

The volumes of waste fluids and gases from geothermal plants are very large. Even if the plant is temporarily shut down, the wells normally are kept operational and, as such, the waste production is continuous.

At The Geysers, California and Larderello, Italy, the production of liquid effluents from condensed steam runs an estimated 7.7 million and 4.8 million metric tons/yr, respectively, and waste gases (primarily CO_2 and H_2S) are about 0.27 million and 1.6 million tons(M)/yr, respectively. If the dissolved solids were removed from the condensate at The Geysers, 4600 tonsM/yr of solid waste would be generated. Although abatement methods using iron compounds have reduced the amount of H_2S released, the amount of solid wastes has increased by a factor of 4 or 5.

At the flashed-steam plants (Wairakei, Cerro Prieto and Hatachobaru), the primary volume of waste comes from the separators and totals about 80 percent of the well flow (see Table 5.1). Thus, Wairakei must dispose of about 60.5 million tons(M)/yr of fluids from the separators plus 1.5 million tons(M)/yr of condensate.

Table 5.1 does not provide data on thermal wastes, but estimates can be readily made from efficiencies. If we assume that the dry-steam power plants extract 15 percent of the energy and the flashed-steam plants 8 percent, then dry-steam and flashed-steam 100 MWe plants will dispose of 567 MWt and 1150 MWt respectively. In dry-steam plants the heat is dissipated in the cooling towers; in flashed-steam plants the heat is divided between the waste waters and the cooling towers. Axtmann[7] notes that while the Wairakei plant was producing 143 MWe, it was discharging 850 MWt into the Waikato River

TABLE 5.1. Estimates of Geothermal Wastes from Existing Power Plants

Power Plant Location	1977 Output, MWe	Reservoir Type[a]	Reservoir Temp, °C	Fluid Production Rates[b]: Well Flow T/MWh	Well Flow T/yr $\times 10^6$	Condensate[c] T/MWh	Condensate T/yr $\times 10^6$	Total Dissolved Solids ppm	Total Dissolved Solids T/yr $\times 10^3$	Gas Wastes % gas/steam wt	Gas Wastes T/yr $\times 10^3$
The Geysers, U.S.	520	DS	200	7.5	4.2	1.7	7.74	600[d]	4.65[d]	0.8	273
Larderello, Italy	420	DS	220	8.9	32.7	1.3	4.78	NA	NA	5	1640
Wairakei, New Zealand	193	FS	260	44.8	75.7	1.8	1.47	4,400[e]	333	2.2	333
Cerro Prieto, Mexico	75	FS	270	31.5	20.7	1.3	0.854	20,000[e]	414	1.2	49.7
Hatchobaru, Japan	50	FS	290	20	8.76	0.8	0.350	4,700[e]	41.2	0.3	5.26

(a) DS = dry steam; FS = flashed steam.
(b) Tonne/MWh = 1000 kg/MWh. Yearly rates of 8760 hr/yr assume continuous well flow.
(c) Condensate flow varies with weather conditions.
(d) TDS at The Geysers in condensate. It varies from 300 to 1000 ppm with weather conditions.
(e) TDS of wellhead fluids. At Cerro Prieto, fluids in the evaporator pond have about 75,000 TDS.

and 725 MWt into the atmosphere. He notes that this waste heat is roughly equivalent to the waste heat from a 1000 MWe fossil-fueled plant operating at about 38 percent efficiency, and that water vapor added to the atmosphere is comparable to that from a 300 MWe, fossil fueled plant. In any case, it is evident that waste disposal at geothermal plants is a major consideration and in the final analysis, could impede site development.

Only two basic methods of liquid waste disposal exist: surface disposal or injection. The technical design criteria are discussed in this chapter, but it must be recognized that the legal constraints (see Chapter 7) may exert a greater influence on the nature of the disposal system than do the technical aspects.

Surface disposal is the most economical disposal method if the spent geothermal fluids can simply be dumped into the local surface drainage system. Condensate was discharged into the Big Sulphur Creek at The Geysers for many years, until the levels of boron and other contaminants in the fluids caused regulators to require injection. Surface disposal continues into the Waikato River at Wairakei even though high arsenic concentrations have been a problem to fish and plants. Injection and ocean discharge were selected at Ahauchapan after several alternatives were studied. However, at Cerro Prieto, Mexico, wastes are ponded and the overflow is drained into the ocean. For some operations, ponding and disposal by evaporation may be practical if the deposits of salts and silica can be removed periodically. Of course, possible recovery of useful minerals from ponding operations should be considered in the design of a disposal system.

The technical design of a disposal system will depend upon economics, safety, technical feasibility and environmental acceptability. Some of the primary engineering considerations are: flow rate of the fluids, temperatures, scale and deposition, corrosion, and the presence of toxic contaminants.

5.1 SURFACE WASTE DISPOSAL

Surface disposal has been practiced at one time or another at all major power plants. The primary advantages of surface disposal are the simplicity of the operation and the favorable economics. For flashed-steam plants, such as Wairakei and Cerro Prieto, discharge lines flow directly into holding ponds for cooling, and canals carry the overflow into the local drainage system. Dry-steam plant condensates can be disposed of in the same manner, but the volume of discharge is less per kWh. Maintenance is relatively simple and consists primarily of removal of scale and precipitates that clog the canals.

Surface disposal is not without some adverse environmental impacts. First, toxic chemicals, such as arsenic, mercury, and boron are often present in sufficient quantities to be hazardous to wildlife, fish, and plant life. The liquid effluents may be hot and acidic, will probably contain salts, and will almost certainly contain silica, which can cause scaling and may precipitate out. Secondly, all of the noncondensable gases will ultimately escape into the atmosphere and could pose problems. A third disadvantage of surface disposal is that the water withdrawn from the reservoir is not used for recharge. Consequently, the reservoir will be depleted if the discharge rate exceeds the natural recharge rate. Simultaneously, the thermal energy in the hot discharge water is lost and cannot be returned to the reservoir. Fourth, the withdrawal of fluids can cause land subsidence in some geological structures.

For all these reasons, new environmental laws have been adopted that affect many disposal sites. At Otake, Japan, for example, injection is required by law. At The Geysers, California surface disposal is forbidden when the concentrations of boron and ammonia in the condensate exceed state standards for surface disposal. Within the context of disposal regulations and despite its disadvantages, surface disposal probably will continue to be a viable option at many sites, especially at plants involved with non-electric geothermal-energy applications.

5.2 INJECTION OF GEOTHERMAL FLUIDS

For several decades, the oil industry has injected saltwater into oil reservoirs to enhance oil production and to control land subsidence (see Chapter 6). Injection into geothermal reservoirs is relatively new and is also motivated by a desire to enhance production in addition to disposing of geothermal liquids. In recent years, the public's awareness of environmental issues and legislation spawned by these concerns have led the geothermal industry to consider injection as a primary method of waste disposal. Fortunately, with proper engineering and design, injection is a feasible disposal method.

Aside from waste disposal, a number of other advantages can accrue from the injection of geothermal fluids into a reservoir. Water returned to the reservoir is conserved and, consequently, can add additional life to a reservoir whose natural recharge is limited. In addition, the injected water from flashed-steam plants may contain considerable thermal energy, which is conserved by putting it back into the reservoir. Land subsidence occurs at Wairakei as a result of the extraction of the geothermal fluids, but injection of the waste fluids should aid in controlling the subsidence. For these reasons, injection may be the most environmentally acceptable method of handling geothermal fluids, but the problem is to do it economically. The potential disadvantage of injection as a disposal method is that one cannot tell, for sure, where the fluid will go. A possibility exists that unknown faults, fractures, highly permeable regions, or unlogged wells may permit channeling of the fluids into potable acquifers or surface waters.

Injection Wells

Injection wells are drilled and cased in essentially the same manner as production wells and, in fact, production wells are sometimes used for injection. Normally a slotted liner is placed in the injection well in the injection region to prevent the downflow of water from causing sloughing and filling of the hole. In production wells this zone is often left open and uncased.

In some instances it is desirable to use an injection well that has been drilled deeper than the producing wells. Deeper injection wells allow the cooler water to become heated before it reaches the producing well, which extends the life of the producing well. Injection need not take place in the same formation from which the fluids were taken; fluids can be injected into a nonproducing zone if the permeability of that zone is high enough.

Injection fluids may flow into the reservoir under the weight of gravity of the column of water in the well. High injection rates can be obtained by this method for geothermal reservoirs that are highly permeable. When the hydrostatic pressure of the reservoirs exceeds the hydrostatic head, however, artesian flow from the wells will occur, and injection can be accomplished only by overcoming this pressure. In the Niland field in the Imperial Valley, Union Oil encountered a wellhead hydrostatic pressure of 200 psi, and injection had to be accomplished by pumping at pressures in excess of this hydrostatic head.

The wellhead valves and equipment are essentially the same for injection wells as for production wells. Relief valves for safety and blowout protection are required.

Such critical factors as the location of injection wells and their depths are dependent upon local geology, geophysics, and geochemistry. Injection wells must be located far enough away from the production wells to prevent undesirable cooling of the production fluids but close enough to maintain reservoir pressure. Both conditions can be met by injecting the cooler water at the periphery of the producing geothermal-energy fields, or at significantly different depths. However, pipeline and pipeline maintenance costs provide incentive to minimize the lineal distances between the power plant and the injection wells. Initially, injection wells should be located 600 to 900 meters outside of the production zone, according to a study by Bodvarsson.[25] After more knowledge of the reservoir is gained, the spacing for injection wells may be changed.

Costs can be lowered by converting inefficient production wells into injection wells, in which case the location is predetermined. Unfortunately, direct water flow between injection wells and production wells along reservoir fractures may occur and quench the production well. Undesirable ducting has occurred at Larderello over a distance of several hundred meters.

In general, the fluid in the reservoir is in motion prior to the injection of the fluids and is controlled by three types of gradients: the hydraulic pressure gradient, the thermal gradient, and the salt concentration gradient. In thick aquifers generally encountered in geothermal reservoirs, these gradients induce convection currents that generally are not present in shallow, constant-density fluid systems. The flow and movement of fluids injected into such a system depend, among other things, on the state of motion in the aquifer prior to injection and the modification of the gradients caused by the injection process.

Mathematical models can be helpful if considerable drilling has been done and information on the reservoir is available.[26,27] However, because the flows tend to depend rather heavily upon bulk permeability and fracture patterns at the actual point of injection, the models can provide little more than general guidance. In most cases, injection wells are located by a combination of modeling, experience, and trial and error.

5.3 CORROSION, SCALING, AND PLUGGING

Geothermal resources have at least four distinguishing characteristics, namely: 1) a relatively low temperature when compared with fossil fueled systems; 2) working fluids that may contain corrosion-aggressive species; 3) large volumes of liquid; and 4) fluids that contain potentially valuable by-products.

The temperatures and pressures of geothermal fluids are relatively moderate compared to fossil fired boilers. The chemical complexity of some of the geothermal fluids more than offset their low temperatures and pressures. Geothermal effluents slated for liquid disposal may be in the same chemical and physical state that they were at the wellhead, or they may have undergone various physical and chemical modifications. The changes may have taken place in the power plant or in an effluent treatment system designed for by-product recovery or contaminant removal. Futhermore, with the possible exception of the turbine, disposal systems can involve virtually all of the power plant's equipment and instrumentation/control facilities. In fact, corrosion problems may be worse in the disposal system than they are in the power plant, because the fluids may pickup oxygen from exposure to the air.

At Wairakei, New Zealand, and Ahuachapan, El Salvador, where the geothermal waters are allowed to flow through open weirs and ditches, precipitation and scale build up on the concrete walls and require periodic removal. Experiments have been undertaken at Ahuachapan to establish controlled scaling and precipitation in settling ponds, where the wastes can be more easily removed. Of course, a solid waste disposal problem is then created, as the salts and precipitates must be removed from the flocculation basins. At Wairakei, the recovered materials are used for road repairs and land fill. In some cases, the recovery of minerals from the precipitates may be financially rewarding.

Another liquid disposal approach is to inject the geothermal-energy effluent at as high a temperature as possible and with a minimum transportation distance for the effluents. This technique is proving quite successful at Ahauchapan.

The effects of plugging and scaling on subsurface equipment are considerably more difficult to analyze and correct than the effect on surface equipment. We know that scale and precipitates tend to collect in the wellbore, slotted liner, and injection zone immediately around the slotted liner, all helping to decrease the injectability and usefulness of the well. In the wellbore itself, these impediments sometimes can be removed with reaming tools commonly used in the oil industry. Acidification and chemical treatments can also be employed both in the wellbore and in the formation, but these remedial measures add to the maintenance cost of the disposal system.

Normally there is a trade-off between the cost of installing new wells and the cost of paying for maintenance on old wells.

General Corrosion

Geothermal primary fluids vary substantially in chemical composition on a worldwide basis, between different wells within a given field, and for a given well at various times during its operating history. The chloride ion (Cl^-) contained in geothermal fluids is generally regarded as the principal corrosion-aggressive species in geothermal fluids. Hydrogen sulfide (H_2S) is second in prominence as a corrosion stimulant. Many other elements or compounds contribute to corrosion either individually or in synergism with other components. Data generally indicate higher corrosion rates for fluids that have been aerated over deaerated fluids.

Stress-Corrosion Cracking

Selecting materials for use in disposal systems should include consideration of the possibility of stress-corrosion cracking; which is the failure by cracking of a material that is under constant tensile stress.[28] Stress-assisted corrosion can occur if: 1) the material is in an electrolyte, i.e., if it conducts electricity; 2) a cathodic depolarizer (e.g., oxygen) is in the electrolyte; 3) the part is under stress; and 4) there is sufficient contact time with the metal to permit electrochemical action to occur.[133] Crack propagation proceeds intergranularly or transgranularly through the metal cross-section, and failure may occur after only a few minutes, or after months, or years.

Hydrogen sulfide is present to some extent in many geothermal primary fluids. Below 2 to 5 ppm, H_2S is not generally regarded as a serious threat to structural stability. Many geothermal fluids have higher concentrations than these levels, and so hydrogen sulfide has to be considered a potential problem in the design of the waste disposal system. Sulfide cracking is more likely to occur in high-strength materials.[21]

The complexity of a geothermal fluid's interaction with a structural material, under a given service situation, forces us to use in-service testing for material qualification. The chloride/sulfide stress-corrosion cracking of geothermal materials is a prime example of a corrosion problem whose severity is site-specific.

Tables 5.2 and 5.3 present stress-corrosion cracking data for various materials under environments presented by the Wairakei and Cerro Prieto sites, respectively. The data are encouraging, because for the most part, these materials are not specifically designed to resist chloride/sulfide cracking under severe service situations.

Scaling and Plugging

Several comprehensive reviews have been made of the geothermal scaling problem.[32,33] According to Shannon et al.,[34] the major sources of scaling and plugging are:

- Silica and silicates. Silica appears in three forms (amorphous, cristobalite, and quartz), each with different solubility characteristics as a function of temperature. Changes in temperature, pH, salinity, and other factors can cause deposition in one or more forms. Silicates of iron, aluminum, magnesium, calcium and phosphorus are also thought to contribute to scaling.
- Calcium carbonate. Calcite is deposited as the result of flash boiling and the release of carbon dioxide. Deposits occur immediately downstream from points of flashing.
- Metal sulfides, sulfates, oxides and carbonates. As pH and temperature change, sulfides of iron, antimony, lead, copper, silver, and zinc may be deposited, as well as barium and calcium sulfates. Metal oxides and carbonates may also form.

Geothermal scaling action at a Cerro Prieto well is indicated in Figure 5.1. Percentages of scale deposition are expressed as a function of depth for those compounds most often found in geothermal systems - NaCl, FeS, $CaCO_3$, and SiO_2.

TABLE 5.2. Stress Corrosion Behavior in Waikarei Geothermal Media[a]
Source: T. Marshall and W. R. Braithwaite (Reference 30)

Alloy	Tensile Strength, psi	Stress Corrosion Behavior in Geothermal Media[b] Cracking[c]	Microfissuring[d]
Titanium	≥93,000	No	No
Aluminum	16,000	No	No
Austenitic stainless steels	84,000 - 100,000	No	Aerated steam only
Ferritic[e] stainless steels	>100,000	Yes	Yes
	<100,000	No	No
Carbon and low alloy steels	≥88,000	Yes	Yes
	<88,000	No	Yes
Brass, 60/40	51,000 - 58,000	No	No
Brass, arsenical 70/30	54,000	Bore water only	No
Bronze	22,000	No	No
Aluminum bronzes	--	Yes	No
Silicon bronze	--	Yes	No
Cupronickel	90,000	No	No
Copper	36,000	No	Yes
Beryllium copper	Rockwell C38[f]	Yes	No
	Rockwell B47	No	Yes
Inconel	90,000	No	No
Nimonic 75	120,000	No	No
Monel	71,000 - 80,000	No	No
K Monel	Rockwell C25[f]	NO	No

(a) Typical Wairakei bore fluid properties:

Temperature: 255°C
pH: 8.4

Chemical	ppm	Chemical	ppm
SiO_2	690	Cl	2260
Li	14.2	SO_4	36
Na	1320	HCO_3	19
K	225	NH_3	0.15
Mg	0.03	CO_2	19
Ca	17	H_2S	1.0
F	8.3		

(b) Constant deformation test in media listed in Table A.4 (Appendix A).
(c) Stress corrosion cracking in one or more of the above media.
(d) Microscopic surface fissuring believed to be a borderline form of stress corrosion.
(e) Martensitic in the hardened condition.
(f) Hardened to spring temper.

TABLE 5.3. Stress Corrosion Behavior in Cerro Prieto Steam
Source: A. Manon (Reference 5.11)

Type of Steam	Material	No. of Failed Specimens	Observations
Nonaerated[a]	12Cr	0 of 3	
	12Cr-Mo-W	0 of 3	
	1Cr-Mo-0.25V	2 of 2	Microscopic cracks were observed
	3.5Ni-Cr-Mo-V		
	12Cr-0.2Al	0 of 3	
	15Cr-1.7Mo	0 of 3	
	Aluminum	0 of 3	
	Deoxidized copper	0 of 3	
Aerated[b]	12Cr	0 of 3	Microscopic crack
	12Cr-Mo-W	2 of 2	100% failure
	1Cr-Mo-0.25V	1 of 2	50% failure
	3.5Ni-Cr-Mo-V	0 of 3	Intergranular corrosion
	12Cr-0.2Al	0 of 3	Intergranular corrosion
	15Cr-1.7Mo	0 of 3	
	Deoxidized copper	2 of 2	Failure do to general corrosion

(a) Nonaerated steam:
Pressure = 4.3 kg/cm^2 (61 psig)
Temperature = 147°C (296°F)
CO_2 = 1.95wt%
H_2S = 0.20wt%
Cl^- = 13.3 ppm
Moisture = 0.7wt%

(b) Aerated steam:
Pressure = 1 atmosphere (14.7 lb/in.^{2} abs)
Temperature = 70°C
CO_2 = 1.6wt%
H_2S = 0.16wt%
Cl^- = 7 ppm
Moisture = 0.7wt%

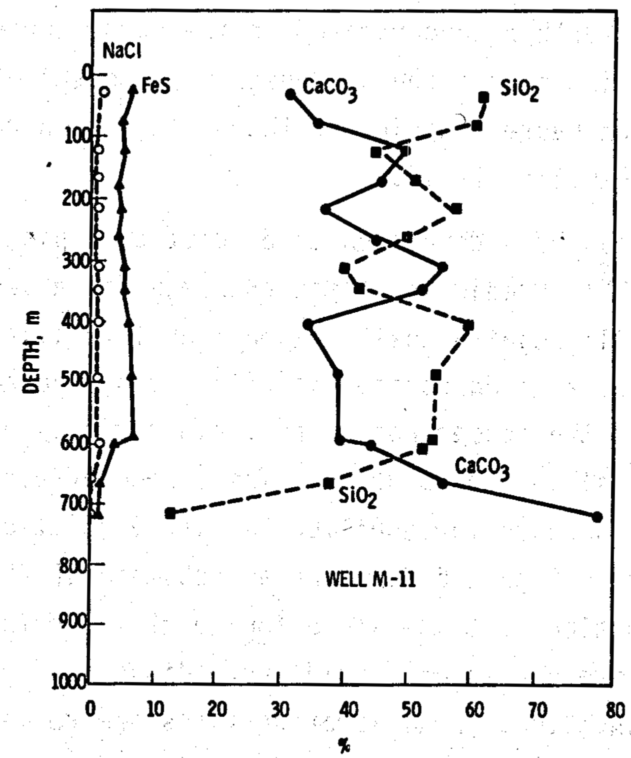


FIGURE 5.1. Various Scale Deposits in Cerro Prieto Casing as a Function of Depth Source: S. Mercado and J. Guiza (Reference 35)

If the geothermal fluid is in chemical and thermal equilibrium with the rock formations, then scaling and deposition can occur with any change (physical or chemical) that upsets the equilibrium. In other words, at every stage of power production or waste disposal during which fluid changes occur, scaling can be a problem. Changes in pH and decreases in temperature appear to be the primary factors. Of course, temperature decreases are unavoidable when energy is extracted from the hot fluids. Increases in pH occur whenever hydrogen sulfide and carbon dioxide are released (as in the flash separators and barometric condensers), but changes can occur at any stage in the system.

These problems apply to both steam and liquids. Steam inherently carries water droplets that contain salts and scale-producing contaminants. Other contaminants such as borate compounds are carried directly by the steam.

These contaminants are further concentrated in the steam condensate, which is pumped through the cooling towers and condensers. Disposal of the excess condensate by injection can cause plugging of the wells, which has occurred at The Geysers, U.S., and Larderello, Italy.

A computer model has been developed to predict precipitation and scaling in a dynamic system.[125] Predicting these phenomena is a very difficult problem and probably will require onsite experimental facilities to verify the mode. The solubility of a given species is affected by the activity of the basic solvent (H_2O) and the concentration of various dissolved species (including hydrogen ions) in the solution. The strong effect of temperature on the rate at which a species may equilibrate with a solution (precipitate or dissolve) is indicated in Figure 5.2, where an estimate of the equilibrating time is given as a function of temperature for quartz. In the temperature region applicable to some phases of liquid waste disposal, very long equilibrating times may be involved. Equilibrating times are reflected in the kinetics data for quartz deposition given in Figure 5.3, where scaling rate versus temperature is given for various concentrations of SiO_2 in the solution. Hold-up times in the disposal system should be kept to a minimum to reduce the silica precipitation in the system, transfering the problem to the well or the receiving formation.

Silicon dioxide deposition (i.e., nucleation and growth) is apparently increased by the presence of chloride ions and CO_2. Other factors encouraging SiO_2 deposition are surface roughness (from prior deposits or corrosion) and high pH. Among the expedients suggested for control of SiO_2 scaling are acidification (by HCl) and anti-catalysts to discourage nucleation and growth of deposits.

Sulfide deposition is a frequent problem in geothermal plants. Oxidation of sulfur species to sulfur has been suggested as one technique to reduce sulfide scaling.

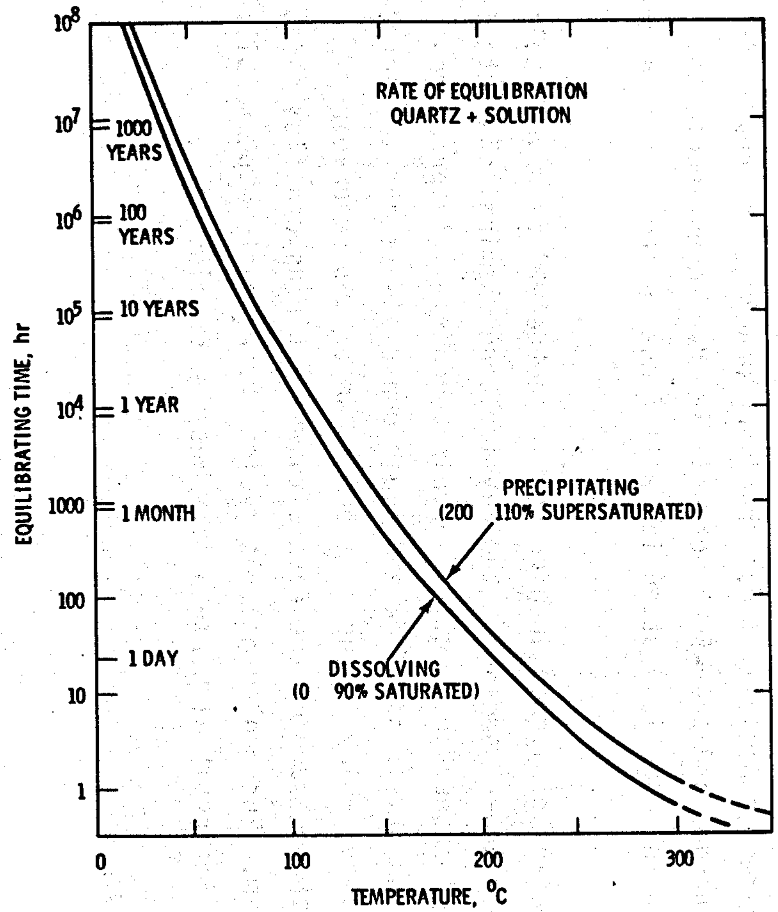


FIGURE 5.2. Estimation of Equilibrating Time for Quartz + Solution
Source: H. L. Barnes and J. D. Rimstidt (Reference 36)

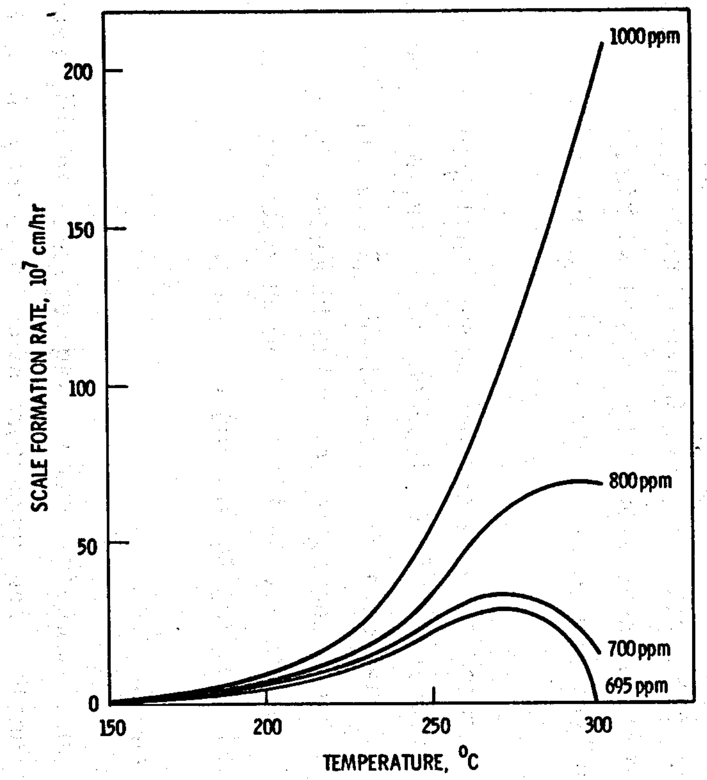


FIGURE 5.3. Rate of Quartz Scale Formation Versus Temperature
Source: W. F. Downs et al. (Reference 37)

As noted by Vetter in a comprehensive, qualitative review of scaling problems in the petroleum industry,[38] thermodynamic analysis has a limited capacity to predict scaling phenomenon under actual working conditions. This limitation affects our ability to deal with a kinetic phenomenon, such as scaling.

Scaling is not expected to have serious operational consequences for those disposal techniques involving surface dispersal of waste, although periodic removal and disposal of the scale may be required. Scale can offer protection against corrosion, or it can aggravate corrosion processes by acting as crevices through which electrochemical action is concentrated on a small portion of the underlying metal, leading to pitting or cracking.

5.4 GEOLOGY AND SUBSURFACE

A variety of disposal techniques are being reviewed in this report. However, with respect to geology and subsurface hydrology, only injection of spent geothermal fluids will be discussed. Injection may take place in producing zones or in areas that are buffered from the producing zone. It is true that surface disposal schemes, especially those involving ponding, may result in infiltration and recharge, and therefore potentially adverse environmental impacts. However, in this section, attention will focus on the deeper reservoir environment.

Successful injection of liquid into or near a geothermal reservoir will depend on a reasonable understanding of the physical and chemical characteristics of the individual reservoir, e.g., reservoir boundaries, temperatures, pressures, recharge potential, and rock and fluid constituents and concentrations.[39] Permeability, which is one of the most important reservoir characteristics, is the measure of the ease with which fluids can flow through the underground system. For geothermal reservoirs, both fracture permeability and intergranular or interstitial permeability must be considered.

The primary objective of this section is to discuss how subsurface injection might perturb the reservoir temperatures, pressures, and/or premeabilities. Many of the factors are interactive and have synergistic effects upon each other. Most of these factors and their interactions can be identified by site-specific testing of the receiving formation and the waste fluids. This section is presented in the following categories:

1. Potential permeability changes
2. Potential reservoir pressure changes
3. Potential reservoir temperature changes
4. Potential environmental impacts
5. Exploration techniques.

Potential Permeability Changes

One of the primary questions concerning any waste fluid injection program is how the operation might affect the formation permeability. It is necessary to have some understanding of the receiving reservoir rock and fluid properties and the waste fluid properties. Some of these properties are presented in the lists that follow:

Example Reservoir Rock Properties

A. Areal extent and stratigraphy
B. Porosity and permeability
C. Continuity, homogeneity and isotropy
D. Mineralogy and chemistry
E. Stress-strain behavior
F. Thermal properties

Example Reservoir and Waste Fluid Properties

A. Temperature and pressure
B. Volumetric flow
C. Viscosity and density

D. Dissolved and suspended constitutents[a]

E. Acidity (pH) and oxidation potential (Eh)

F. Dissolved gases

Once the rock and fluid properties are identified for the host formation and for the waste fluid, one can address the possibility of adverse permeability change. Decreases in permeability can result from plugging due to filtering of suspended solids from the waste fluid stream, scale formation or changes in the receiving reservoir. The suspended solids can be caused by several factors: precipitation due to temperature decreases or loss of dissolved gases; reactions from mixing noncompatible fluid streams; reactions between the waste fluid and the host fluid; or corrosion products from the piping or power system. Scale formation can occur at any place where physical or chemical fluid changes take place, i.e., in the system piping or the receiving formation. The scale generally contains silica, calcium carbonate, metal sulfides, metal sulfates or metal oxides. Detrimental reservoir changes can be caused by clays that are hydrothermally formed, compaction of the rock matrix, or swelling of naturally occurring clays.

Potential Reservoir Pressure Changes

Geothermal deposits can vary in pressure from a less-than-hydrostatic level (0.43 to 0.52 psi/ft of depth) to a pressure approaching lithostatic levels (1.0 psi/ft). Any variation in this ambient pressure subsequent to energy exploitation will depend on the amount and time history of mass withdrawals, the enthalpy of the fluid, the amount and time history of natural reservoir recharge, and any matrix consolidation.

As stated by Whiting,[40] geothermal reservoirs possess relatively inactive water influx characteristics. Field experience to date generally tends to support this assertion. For example, many geothermal fields support subnormal pressures, and in some cases, the extraction of fluids has resulted

(a) Permeability factors - major cations (Na^+, K^+, Ca^+, Mg^+), major anions (HCO_3, SO_4, Cl^-), and silica. Environmental factors - trace constituents (boron, arsenic, hydrogen sulfide).

in a reduction in delivery pressure. This suggests that geothermal reservoirs are generally of the depletion type with negligible water recharge over the short term. As increasing quantities of fluid are removed, the delivery pressure can be expected to decrease.

Naturally, this observation may not hold true for every reservoir configuration. An extensively fractured zone may provide adequate permeability to permit significant recharge to the producing zone. Also, vapor-dominated reservoirs may not exhibit short-term depletion because of the relatively small amount of mass that is extracted at one time.

In the absence of adequate natural recharge, artificial recharge via injection of waste fluids into the producing zone may be necessary to maintain the reservoir pressures. Optimum injection well location and spacing will require detailed knowledge of the receiving formation.

Potential Reservoir Temperature Changes

The per unit cost of energy conversion of any geothermal resource depends primarily on the fluid temperature.[41] Any waste disposal activities that might result in a reduction of the production fluid enthalpy should be avoided. One area of concern is the potential channeling of cooler water from the injection wells to the warm producing wells through fracture zones. This quenching phenomena could result in a reduction in the available thermal energy or completely destroy the usefulness of the well. Field testing, well effluent monitoring,[a] and careful spatial siting of the disposal wells should reduce the probability that this problem will arise.

The reservoir rock is in thermal equilibrium with the formation waters, and since the majority of the subsurface volume is occupied by the solid (e.g., 20% voids-80% solid), the rock serves as a storage zone for sizeable quantites of heat. Injection of the spent geothermal fluids may be a vehicle for extracting some of this stored thermal energy, thereby extending the useful life of the producing wells.

(a) A chemical front may proceed the thermal front and tracers can be employed to monitor channeling.

Potential Environmental Impacts

Potential environmental impacts associated with subsurface disposal of spend geothermal fluids include: 1) thermal, chemical, and/or biological contamination of aquifer systems bounding the production zone; and 2) perturbation to the normal seismicity in the area.

The unchecked intrusion of waste fluids into potable aquifers bounding a geothermal reservoir will have adverse environmental impacts. For most power producing sites, the planned well release of waste fluids to a potable aquifer is not permissable. Poor completion practices, open abandoned wells, and fracturing of low permeability zones during fluid injection can be responsible for the intrusion of waste waters into these aquifer systems.

Any injection system must be thoroughly planned and designed, and must consider and allow for damage due to acid etching and hydrofracturing of the wells (which are means of stimulating injection). That is to say, the casing size, material, and the cementing program must be able to withstand maximum hydrofracturing pressures for that system. With adequate design and planning for the entire system, along with prudent well completion practices, the probability of environmental damage should be greatly reduced.

Many individuals are speculating about the possibility of altering the normal seismicity of the area as a result of fluid production (and subsequent pressure decrease) or fluid injection (and subsequent pressure increase). The issue boils down to the creation of a stress whose normal compressive pressure and interstitial pore pressure are different. Increasing the pore pressure in some materials enables stress relaxation by strain response at lower effective stress levels, thus, potentially increasing seismic frequency at the expense of magnitude or creating a seismic strain response. Conversely, decreasing pore pressure can in effect lock a fault plane and can thus demand a higher effective stress prior to any strain response. This could potentially lead to fewer but larger seismic events. Additional pore pressure due to injection would not be of a magnitude sufficient to generate fault slip unless excessively high pressures and/or volumes are involved.

The pros and cons of inducing seismic events and earthquakes as a result of injection have been widely discussed by the geothermal scientific community. Two well-documented cases, in which injection in nongeothermal reservoirs did cause seismic events, are often cited. At the Rocky Mountain Arsenal near Denver, Colorado, disposal of chemical wastes in a deep well at very high pressures into relatively dry formations caused seismic events up to magnitude 5 on the Richter scale.(42,43,44,45) Also, at the Rangely Oil Field in Colorado, water flooding in excess of normal hydrostatic pressure has induced seismic events.(45) While it will be necessary to continue to monitor injection activities at geothermal-energy fields in order to identify induced seismic events, experience to date would indicate that the problem is over-exaggerated. Injection either on a regular basis or an experimental basis has been undertaken at various times at most major power-producing geothermal fields throughout the world. Seismic monitoring occurs routinely at all of the sites, and an accumulation of experience equivalent to many decades of operation shows that macro-seismic events are not induced in geothermal fields as a result of injection.

No earth tremer of significant magnitude has yet been attributed to steam production. Within the last year, however, analysis of microactivity at The Geysers in California has shown increased activity (1 on the Richter scale) in the location where steam is extracted for power production.

Exploration Technique

Determination of subsurface hydrogeological characteristics has been an extremely difficult problem. Predicting the technical success, and hence desirability, of geothermal-energy effluent injection requires readily interpretable surface measurement data and sufficient subsurface information. Unfortunately, surface measurement techniques to date have produced ambiguous results. Most of the drilling that has been accomplished in geothermal-energy resource areas has been directed toward providing production and injection wells rather than good subsurface data. Drilling is extremely costly, and extrapolation from a statistically limited set of subsurface data can produce erroneous conclusions. Therefore, as new geothermal-energy reservoirs are studied, an increased emphasis will need to be placed on obtaining more complete and useful surface and subsurface information.

Surface measurements and near-surface measurements incorporate heat-flow measurements; electrical, magnetic, gravimetric and seismic geophysical techniques; geochemical analysis of surface fluids and gaseous emissions; interpretation of local and regional geological structural surface features; the determination of the amount of volcanism and the type of material involved; the assessment of climatic history and associated ground water information; and determination of the hydrothermal alteration of surface rock.

Subsurface explorations rely on new and previous borehole records, downhole logging surveys, and analyses of cuttings, cores and extracted fluids. Due to the typically heterogeneous nature of geothermal reservoirs, additional testing will be necessary to obtain information on the ability of a reservoir to accept injection fluids at certain rates.

5.5 WASTE DISPOSAL AT SPECIFIC GEOTHERMAL FIELDS

The chemistry of geothermal fluids and the generic problems associated with the various methods of liquid waste disposal have been outlined above. This section discusses specific geothermal fields and briefly describes the disposal methods currently in use at a representative sample of international sites, including sites in the U.S. that are in advanced stages of development.

Larderello, Italy

In the 52 years that geothermal fields in the vicinity of Larderello have been operational, steam temperature has increased approximately 40^{o}C; the hydrostatic water level has dropped several hundred meters; the quality of the steam has changed from saturated to superheated; and the reservoir pressure has decreased. The average life of a production well at Larderello is about

22 years. A significant decrease in pressure at the well (caused by a combination of steam utilization and formation plugging) is a sure sign that the well is nearing the end of its usefulness. Over 470 production wells have been drilled at Larderello and Monte Amiata to an average depth of about 1000 m, using bore diameters up to 34 cm (13-3/8 in.). Well spacing of 100 to 180 m radial distance between production wells has proven successful. Presently, 20% of the wastes are injected into the periphery of the field and the rest is discharged into local streams.(46)

Injection experiments have taken place both at the periphery of the field and in the producing regions. In one instance, channeling of cold water over several hundred meters quenched a production well. This effect is believed to have been caused by flow of the cooler water along a major fault into the region of the producing well. One set of injection tests was undertaken in 1973 in the Viterbro Region using injected water at 62^{o}C at flow rates of 3.5-35.5 ℓ/sec. The injection was accomplished under gravity flow for 9 days into a well 1100 m deep that passed through a very permeable carbonate formation first encountered at 700 m. The injection did not trigger any seismic activity: a network of five microseismic stations that had been established well in advance of the experiment to monitor seismic activity recorded no movement.(47)

Wairakei, New Zealand

Wairakei first went into production in 1951 and is the second oldest major power-producing field in the world. By 1978, over 1200 x 10^6 tons(M) of geothermal fluid had been withdrawn from the reservoir and discharged into the Waikato River. The reservoir is producing at the rate of 75 x 10^6 ton(M)/yr. The original reservoir pressure of 63 kg/cm^2 (900 psi) decreased to approximately 42 kg/cm^2 (600 psi) by 1970. Between 1962 and 1970, the average flow per wellbore decreased from 750,000 kg/hr to approximately 140,000 kg/hr, and the average reservoir temprature decreased from 262^{o}C to 250^{o}C. The highest recorded temperature at Wairakei is 270^{o}C.

The 61 production wells drilled at Wairakei have an average depth of 760 m. A production bore diameter of 19 cm would enable them to produce considerably greater flow if the original reservoir pressure was maintained. The production wells are spaced 50 to 70 m apart, and careful reservoir management is now in effect to avoid further decrease of the reservoir pressure and to prevent interaction between the wells.

Bench marks for the measurment of land subsidence were established in 1950 prior to the exploitation of the field, and monitoring has continued periodically since that time. Subsidence has affected an area 65 km^2 in size and continues at an average rate of 40 cm/yr. The maximum subsidence to date is slightly in excess of 4.5 m and is continuing. Injection has been considered as a means of controlling the subsidence, but additional decreases in the reservoir temperatures are not desirable and, consequently, injection is not being done on a regular basis at this time.[48,49,50]

Disposal of the liquid wastes into the river is causing some problems. The trout population has decreased in the vicinity of the discharge point, and those that survive are in poor condition. Average arsenic concentration in the river is about 0.04 ppm, but at low river flow the concentration can reach 0.25 ppm.[7] The maximum level for drinking water in the U.S. is 0.05 ppm.

About half of the trout caught in the upper Waikato River have a mercury concentration higher than 0.5 mg/kg, which is the generally allowable maximum mercury concentration for fish caught for human consumption. Plant growth in the river has increased due to the increased nitrogen level. Any further geothermal development will require injection, because the Waikato river is now receiving the maximum allowable contamination from the Wairakei facility.[51]

Otake and Hatchobaru, Japan

Otake and Hatchobaru are flashed-steam systems located in similar geological structures consisting mainly of the Hohi volcanic complex and altered pyroxene andesities, lava, and tuff breccias. Two geothermal reservoirs or producing zones exist. An upper zone starts at approximately 250 m in depth and continues to approximately 550 m. Both above and below it are relatively impermeable compact layers consisting mainly of lava. The top of the lower reservoir is approximately 1000 m below the surface and extends to an unknown depth. The Otake power plant taps only the upper reservoir at a temperature of 200°C, whereas the Hatchobaru plant taps the lower reservoir at approximately 230°C. Typical wells produce 2 MWe at Otake and 3 MWe at Hatchobaru but in most respects the two fields are very similar. Pressures under shut-in conditions on these wells range from approximately 7 to 20 kg/cm^2. The water chemistry is relatively favorable for power production, with pH ranging from 6.7 to 8.4 and total dissolved solids from 2500 to 5000 ppm. Ten wells have been drilled in the Otake area, ranging in depth from 250 to 600 m with bore diameters of 8 in. The 10-MWe plant at Otake went into commercial operation in August of 1967 with five production wells. Waste water was dumped into the local drainage system until 1972, when three wells were drilled for injection purposes. By 1975, more than 8×10^6 T of the fluid had been disposed of through injection.

Prior to the drilling of the three injection wells, an injecting experiment was conducted on production well No. 10 to test for possible mutual interference between the wells. The No. 10 well lies at the centroid of a triangle defined by wells No. 7, No. 8, and No. 9. Two legs of the triangle are approximately 180 m long and the third leg 100 m. The No. 10 well in the center of the triangle is thus located 110, 50, and 70 m from the No. 7, No. 8, and No. 9 wells, respectively. During the drilling of well No. 10, 1 kg of fluoresceine sodium salt was mixed with the drilling fluid and injected into the well. The other three wells were then allowed to flow, one at a time, and the fluids for each were surveyed for a period of four days. No evidence of the reagent was observed in wells No. 7 and No. 9, but approximately 100 g were ultimately found in well No. 8. Also, communication between wells No. 10 and No. 8 was evident in a reduction of the quality of the steam being produced from well No. 8. As a result of these experiments, the three injection wells drilled in 1972 were located 150, 350, and 500 m from the closest production well (well No. 8).

The casing program for injection wells is identical to that for production wells, which have a capacity of 310 to 600 ton(M)/hr under gravity flow. Some reduction in capacity of the injection wells has been noted due to build-up of scale deposits of $CaCO_3$. For example, in well No. R1, the initial flow rate of 310 ton(M)/hr was reduced to 120 ton(M)/hr in 3 years. During that same period of time, the scale buildup on the casing at the wellhead measured 25 mm. The hydrostatic water level had changed from 150 m in depth to 120 m during the 3 year period.

Chemical tracers are periodically added to the injected fluids. The production wells and natural springs in the vicinity are periodically monitored. In over 5 years of monitoring, the tracers have not been detected at any of the monitoring stations. A four-station seismic network has been in operation at Otake since early 1972 prior to the beginning of injection. To date, none of the seismic events observed is associated with injection.

One very favorable effect occurred at Otake as a result of the injection of fluids into the reservoir. Prior to 1972, the net power produced by the production wells had decreased from 10 to 8.7 MWe in a period of 4 years, and production was continuing to decrease at the rate of about 6 percent/yr. After injection began in 1972 on a regular basis, power output recovered to a level of 10 MW and was being maintained at a constant 10-MW level. Recently the flow in the injection wells decreased, and more wells are being drilled. An additional problem is that one production well was quenched by waters from an injection well.[52]

At Hatchobaru, the injectivity of injection wells was also decreasing at a rate of about 6 percent/yr with injected water at a temperature of 60°C. A heat exchanger was installed to extract additional heat for space heating in the buildings, which dropped the injection water temperature to 40°C. The additional temperature decrease caused a super-saturation of calcium carbonate and a decrease in injectivity of about 25 percent/year. Acid cleaning using a 35 percent concentration of hydorchloric acid has been injected in the wells to obtain an acid concentration of 3 to 5 percent. The capacity of the wells approximately doubled as a result of the acid cleaning and the technique is considered successful. At Hatchobaru, 12 wells had been drilled as of 1977 to a depth of approximately 2 km. Five of these were being regularly used for power generation. Injection of waste liquids into the producing reservoir has decreased the enthalpy of all the production wells.[52] A 25-MWe generating facility has been installed with an expected ultimate development of 180 MWe at some future date if the injection problems can be solved.

Cerro Prieto, Mexico

As of 1975, 27 of the 37 wells drilled in the Cerro Prieto field were capable of production and are being used to produce 75 MWe of power. The deepest well is 2630 m, but production aquifers are encountered at 600 to 900 m, 1300 to 1600 m, and 1800 to 2000 m. Wellhead pressures are approximately 90 kg/cm^2, and bottomhole temperatures are approximately 370^{o}C. Maximum shut-in pressures at the wellhead are approximately 95 kg/cm^2. With flow rates of 100 to 400 ton(M)/hr, 16 wells are used to supply the two 37.5-MWe turbines. Each of the wells is provided with a steam separator 1.4 m in diameter and a water discharge line to the evaporation pond. All liquid wastes are dumped into an 16 km^2 evaporation pond, where they are cooled and some of the silica and salts allowed to precipitate out. The resulting overflow of saline water (approximately 25,000 ppm) flows by canal to the Sea of Cortez. Injection has not been practiced to date at Cerro Prieto but is being studied. An additional 75-MWe generating capacity has been installed at this site, and 250 MWe will be installed by 1985.

Ahauchapan, El Salvador

The Ahauchapan field[53,54] is located in the northwestern part of El Salvador about 30 km from the border with Guatemala and 64 km from the Pacific Ocean at an elevation of about 800 m above sea level. The field is believed to be contained within an old caldera that is 14 km in diameter and has been completely filled with volcanic products. The caldera either has a source of heat directly beneath it, or the heat source is nearby and hot water flows laterally into the caldera.

Two major aquifer systems in the reservoir consist of one shallow, low-temperature, low-salinity aquifer extending to a depth of approximately 500 m, and one high-temperature, high-salinity aquifer extending from about 500 m to an unknown depth in excess of 1400 m. The two systems seem to be relatively isolated with a region of low permeability in between them.

The temperature of the lower geothermal reservoir is about 240°C. At the wellhead, the fluids contain approximately 18,000 ppm of sodium, potassium and calcium salts, and an additional 650 ppm of SiO_2. The average steam quality in 1978 was 17%.[127] Mineral deposition and scaling are significant problems, particularly if the temperature of the water drops. It has been estimated that the minimum potential of this field is 5000 MWe/yr, and plans now call for the installation of a third generating unit of 35 MWe size. This will bring the installed capacity of 95 MWe.

Two methods of waste disposal were studied at Ahauchapan between 1970 and 1975: 1) the construction of a precipitation pond and disposal of the fluids through a 86-km canal to the ocean, and 2) injection into the geothermal reservoir. The canal was built and is being used to deliver about 70% of the waste liquids to the ocean, the remainder of the liquids are injected into the producing field to maintain reservoir pressure.

Large-scale injection experiments were successfully carried out in 1970 and 1971, during which time approximately 2×10^6 m^3 of water at 150°C was injected. Injection occurred at rates of 90 and 160 ℓ/sec using the combined driving force of gravity and vapor pressure. An earlier attempt to inject the water at 150°C into a 1525 m well just outside of the geothermal reservoir failed becasue the formation had low permeability. Consequently, a dual-purpose well was drilled within the production area and finished with slotted liner to a depth of 952 m, somewhat below the depths of the production wells. Injection into this well proved successful as long as the temperature of the waste fluids did not drop below 150°C.

To test for interaction between the production wells and the surface springs in the area, several of the springs were monitored, and no changes were observed. When a tritium tracer was injected into the injection well in

1971, a small quantity of tritium appeared in a nearby producing well within 2 days.[53] After a period of a few weeks, a very low level of tritium also appeared in two other production wells, but none was observed in any surface water or freshwater wells. The production wells in which the tritium tracer was found are located 500 m from the injection well. Less than 1 percent of the injected tritium has been recovered and the whereabouts of the remainder is unkown. It is expected that some direct channeling exists between the injection well and the production well in which the tritium was first observed. Mutual interaction will probably occur among these wells if full production and injection are attempted. However, with adquate spacing, injection should be successfully managed in this reservoir.

The Geysers, U.S.

The Geysers geothermal area, which produces dry steam, is located in north-central California in Sonoma and Lake Counties, about 120 km north of San Francisco and 104 km northwest of Sacramento.

Electric power production began in 1960, and until 1969, the condensed steam was discharged into Big Sulphur Creek. Injection began in 1969, and by 1975, over $15.2 \times 10^9 \ell$ had been returned to the geothermal reservoir. As of 1976, approximately $17.9 \times 10^6 \ell$/day was being injected into six deep wells. Approximately 90 production wells have been drilled; the field is under almost continuous drilling and expansion. Wells are typically 22 cm (8-5/8 in.) in bore diameter and are drilled to approximately 1000 m, although some of the deeper wells are 3 times that depth.

The geothermal reservoir is composed of highly fractured shale and sandstone (graywacke). Its temperature is 250°C, and wellhead pressure is about 35 kg/cm^2 (500 psi). The wells typically produce at a rate of 19 kg/sec (150,000 lb/hr) and are spaced as close together as 90 m in some areas. The injection wells are originally used as production wells. A slotted liner was added to keep the borehole open for the injection operation. The first injection well was partially plugged in the lower formations, which caused the injected water to enter permeable zones at higher horizons and cool a nearby producing well. Consequently, injection wells are now drilled deeper than nearby producing wells and removed as far as possible from major producing regions. No pumping power is required for injection, as the water readily enters the formation under a gravitational head. A tracer test was run on one injection well from 1975 through 1977.[55] Results of the test indicate that 18% of the condensate injected into the well was vented in the form of steam at surrounding production wells.

The condensate steam has concentrations of ammonia and boron that exceed California standards for surface disposal into a watershed and, consequently, injection has become a standard procedure. The steam contains approximately 1 percent gases by volume, some of which are injected along with the water. To prevent contamination and plugging of the injected wells, settling basins are used to remove the solids before injection. Deaerating vessels are used to remove oxygen and air from the injection system to control oxidation and corrosion.

Subsidence and microseismic activities are being carefully monitored at The Geysers. An increase in microseismic activity recently has been detected in this area.

State requirements to reduce the emission of H_2S have greatly changed the characteristics and disposal problems. At existing geothermal plants, an iron compound injected into the cooling tower water reacts with the H_2S to form an iron sulfur compound that precipitates out and collects in the cooling tower water sump. The solids are removed from the water before the water is injected into a reservoir. Disposal of these solids is becoming a significant problem. If we assume the steam has an average of 220 ppm H_2S, that 90% is removed in the abatement process, and that the sludge contains 10% iron and 50% water, the amount of sludge produced would be about 15,000 ton(M)/yr. New plants are being installed with other types of H_2S clean-up systems that produce elemental sulfur as a by-product.

Seven condensate spills ranging in volume from 11 to 740 ton(M) were reported during the 16-month period between May 1974 and September 1975.[128] One of these spills occurred on September 9, 1974, when 17 ton(M) of condensate was released, killing an estimated 5000 fish in Big Sulphur Creek. No fish were killed during a second spill of 170 ton(M) on September 15, 1974.[129] The reason that the first spill killed fish and the second did not is that the September 9 spillage picked up mercury and sulfuric acid as it passed through fumaroles and natural geothermal alterations before running into the creek. The second condensate spill on the other hand, traveled some distance over dry ground and partially soaked into surface soil instead of running into the creek.

Berms are being installed around the old power plants. These berms are designed to catch the accidental spills and divert the liquids into sump where they can be pumped back into the disposal system. New plants are being designed with berms.

Valles Caldera, U.S.

The Union Oil Company has been conducting injection experiments at the Valles Caldera near Los Alamos, New Mexico, since 1973. The primary experiments were done in two wells in 1973 and 1974, where approximately 380 x 10^6 of water were injected into the liquid-dominated reservoir. No evidence of a decrease in injectivity was observed during this year and no seismic events were found to be associated with the injection experiment. Injection is thus considered a viable option for waste disposal at Valles Caldera, even though the geothermal fluids have unofficially been reported (sans quantifying data) to have a high silica content.

The geologic structure within the Caldera is exceedingly complex, resulting from a history of collapse, caving, sedimentation, resurgence, periodic volcanism and repeated faulting. Hence, the system is highly receptive to ground water circulation. Valles Caldera's exceedingly high permeability could concurrently create environmental problems.

Imperial Valley, U.S.

The Imperial Valley is part of a sediment-filled, fault-cut and fractured structural depression that extends from the nothern end of the Coachella Valley southward to the Gulf of California. The California portion of this depression is often called the Salton Trough. Geologists believe that rifting apart of the Salton Trough began in the Miocene period, some 10 to 15 million years ago, and has continued to the present time.

A blanket of sediment 20,000 ft thick, derived from the erosion of the continental interior and carried largely by the ancestral Colorado River, has accumulated in this structural depression. Several faults cutting the trough are thought to be active. These include the Imperial Fault, the San Jacinto Fault, the Calipatria Fault, and the extension of the San Andreas Fault. In addition to earthquake activity, episodes of seismic creep are reported along certain faults and, on the basis of limited data available, a complex pattern of subsidence and uplift is suspected in the valley.

The ground-water flow system for the Imperial Valley on a regional basis is complex and not well known. Stratigraphic separation of aquifers is recognized, and in some areas, faults may provide interconnections between shallow and deep aquifers. The quality of the ground water varies considerably depending on location and depth.

Injection of waste liquids will in general depend on the physical and chemical properties of the liquids and the hydraulic and geochemical characteristics of the reservoir. In particular, care must be exercised in mixing wastes from various wells. Waste from a specific well may not present a problem by itself but, when combined with wastes from a second well, may result in precipitation of solids. Even though the components of the precipitate may be present in quantitives of only a few ppm, the extremely high volume-flow rates can lead to the accumulation of excessive amounts of precipitation. Porosity and permeability factors are not sufficiently well known for the valley nor for specific fields so unless experimental programs have been conducted, predictions have to be made about how an area will be affected by injection disposal methods.

Large-scale withdrawal of geothermal water in the Imperial Valley would probably exceed the natural rate of recharge, eventually affecting water levels and supply. Injection should help offset this tendency. Once the geologic and hydrologic characteristics of the valley's reservoirs are known, injection should be feasible.

Salton Sea (Niland), California

Geothermal wells in the immediate vicinity of Salton Sea produce steam from hot-water reservoirs. Steam and high salinity waters flow at the wellhead from a depth of 600 to 1000 m for the upper reservoir and 1000 to 1500 m for the lower reservoir. Total dissolved solids have exceeded 300,000 ppm in some samples and led to corrosion, scaling, and residual-salt disposal problems.

Various companies have experimented with mineral extraction and with using steam as a source of geothermal energy. Injection experiments were begun in 1963, when the Colorado River Basin Regional Water Quality Control Board prohibited the discharge of any geothermal brines into any channel draining into the Salton Sea.(130) Union Oil performed a one-year injection test as an adjunct of a production test during 1964 and 1965 in the Niland area. Over this period, approximately 477 x 10^6ℓ were injected at a rate of about 3.0 x 10^6 ℓ/day. The hydrostatic pressure of the column of water injected the liquids. No loss of injectivity was noted.(57)

Problems recently arose when injection liquids from the Magmamax No. 1 well were replaced with liquids from the Woolsey No. 1 well. (Both liquids contain 60-70 ppm SiO_2.) Magmamax fluids contain small amounts (1 to 2 ppm) of barium, while fluids from Woolsey contain small amounts of sulfate. Individually, these components present no problem, but when they are mixed together, a troublesome barium-sulfate precipitate forms.

Phillips Petroleum Company and San Diego Gas and Electric (SDG&E) are both continuing to investigate the possibilities of brine disposal by injection. The injection well in this area has been stimulated by hydrofracting with only partial success.

Water resources in the Imperial Valley may be affected by the disposal method that is used. Surface discharge disposal that drains into the Salton Sea could change the salinity of the sea. The Salton Sea presently has a TDS of about 39,000 ppm which is greater than average sea water. Increasing the salinity could destroy the existing aquatic life in the sea. Waste disposal methods that increase the probability of subsidence such as the surface discharge or injection outside the producing horizon could change the drainage patterns for the irrigation system. This would not be acceptable if there is a chance that the productivity of the farm land could be decreased. Most of the surface and ground water in the Imperial Valley is not potable and small changes in the salinity of these waters would not have any great affect on the community.

Heber, California

Geothermal waters at Heber are found at depths of about 600 to 3000 m. Sodium chloride is the main dissolved constituent, and silica concentrations are low enough (TDS 14,000-16,000 and 260 ppm SiO_2) that scaling is not thought to be a problem. Separation of shallow ground-water and deeper hot wells is indicated by the different composition of water on the two levels. The separation is probably due to a hundred-meter-thick unit of clay and silt above the geothermal reservoir.(56)

Six geothermal wells have been drilled in an area less than 5.2 km^2 that includes the purposed SDG&E-Cheveron Plant site. They range in depth from 1220 to 1830 m. The leaseholders at Heber have indicated an ability to supply hot brine and to inject cool brine and cooling tower blowdown simultaneously at rates required for the generating unit and the experimental facility.

The down-hole temperature of geothermal brine produced at Heber ranges from 176 to 204^oC, depending on the particular well. It is assumed that the mean temperature of the brine supplied to the plant boundary will be 193^oC. Typically, the number of dissolved solids in the brine is 14,000 ppm and the pH is approximately 6. The amounts of noncondensable gases dissolved in the brine are small compared to those in The Geysers.

All of the brine supplied to Heber is returned for injection, with the exception of a small amount that is flashed to steam in an experimental facility. Blowdown from cooling towers is combined with recycled cooled brine. Fluid is then returned to the site boundary as liquid at a pressure of 22 kg/cm^2, which is the nominal pressure needed for injection. With deepwell pumps, the flow rate per well ranges from 6.0×10^6 to 8.0×10^6 ℓ/day. Based on previous experience, the operator at Heber anticipates requiring one injection well for every two production wells.[58]

Producing energy at Heber from 50 to 60 wells will require about 20 to 30 injection wells for disposal material. The injection wells will be arranged in concentric circular arrays with an array diameter of about 3000 m.

If the hydrologic separation of the geothermal reservoir and the shallow ground water by the clay and silt units is really as adequate as experience has so far shown, and if proper well construction and completion techniques are followed, little or no mixing of deep-injected water with shallower ground water should occur.

East Mesa, California

The East Mesa geothermal field[59,60,61] is a liquid-dominated reservoir that produces steam through fractured sandstone. The U.S. Bureau of Reclamation had been exploring the feasibility of desalting geothermal brines for fresh-water supplies, mineral recovery, and electric power generation. The Bureau drilled five deep wells. Total dissolved solids are about 25,000 ppm at about 2400 m, and about 2500 ppm at 1800 m. The downhole temperatures are less that 200°C. A large number of test holes have been drilled for temperature, geophysical, and core data. Correlation between the wells is difficult to establish.

The injection well (Mesa 5-1) is lined with 19-cm casing to a depth of 1830 m. Injection tests have been run using shallow ground water and brine from a 47,000 m^3 holding pond with injection rates of 1.2×10^6 ℓ/day at

42 kg/cm^2 (600 psi).[a] Recently, however, the injection well became plugged, apparently from excess solids in the waste, and was reopened with an acid injection. Liquid wastes are ponded when the injection well is not operating.

A micro-earthquake network has been established to monitor effects of production and injection of seismic activity in East Mesa. Data so far have shown no relationship among micro-eathquake activity, well production, and injection. Extensometers and tiltmeters are being installed for further monitoring of near-surface effects.

DOE and the Bureau of Reclamation established the East Measa Test Site as a national test site for onsite testing of materials and equipment using actual geothermal brines.

Magma Corporation has constructed a 10-MWe binary cycle electrical power plant at East Mesa. The waste fluids from the plant will be injected into the producing horizon. Start-up tests were being run late in 1979. Full production is expected during 1980.

Roosevelt Hot Springs, Utah

The Roosevelt geothermal field is situated in eastern Beaver County, Utah. Fill sediments in the graben are approximately 1500 m thick in the center of the valley.

Recent faulting in the vicinity of the prospect is indicated by fresh scarps of alluvium and the cutting and displacement of hot spring deposits. Faults appear to be major controlling structures in the subsurface hydrologic regime.

The thermal anomaly is underlain by intermediate and silicic crystalline rocks at the surface or at shallow depths. The reservoir is comprised of this fracture system. The top of the anomaly is within only 900 m of the surface. The fracture zones have a high effective permeability locally, yielding up to

(a) Reported at Geothermal Resources Council field trip, May 12, 1977.

113,000 kg/hr flashed steam in excess of 250°C from the reservoir. Pressures are near hydrostatic, and fluids have less than 8000 ppm total dissolved solids. Tests run on a well by Phillips Petroleum Company indicated that the system is liquid-dominated.

Raft River, Idaho

The Raft River area is located in south-central Idaho approximately 65 km south of Burley, in Cassia County. Hot springs there in 3108 hectares have been classified as a Known Geothermal Resource Area (KGRA). Raft River is a southern tributary of the Snake River; the Raft River Valley lies on the border between the Basin and Range geologic province (to the south) and a volcanic province (to the north-west). The north-south elongate valleys appear similar to the other Basin and Range valleys. The valley is bounded on the west by Tertiary and silicic volcanics traversed by north-trending major faulting, and this faulting appears to control thermal spring location.

The thermal area of interest lies in the southern part of the valley a few kilometers north of the Utah state line. Two shallow wells have been delivering boiling water from a depth of about 122 m for many years. These wells produce from alluvium. Other shallow wells and springs in the area are cooler; maximum temperatures are below 38°C. The valley has been the scene of extensive geophysical work by the U.S. Geological Survey. Chemical temperatures (i.e., temperatures inferred from chemical composition) of 140 to 160°C have been reported for the well water.

Recently, several deep geothermal test wells were drilled, so that they would intercept a fault zone. The wells produce water under artesian conditions at about 150°C and are about 1500 m deep.[62] The water quality falls in the slightly brackish classification ($<$ 2000 ppm).

Regional circulation of water to the area is not well understood. The general belief is that the source of recharge is some distance away, and that the water migrates into the area, percolating downward to the hot monzonite, which heats the water. Upward migration of the hot water is believed to be along faults and fault zones.

Presently, liquid wastes are disposed of by injection. Experiments are being run to determine the feasibility of using the liquids for irrigation of agriculture crops and alcohol production.

A 5-MWe binary plant is under construction at Raft River. The liquid effluents will most likely be disposed of through injection.

6.0 INDUSTRIAL EXPERIENCE IN LIQUID WASTE DISPOSAL

Geothermal power developers are presently focusing greater attention on the problem of liquid waste disposal. In view of the relative newness of applied geothermal power, the experience of other industries can be useful in providing information about how to dispose of large amounts of liquid waste. The purpose of this chapter is to look at the state of the art of liquid waste disposal by the oil industry and other industries. Petroleum companies, for example, have been disposing of great quantities of saline water for at least 100 years. The similarity of some of these brines to geothermal liquids lends itself to ready comparisons. The paper, steel, and chemical industries also deal with massive waste disposal efforts. These waste products may or may not resemble the geothermal brines chemically, but information on disposal methods and treatment techniques can still be gained. (The mining industry also disposes of a great deal of acidic waste water, but this paper does not investigate their disposal program).

6.1 OIL INDUSTRY EXPERIENCE IN LIQUID WASTE DISPOSAL

History of Injection and Disposal Methods

In the past, the large volumes of liquid wastes that accumulate during production of crude oil have been disposed of by dumping into rivers, streams, and lakes. The pollution that this dumping has caused has made it difficult to maintain freshwater supplies suitable for domestic purposes. Due to increasing demands for freshwater for drinking and irrigation, large-volume dumping of oil-production wastes is no longer allowed in most areas of the country.

Shallow earthen pits (sometimes called evaporation pits, retention pits, brine storage pits, or impounding basins) have been used to store and evaporate the brine. Earthen pits are not effective in areas in which the annual rainfall is greater than the maximum water that can be evaporated. The problems associated with shallow earthen pits are similar to those of direct dumping. The wastes leach or percolate into the ground or surface waters, contaminating drinking water supplies and producing changes in chemistry, temperature, and pH of the water which can adversely affect aquatic life. Most brine storage pits, therefore, have been outlawed in recent years, although a few are still used to dispose of very small quantities of brine in areas in which the underlying strata contain no water or only saline water.[63]

The next advancement in surface disposal of brines was lined evaporation pits that prevent seepage and contamination of surface and ground waters. Many materials (e.g., concrete, gunite, asphalt, clay, and most recently plastic films) have been used as liners. The plastic films, generally 0.008 in. or heavier, are made from vinyl, polyethylene, and polyvinyl plastics and must be protected from mechanical damage. The dirt surface of the reservoir must be free of sharp stones, stumps, sticks, clods of dirt or anything that could puncture the lining. It is generally a good idea to dress the surface with a fine-textured material and to spray the area with a weed killer to assure that no weeds will penetrate. To protect the liner from the top, quite often it is covered with a 6-in. layer of fine-textured material and a 6-in. layer of gravel. This covering, however, may very well cost more than the liner itself.[63]

Vinyl films have a tendency to deteriorate when exposed to weather or oil, making it very important to keep the reservoir partially filled at all times. Polyethylene sheets are more weather-resistant and will give adequate service even when exposed to the air and the sun, but they are difficult to join. Heat-sealing is the best method for fusing the material, but it is difficult to heat-seal large sheets in the field. Perhaps when better adhesives are developed for polyethylene, its lower cost and aging properties will make it an attractive liner.[63]

An estimate of the surface area required to handle the brines from various geothermal energy conversion processes is shown in Table 6.1. The capital costs of these ponds (including construction, pond liner, embankment protection, engineering, land and administrative costs) are estimated in Figure 6.1. The operation and maintenance costs include materials, supplies, and labor.[63]

TABLE 6.1. Estimated Water Surface Area Required for Disposal of Geothermal Wastewaters

Geothermal Conversion System	Median Wastewater Rate, ℓ/min	Water Surface Area, Acres
Direct steam power generation	17,000	1450
Flashed steam, binary, total flow power generation	80,000	5335
Direct heating open and closed systems	500	43
Desalination	3,000	257

For years, most oil-field brines have been disposed of by injection into subsurface formations. The liquids are usually treated prior to their injection at ambient temperature. Due to increased awareness of environmental pollution and, in some cases, enhanced oil recovery, this method of waste disposal is almost exclusively used for disposal of oil-field brines today.

One of the first subsurface disposal techniques involved the use of less than 300 m wells. Higher injection pressures were required to maintain a high flow rate, raising the cost of disposal. Unfortunately, these shallow wells also increased the chance of contamination of freshwater supplies. It was soon found that deeper formations suitable for accepting brine actually resulted in a less costly disposal system. Deep wells accept large amounts of brine by gravity, reducing the need for injection pumping and thus reducing operating costs. Deep wells also reduce the chance of contamination of freshwater aquifers because the disposal point is located below the aquifers. Currently, all disposal wells are sealed to at least 60 m below the deepest freshwater aquifer.[64]

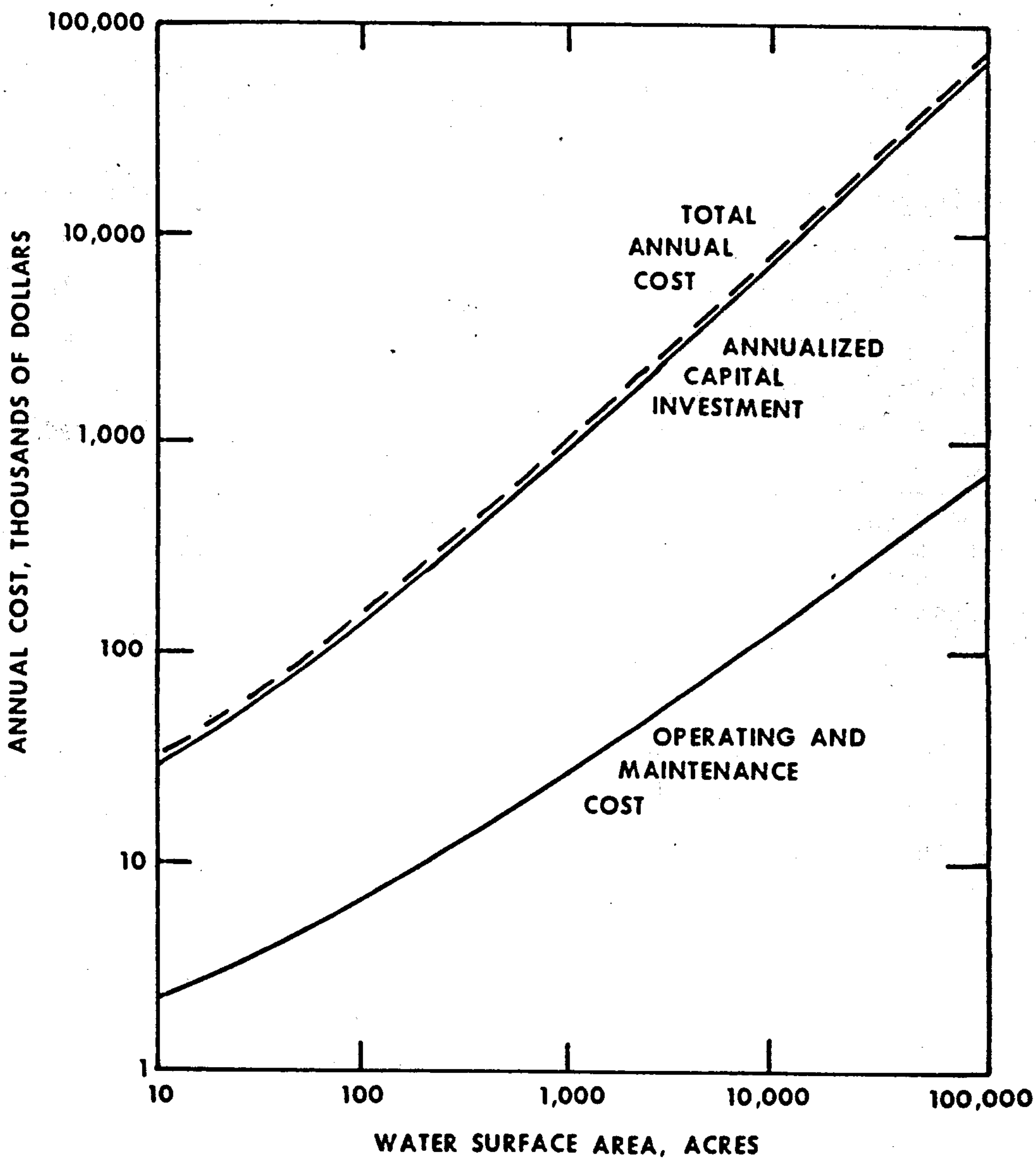


FIGURE 6.1. Total Annual Cost of Evaporation Ponds Versus Surface Area

In the past few years, a number of wells have collapsed that use Portland cement containing a high percentage of silica. American Petroleum Industry (API) standards for oil well cements have been applied to geothermal well construction in the absence of any other criteria. A task group within the API committee for standardization of oil well cements, has been formed and is investigating the matter of developing revised standards.

Types of Liquid Wastes and Volumes

Oil-field liquid wastes cannot be generalized into one type of brine. Concentrations of dissolved solids vary from less than 100 to more than 10,000 ppm. Chemical constituents of brines from different formations also vary widely, as do the chemistry of brines at different sites within the same formation. Sometimes brine taken from wells located less than a mile apart causes serious problems when mixed, because of the chemical reaction and precipitation. Most of the produced brines have sodium or calcium chloride as their major constituent, but magnesium, bicarbonate, and sulfate predominate in some. Many other elements are present as minor constituents and as trace elements, some even in commercially economic quantities. Table 6.2 shows the major constituents of some representative oil field brines.[65]

The problems of plugging, scaling and corrosion will probably be greater for geothermal plants than for oil-producing plants because in general, geothermal liquid wastes contain substantially more dissolved solids than do oil wastes. The greater volumes of brine produced at geothermal stations will additionally escalate the incidence and severity of plugging, scaling and corrosion: approximate 8×10^7 liters/day of liquid waste is disposed of at the largest oil field in the United States.[2] In contrast, the 100-MW Salton Sea geothermal plant will produce 9.5×10^7 liters/day, and the 50-MW East Mesa geothermal plant will generate 12×10^7 liters/day.[25]

Present Treatments and Disposal Equipment

The success of a disposal system depends upon a careful analysis of the field's brine chemistry and the geologic formation. It would be impossible to describe all the specialized systems that have been engineered for each brine, but most systems can be discussed in terms of the methods they have in common, i.e., chemical and mechanical treatments.

Chemical treatment methods include coagulation; precipitation control; corrosion control; pH fixation; and silica, iron, and manganese removal. Mechanical treatments include sedimentation, filtration, and aeration.

TABLE 6.2. Analyses of Natural Groundwaters Showing Major Constituents of Various Types of Brines[a]
Source: E. C. Donaldson (Reference 5.49)

Type of Brine	Formation	Location	Na	Ca	Mg	Cl	HCO	SO
Sodium chloride	Big Injun	PA	52,200	1,730	3,910	121,000	70	320
Sodium carbonate	Ellis	MT	3,140	90	80	2,890	4,040	820
Sodium sulfate	Coalinga	CA	3,290	390	340	2,520	360	7,260
Calcium chloride	Arbuckle	KS	4,230	16,900	8,430	60,100	42	1,190
Calcium carbonate	Embar	WY	140	140	30	10	210	190
Calcium sulfate	Madison	WY	580	870	180	1,070	1,080	1,940
Magnesium chloride	Lodgepole	Manitoba, Canada	44,900	3,260	67,340	94,900	2,140	4,800
Magnesium carbonate	Uinta	CO	450	428	542	90	1,185	1,038
Magnesium sulfate	--	NM	100	1,000	25,000	9,000	0	60,000

(a) ppm.

When untreated or colored waters are passed through a granular filter the color and some of the turbidity per se usually escape through to the other side. Coagulation is a process whereby turbidity, oil, and color are transformed into a soft, semi-solid or solid mass (also called a floc), which settles out in sedimentation or can be filtered out.(63) Three types of coagulants exist: coagulating agents, coagulating aids, and natural coagulants already present in the water. Coagulating agents are usually compounds of iron or aluminum (when found in the natural environment, they are most often sulfates and acids) that react to form a gelatinous substance. The agglomeration of this mix into larger particles, - flocs - depends on physical agitation or mixing of the water. Coagulating aids, on the other hand, do not themselves cause coagulation but help a coagulant to perform properly. Natural coagulants are still different: they are waters that form flocs with only minor treatment.(63)

Precipitation usually occurs when the subsurface pressure, temperature, or oxygen content of the brine is changed. Precipitation can be reduced by using a closed system that prevents air from coming in contact with the fluid. Elimination of oxygen from the system also reduces corrosion problems. Silica, iron, and manganese are not usually a problem in oil field brines, but where it is advantageous to do so, they can be removed from solution by several methods, such as lime addition or oxidation.

Sedimentation is the process by which suspended or coagulated materials separate from water by gravity. Sedimentation basins are used to remove natural and flocculated turbidity. When used in conjunction with a filter, sedimentation usually increases the effectiveness of a high-rate filters.(63)

Filters can be separated into four categories: those made of loose or granular material (sand or mixed media); felted or woven material; rigid, porous material; and semipermeable material. Sand filters are used most often in the field. Slow sand filters operate at rates of 1750 to 5300 ℓ/day per m^2 (0.03 to 0.09 gal/min per square foot) of filter area. Rapid, high-rate sand filters can operate from 8800 to 17,600 ℓ/day m^2, but they require more uniform sand and improved water treatment. The filter area for the 100-MWe plant described in Chapter 2 would be about 28,000 m^2 for the average slow filter and 7500 m^2 for the average rapid filter. Felted or woven filters are occasionally used, although their high construction and maintenance costs make them uneconomical. In the treatment of oil-field brines, rigid, porous filters are not frequently used, and semipermeable filters are not appropriate because colloids are not a big problem.(66)

An average cost estimate for filtration is shown in Figure 6.2. This graph was based on a filtration rate of 160 ℓ/min/m^2, which is highly dependent on the fluid and the filter media. Filters must be cleaned when the system pressure drops below a certain point as a consequence of solids loading and flow rate.(68)

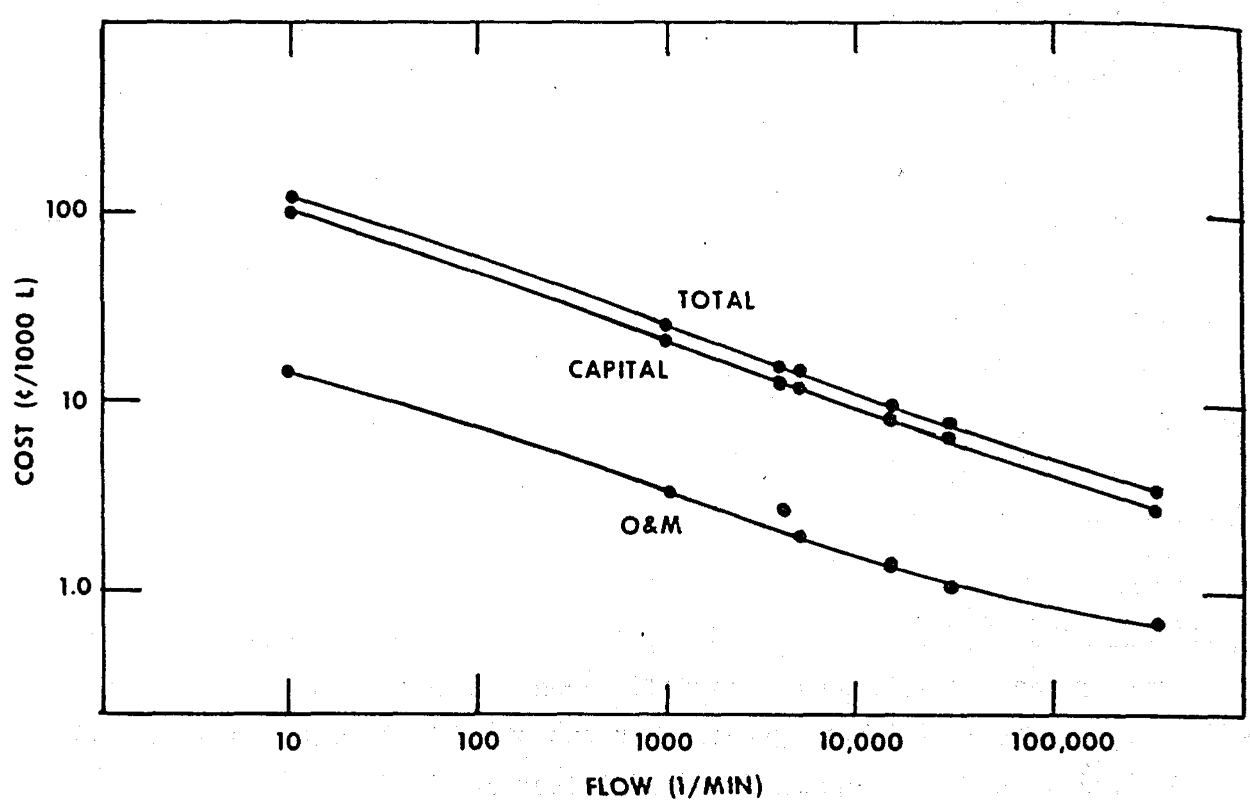


FIGURE 6.2. Cost Estimates for Filtration

Aeration is used in water treatment to remove undesirable gases from water or to introduce a gas into water for the purpose of causing a chemical reaction. It is quite often used when a closed system is not desired and advantages can be gained by completely oxidizing and precipitating the salts or hydroxides before sedimentation.[63]

Well stimulation is sometimes required when the brine has not been properly treated and has plugged the well and/or the formation. Acid etch (usually HCl), explosives, and hydrofracutring are usually used to stimulate a plugged or sluggish injection well. (Of course, the well must be designed to accept the hydrofracturing or explosive pressures without collapse.) These are costly procedures and should be avoided if at all possible.

Disposal equipment can be divided into two groups: surface and subsurface. Surface equipment includes the collection and storage systems, sedimentation and treatment tanks, filters, pumps, and chemical feeders. Subsurface equipment includes the well itself and the disposal formation.

Collection and storage systems are made up of the collecting lines (usually cement/asbestos, steel, clay, or in special cases, epoxy-plastic) and the storage tanks, which can be made of cement or steel. Receptacles and transport lines that handle highly corrosive brines may have to be constructed of special materials, or be given additional protective coatings. Sedimentation treatment containers are usually wooden or steel tanks or concrete pits. The size and type of injection pump required for a given operation are determined by wellhead pressure, volume of fluid, and the peak rate of injection. Occasionally, an injection pump is not needed if the formation is permeable enough to accept the brine without pumping.[66]

The injection well itself must be properly designed, of course, for successful operation (see Chapter 4). Oil-field injection wells generally have an injection tube centered in the injection casing.[65] "Packers" are used to trap a liquid in the annulus between the injection tubing and the injection casing. This liquid is monitored to detect leaks in the injection tubing.

The formation into which the brine is injected is probably the most important part of the disposal system. Presently, much of the waste water that is generated in the oil fields is injected into the producing formation. The injection is used to maintain pressure in the field and to enhance recovery. Some oil fields have adequate natural recharge to maintain field pressure. Waste water is then injected into another permeable formation. Compatibility tests are run to determine possible reactions between the existing formation, formation fluids, and the injected fluids.[64]

Problems

The problems of disposing of saline water are both operational and environmental. The operational problems involve brine chemistry; compatibility with the formation and formation waters; corrosiveness; precipitation; and plugging of well-bores. Environmental problems include potential pollution of underground freshwater aquifers, surface leaks, and seepage from evaporation and sedimentation ponds.

In that oil-field brines have different chemical natures, each must be evaluated and tested individually to determine the operational problems and the required treatment. A few problems, however, do seem to be common to most brines.

When brines are exposed to the atmosphere, as in an open brine conditioning system, oxidation will cause precipitation of salt and hyroxides. Quite often these precipitates will clog pipes and valves and damage pumps and equipment. One way of handling this problem is to exacerbate the oxidation through aeration and then remove the precipitates through sedimentation and filtration. Another method is to install a closed system, which essentially prevents the brine from ever being exposed to the air.[67] A closed system preserves the physical and chemical properties that the brine had at the production well, increasing the chances that the injected fluid will be compatible with the formation into which it has been injected. Closed systems are less costly than their open counterparts, because they require less surface equipment, since aeration and sedimentation are eliminated. Exposure to the atmosphere is sometimes prevented by either maintaining a pressurized blanket of inert gas[63] or a layer of oil on top of the brine.

Scaling is another common and very serious problem. Scale is defined by O. J. Vetter[38] as "a secondary deposit of mainly inorganic chemical compounds, caused by the presence or flow of fluids in a system at least partially man-made." The three most predominant forms of scale are $CaCO_3$, $CaSO_4$, and $BaSO_4$. These scales can cause very serious flow restrictions in pipes or equipment at any point in a disposal system. One pipe originally 20 cm in diameter, for example, was reduced through severe scaling to a diameter of 6 cm. Flow restrictions such as these necessitate higher injection pressures, cause less oil production, and sometimes complete plugging of a well. It is estimated that $1 billion/yr is lost by the oil/gas industry in the U.S. due to scale alone.[38]

To reduce the scale problem, three different problem areas must be confronted: prediction, inhibition, and removal. Current prediction methods based on thermodynamic kinetic analyses tend to overemphasize the problem. If system conditions are mild - i.e., if the temperatures are not too high and only a small amount of scale is being formed by a large volume of water - scale can be effectively inhibited by adding chemicals to the fluid. Scale inhibitors become nearly ineffective, however, at temperatures above 175°C (350°F). Experienced plant operators can prevent numerous problems by correctly analyzing the situation in advance and then applying the appropriate chemical inhibitors.

Scale removal techniques fall into two categories: chemical methods and mechanical drilling or reaming. Drilling or reaming should really be considered a last resort for mechanical removal of scale from within the injection well, because it is very expensive and complications can occur. Mechanical methods do not clean out the formation beyond the well-bore and actually tend to plug the well by squeezing the drilling cuttings into the production slots or holes. Removal of scale from surface piping can be done if the system is designed to permit easy insertion and removal of the mechanical devices.

The difficulty and success of chemical scale removal depend on the nature of the scale. The easiest scale to remove, calcium carbonate, is usually dissolved with hydrochloric or organic acids. A 5000-gal. acid stimulation of a 5000-ft well would cost about $6,000.00, while a 10,000-gal. stimulation would run $8,000.00. Chemical gypsum or $CaSO_4$ is harder to remove than calcium carbonate and is most successfully taken care of with a two-step converter. These converters, mainly proprietary compounds containing low-molecular weight organic acids, transform the gypsum to a salt that is acid soluble. This compound is then mixed with acid, usually hydrochloric, and pumped out of the well. Barium sulfate is the most difficult scale to remove because it has an extremely low dissolution rate when paired with any of the known solvents. Long dissolution times are impractical for well stimulation.

Corrosion is another serious problem that confronts disposal-system designers and operators. Brines that contain a significant amount of dissolved oxygen are expecially corrosive to ferrous metals. All of the elements that contribute to serious corrosion of oil-field equipment are present in the salt-water disposal system. Galvanic corrosion can occur when two dissimilar metals are in contact in the presence of an electrolyte. The metal with the lowest reduction potential will be sacrificed as the anode. This type of corrosion is found at pumps, valves, and fittings for which different metals are used. Similar corrosion can occur at two different sites on the same piece of metal if one site has a reduced oxygen concentration. Oil-field acids are produced by high concentrations of carbon dioxide or sulfate salts, which can be very corrosive to bare metal surfaces.[69]

In summary, formation plugging can be caused by solids or entrained gases in the injection fluid; reactions between injected and interstitial fluids; autoreactivity of waste at aquifer temperature and pressure; and reactions between injected fluids and aquifer minerals. Plugging can also be caused by bacteria, mold, and fungi.[64]

Natural clays, such as montmorillonite and vermiculite, swell when they come in contact with freshwater. When either of these clays is in the receiving formation, the swelling will reduce the permeability and may completely plug the formation. Once a formation is plugged with swelling clays, it takes a long time for the zone to become permeable again.[70] The problem can be prevented by checking the formation for clay deposits before injecting fluids into the well; if clay is present, salt should be added to the water to retard hydration and subsequent volume increase of the clay.

Environmental problems may be caused by both surface and subsurface disposal of brines. Surface problems mainly include leakage from collection lines; malfunction of pumps and other system components; poor design of separators and settling tanks; and lack of spare or emergency systems to take over in the event of system malfunctions. Subsurface problems include contamination of underground freshwater aquifers either by leaks in the casing or by some kind of channeling from the disposal formation itself to the freshwater zones above. These leaks can be caused by corrosion of the injection well tubing, which enables the injected fluid to enter formations other than the intended one. These leaks can also be caused by unanticipated fractures that allow for channeling between the formation accepting the injected fluids and formations containing freshwater aquifers. Fracturing of the formations can be induced if the fluids are injected under sufficiently high pressure.[71] To protect the freshwater aquifers, surface casing is cemented to the formation to a depth of at least 60 m below the lowest freshwater supply.[65] Inside the surface casing, there is an injection casing and then the actual injection tubing. The potential for underground pollution can be reduced by careful geological analysis of the receiving formation for vertical fractures or leaks to higher freshwater-bearing strata.[63] Abandoned and poorly plugged wells can become channels into ground water systems; therefore, thorough review of all existing wells in the area is necessary.

Most surface pollution problems can be eliminated by proper design of the system. An essential design consideration is that of back-up equipment to handle the large amount of brine that is released when malfunctions occur or when the main well needs cleaning or unplugging. One method of providing back-up equipment would be to provide three units, any two of which could handle 100 percent of the system's peak capacity. A problem in one line then would not affect the operation of the entire system. Properly designed settling tanks should be large enough and allow a sufficient amount of time for the solids to settle out and prevent plugging and overflowing. Emergency storage facilities, pits or tanks, should also be included in the system. These tanks must be sized to retain the amount of water that might be lost from the system during a severe malfunction at peak flow for the longest possible time. Construction of a levee around the entire saltwater disposal site, including the emergency storage facilities, would provide an added measure of protection.[69]

Costs

It is difficult to arrive at a generic cost of brine disposal in the oil and gas industry. The variables involved include the extent to which the brine must be treated to satisfy compatibility with the receiving formation; the permeability, depth, and extent of the receiving formation; whether or not an abandoned well is available for injection; and the operating and accounting practices of each company.[63] Some key factors that determine the cost of treatment systems are: 1) the pH of the waste; 2) the tendency of the brine to form precipitates; 3) the size and amounts of dissolved solids; 4) corrosiveness; and 5) the physical and chemical characteristics of the formation.[65] The single biggest factor that makes an injection system expensive, though, is the depth of the well.[63]

A complete waste-injection system constructed in New Mexico in 1960 cost $562,000 while another construction in Amarillo, TX, in 1969 totaled $149,796. This divergence illustrates the wide range of capital costs and the importance of being site-specific when determining costs. The average cost of drilling and completing and oil well in 1971 was \$57.60/m (\$17.56/ft) of depth, but the actual figures ranged from \$14.00/m in Nebraska to \$95.00/m in California.[65]

Operating costs also vary widely, depending somewhat on the volume of waste for disposal. For example, at East Texas oil field, where approximately 8×10^7 ℓ/day (500,000 bbl/day) are injected, the operating costs are about 12.6 to 18.9 ¢/1000ℓ (2 to 3¢/bbl);[2] whereas at Hastings field, where only 8×10^6 ℓ/day (50,000 bbl/day) are injected, operating costs run closer to 4 to 5¢/bbl. To reduce costs, oil companies have banded together and formed large disposal companies to handle all waste injection.[2] The 2¢/bbl cost, in 1971 dollars, would project to a cost of about 20 mills per kWh in 1976 dollars for a binary plant at Heber.[46] If worst-case operating costs are assumed to be 5¢/barrel, this would project to 50 mills/kWh.

When evaluating the costs of brine disposal in the oil and gas industry, one should consider the possibility of recovering the minerals dissolved in the brine. These chemicals could help pay for all or part of the disposal costs. Recovery of certain minerals, though not economical by itself, can be justified as part of the treatment if it makes the brine more easily injected or environmentally safe. It is important to take into account the costs of putting the raw mineral, as it precipitates from the brine, into its marketable form and transporting it to market when evaluating the worth of the brine.[72] Availability and extent of alternate supplies, political situations, and new recovery technologies may alter the economics of mineral recovery from brines. Minerals that are currently being produced from sea water or underground brines are salt, magnesium metal, lithium, sodium, potassium, calcium, chlorine, bromine, and iodine. Potable water can also be considered as a by-product of treated brines.

In 1971, the U.S. Bureau of Mines Laboratory in Bartlesville (now the Bartlesville Energy Technology Center) conducted a study to evaluate the value of brines disposed of at 40 facilities. Scientists determined the maximum worth, the brine worth, and the brine value of each sample and compared each of these values to sea water and to a brine that is currently being mined for mineral recovery.[73] The results of this study are shown in Tables B.1 through B.5 in Appendix B. Table B.1 compares the chemical constituents of each of the brines to sea water (brine #1) and to a commercially exploited brine (brine #3). Table B.2 gives the formulas used to calculate the value and worth of each brine. Table B.3 shows the market values of the recovered chemical, which were used to determine brine worth. These values will change with time and may need to be re-evaluated. Table B.4 has sample calculation and Table B.5 lists the brine worths and brine values for each of the 40 samples.

It appears that only brines #2, #13, #14, #15, #16, and #17 were close in value to the commercially exploited brine (Smackover) indicating, perhaps, that a majority of disposal brines are not rich enough in minerals to justify reclamation efforts. (On the other hand, some minerals have been economically recovered from the ocean, even though sea water contains lower mineral concentrations than the Smackover formation.) In Table B.5, column 4, a ratio has been calculated of commercial brine worth versus disposal brine value. The Smackover sea water ratio is about 20; and the authors suggest this value as a minimum limit for brines that are worth investigating for mineral recovery. Two of the brines, #30 and #42, really should not be considered brines at all, for with a little treatment, both could be used for drinking water and irrigation.

6.2 NON-OIL-INDUSTRY EXPERIENCE

History of Disposal Methods

Industrial wastes have been traditionally dumped into rivers, lakes, and streams for disposal. The volumes involved are usually smaller than those in the oil industry, but quite often these wastes are more harmful to the environment. Inland waters, such as Lake Erie, have been polluted by these actions, and, even today, industry is paying heavy fines for not conforming to pollution standards.

Injection of industrial wastes is an alternative method of disposal that is relatively new and gaining in popularity. Whereas the oil industry has been injecting brine since the early 1920's, as of 1950 there were no injection wells specifically designed to handle industrial wastes. However, by 1972, some 200 wells were in operation (Figure 6.3).[74] The proliferation of subsurface disposal wells is in part due to the tightening of restrictions governing surface disposal of noxious and toxic wastes. The emphasis on injection will probably continue, as long as a way is not found to make noxious wastes suitable for surface disposal.

Types of Wastes and Volumes

Industrial wastes vary from extremely corrosive pickle liquor produced by the steel industry, to incompatible basic wastes, which cause precipitation and plugging, to noxious or toxic chemicals, which must be processed in closed systems.[65] Volume flows differ from 0.12 ℓ/sec (2 gal/min) for an oily disulfide waste from a fractionating unit to as high as 70 ℓ/sec (1100 gal/min) for a basic sodium chloride solution.

Industrial wastes can be divided into two categories: inorganic and organic. Organic industrial wastes are injected into underground formations with little or no trouble. Table 6.3 lists the organic wastes most often injected.[65]

Inorganic industrial wastes can be broken down into acidic, basic, and neutral waste classifications (see Table 6.3).[65] Neutral wastes are the easiest to contend with, occasionally requiring only filtration. Often, though, when dissolved constituents are present, more complicated treatment is necessary. Basic inorganic wastes, on the other hand, are often incompatible with formations and formation brines, causing problems with continual waste injection. Acidic inorganic wastes are generally compatible with formation brines and are easily injected. However, they are highly corrosive and hard on surface equipment. The corrosion products from these reactions can also cause plugging of the formation, as well as leaks and short equipment lifetimes.

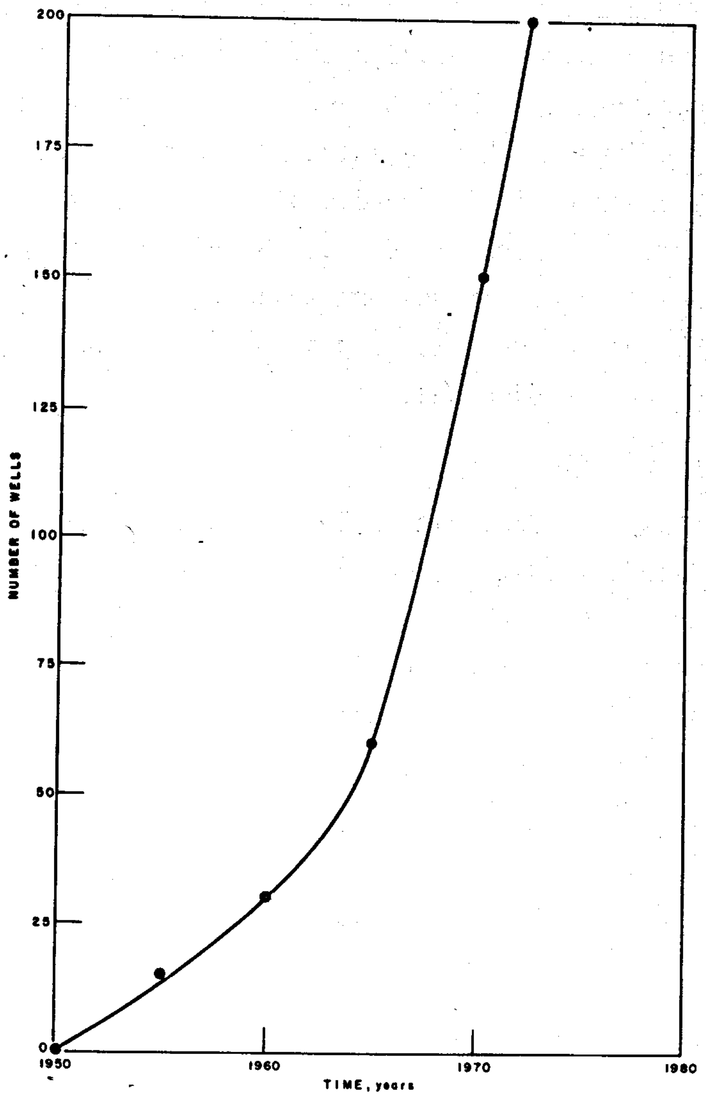


FIGURE 6.3. Growth of Industrial Underground Injection Systems in the U.S. After 1950
Source: E. C. Donaldson (Reference 74)

Present Treatment and Disposal

The oil industry has turned almost completely to subsurface injection for waste disposal, but other industries still use treatment and surface disposal. Industrial waste volumes are generally lower, and surface disposal of certain

TABLE 6.3. Organic Wastes that are Being Injected Into Deep Geologic Formations
Source: E. C. Donaldson (Reference 65)

No.	Description of waste	Injection rate, gpm	Injection pressure, psi	Depth of well, ft	Description of formation	Years in operation
	Neutral Wastes					
1.	NH_4Cl (15,000 ppm); NaCl (1,600 ppm); $CaSO_4$ (260 ppm); Na_2CrO_4 (40 ppm); $ZnCl_2$ (5 ppm); urea (4,000 ppm)	900	200	900	Limestone - vugular	1
2.	$(NH_4)_2SO_4$ (32%); NaCl (1.5%); nitriles (0.07%); BOD = 10,000 ppm; pH = 6.7	1,000	500	7,000	Sandstone - 700' thick, Ø = 28%, k = 300 md	1
3.	Na_2SO_4 (800 ppm); NaCl (300 ppm); NaF (20 ppm); $NaNO_3$ (3 ppm); $FeCl_3$ (2 ppm); $MnSO_4$ (2 ppm); $ZnCl_2$ (5 ppm); phenols (500 ppm); detergents (300 ppm); BOD = 50 ppm; pH 7.9	50	0	3,000	Limestone - vugular	3
4.	Na_2SO_4 (2,000 ppm); Na_3PO_4 (10 ppm); $FeCl_3$ (800 ppm); $NaNO_3$ (100 ppm); Na_2CrO_4 (10 ppm); pH = 7.5	80	0	3,800	Dolomite - vugular	8
5.	NaCl (1,800 ppm); $CaCO_3$ (400 ppm); $MgCO_3$ (400 ppm); $(NH_4)_2SO_4$ (1,500 ppm); hydrocarbons (1,500 ppm); pH = 8.0	50	400	1,100	Unconsolidated sand - Ø = 32%, k = 2,000 md	6
	Basic Wastes					
6.	NaOH (3.0%); Na_2SO_4 (1.0%); phenols (1.0%); acetone (0.2%); pH = 12	100	300	6,500	Sandstone with beds of sand, gravel and clay. Ø = 28-32%, k = 200-1,000 md	1
7.	NaOH (7.5%); Na_2S (1.2%); Na_2CO_3 (2.2%); Na_2SO_4 (0.7%); NaCl (0.3%); Phenols (0.5%); mercaptans (0.4%); BOD = 5,000 ppm; pH = 9.4	350	400	6,950	Unconsolidated sand - 250' thick	1
8.	NaOH (1.5%); Na_2CO_3 (5.4%); NaCl (13.1%); glycerine (5.0%); epichlorohydrin (4.6%); epoxy resin (1.9%); phenol (3.2%); acetone (1.6%); pH = 11.2	150	200	6,200	Sandstone with beds of sand, gravel and clay. Ø = 28-32%, k = 200-1,000 md	2
9.	$NaHCO_3$ (395 ppm); NaCl (9,100 ppm); $CaSO_4$ (1,360 ppm); Mg SO_4 (1,500 ppm); NH_3 (1,000 ppm); adipic acid (1,500 ppm); soluble organics (1,000 ppm); pH = 8.5. Waste HCl (6.0%) and HNO_3 (4.0%) are added at the injection pump manifold.	1,100	1,000	5,800	Limestone - vugular, with sand inclusion in some areas. Ø = 18%, k = 5 md.	6
10.	NaOH (4.0%); NaF (2.8%)	50	150	4,300	Unconsolidated sand	2
11.	NaOH (5,000 ppm); NaCl (32,000 ppm); hydrocarbons-unsaturated (1,500 ppm); BOD = 3,000; pH = 10	200	100	7,200	Unconsolidated sands containing shale and clay Ø = 27, k = 1,000 md	3
	Acidic Wastes					
12.	H_2SO_4 (7.0%); Na_2SO_4 (3,000 ppm); $CaSO_4$ (800 ppm); $Fe_2(SO_4)_3$ (700 ppm); $CrSO_4$ (150 ppm); acetic acid (100 ppm); pH = 1.0	100	300	3,800	Unconsolidated sand alternating with shale 1,500' thick, Ø = 20%, k = 1,200 md	2
13.	HCl (3.1%); $FeCl_2$ (1.8%); $FeCl_3$ (1.5%); pH = 2	100	50	4,200	Unconsolidated sand, containing clay and shale, k = 1,500 md, Ø = 32%, k = 1,500 md	1
14.	$(NH_4)_2SO_4$ (0.2%); H_2SO_4 (0.2%); HNO_3 (50 ppm); organic acids (50 ppm); Nitriles (100 ppm), pH = 2.5	350	100	4,500	Unconsolidated sand 800' thick, Ø = 32, k = 1,500 md	2
15.	NaCl (9.3%); Na_2SO_4 (27.7%); H_2SO_4 (7.8%); HCl (4.9%); H_2O_2 (2.7%); Organic acids (4.7%); Organic peroxides (3.3%); alcohols (1.9%); ketones (1.1%)	30	750	3,700	Sandstone containing chalk. Ø = 20-25%, k = 10-1,000 md	3
16.	HCl (1.1%); $FeCl_2$ (23.4%)	150	0	2,300	Sandstone - Ø = 12%, k = 100 md	6
17.	H_2SO_4 (8.5%); $FeSO_4$ (13.0%)	150	0	2,300	Sandstone - Ø = 12%, k = 100 md	6
18.	HCl (12.0%); H_2SO_4 (2.0%); NaCl (10%); acetic acid (2.0%); chloroacetic acid (1.0%); chlorinate hydrocarbons (0.5%)	200	0	4,000	Limestone - vugular	12

mildly toxic wastes can be more economical than deep formation injection. Subsurface injection, however, is becoming more popular as the environmental restrictions concerning surface disposal of noxious or toxic chemicals become more strict. Certain controls prohibit dumping on the basis of chemical content, temperature, and biological compatibility.

The equipment used to inject industrial wastes into subsurface reservoirs (see Figure 6.4) is the same as the injection equipment used by most oil companies. (Sometimes the machinery may be slightly modified to accommodate specific industrial-waste types.) The sedimentation and flocculation basins used are the same--usually cement or lined ponds with baffles and rakes--followed by an effective filtration system. Many types of chemical feeders are available to distribute the necessary chemicals. The wastes are then stored in a tank with a level sensing device to prevent cavitation of the pump. Pump and well designs are the same for industrial wastes as for oil-field brine.[74]

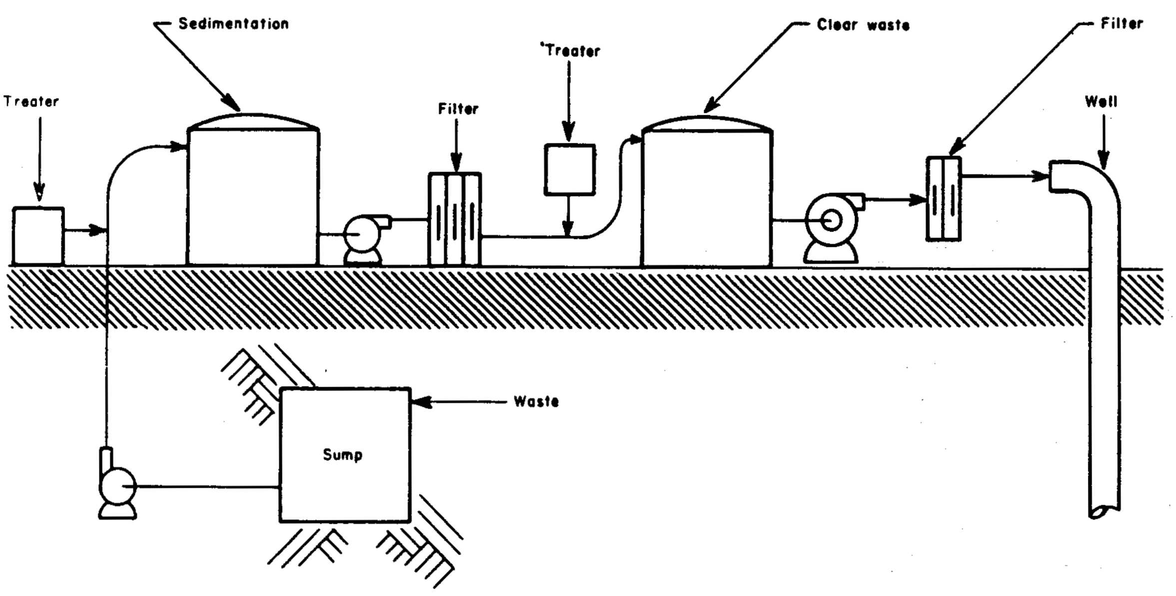


FIGURE 6.4. Surface Equipment Used in Subsurface Waste-Injection Systems
Source: E. C. Donaldson (Reference 74)

Problems

Subsurface disposal wells in both geothermal and oil industry sectors are prone to plugging and erosion caused by precipitation, to scaling, corrosion, and to formation plugging due to inefficient filtering of waste waters. If the precipitation is caused by oxidation, the problem can be solved by using a closed system. If, on the other hand, precipitation is caused by the waste cooling down or by a chemical reaction, some kind of chemical treatment may be necessary to keep the constituents in solution. Scaling and corrosion can be combated with inhibitors, corrosion-resistant tubing, cathodic protection, and various coatings.

In addition to these major injection problems, some industrial wastes have special problems of their own. The basic wastes tend to precipitate salts and hydroxides upon mixing with formation brines. If resin-like materials are present, they may polymerize and plug the formation pores, also. Dilute neutral wastes can react with certain clays such as montmorillonite or illite, causing them to swell and lose permeability. Sometimes, when the waste is extremely incompatible, it is necessary to inject a large volume of some non-reactive fluid into the well before injecting the waste. Mixing will still occur between the injected waste and the formation brine, but should occur far enough away from the well bore to prevent plugging. Highly acidic wastes can corrode surface equipment and create insoluble corrosion residue that can plug the formation. Once the corrosion problem is solved, however, the acidic wastes inject quite easily.(65)

Many of the organic industrial wastes can, indeed, be injected with little or no problem. However, those wastes containing aldehydes, phenols, and nitriles have a tendency to form water-soluble gum at the formation face. This gum can sometimes be removed by acidizing, but it may also be necessary to ream or redrill the well. As with the inorganic wastes, there are also a few organic wastes that are too noxious or toxic for surface disposal and must be disposed in a closed system.(65)

Costs

The costs for industrial waste disposal are as varied as the types of waste and the methods of disposal. It is impossible to try and generalize any kind of cost schedule for these systems. They range from $30,000 (in 1971 dollars) for a system with no pretreatment to $1,400,000 for a system with extensive pretreatment and a 3700-m deep well.(65)

Few data on the costs of surface treatment are available. In general, depending on the nature of the waste and formation, the surface disposal systems tend to offer a lower initial capital investment but a higher operating cost.

Costs of waste injection systems depend on the depth of the well, the tendency of the brine to form precipitates, the size and amount of dissolved solids, the pH factor, the corrosiveness, the characteristics of the formation, and the volume of the brine to be disposed. Donaldson has provided a very general and rough estimation of injection well costs:(65)

Dimensions, meters:	
Depth of well	915
Length of surface casing (26.7 cm)	100
Length of injection casing (17.8 cm)	915
Length of injection tubing (7.6 cm)	915
Cost, dollars:	
Drilling, completion costs	$ 50,000
Tests	10,000
Engineering	20,000
Surface equipment	120,000
Total	$200,000

6.3 COMPARISON OF INDUSTRIAL WASTE DISPOSAL TECHNIQUES AND THEIR APPLICATION TO GEOTHERMAL LIQUID WASTE DISPOSAL: PRELIMINARY ASSESSMENT

Not all industrial brine disposal experience is applicable to the geothermal field. In many respects, however, the similarities in techniques and systems designs make inter-industry comparisons worthwhile.

Geothermal liquid wastes are generally very similar to those produced during oil resource extraction, though sometimes the dissolved solid content and the temperature of the geothermal wastes are substantially higher. Geothermal brines are injected into formations similar to those used by the oil industry, so that some of the geological and hydrological knowledge about disposal formations can be transferred. Problems experienced in the industrial and oil-company sectors should be anticipated by geothermal disposal personnel. Undoubtedly, there will be compatibility problems with formation and formation waters, problems of plugging, precipitation upon cooling or oxidation, and problems of corrosion and scaling. Well plugging problems have plagued all but one geothermal brine injection well; the lone success was credited to a well whose operation was monitored for less than the customary life cycle of most wells.

The major difference between the oil industry and the geothermal-energy industry is disposal programs is attitundinal. In the oil-field brine-disposal industry, it is assumed that the brine must be treated (sometimes quite extensively) before injection, whereas in the geothermal-energy community, the policy seems to be one of little or no treatment. By virtue of its experience in the disposal field, the oil industry has learned that injection of untreated brines is seldom, if every successful over an extended period of time.

Two of the most important differences between the oil-field brine-disposal systems and those proposed for geothermal use are the volume and rate of fluids that must be disposed. The East Texas Salt Water Disposal Company injects at the average rate of 1 x 10^6 ℓ/day per well. Even with these low rates, the oil field injection wells require periodic treatments with acid to maintain well flow. The East Mesa system proposed above results in an injection flow of approximately 6 x 10^6 liters/day per well for untreated brine. The Salton Sea systems result in 2 x 10^6 liters/day per well for untreated brine and 1.4 x 10^7 liters/day per well for treated brines.[25] It may be possible to design a well to handle that rate of flow for long periods, but the problems of formation plugging, scaling, and corrosion can be expected to escalate with the volume unless the formation permeability is high.

Another difference between oil-field and geothermal injection is the temperature of the injected brine. In the oil fields, the brine is handled, treated and stored long enough so that it reaches ambient air temperature before it is injected. Geothermal fluids, on the other hand, tend to be injected into the formation at much higher temperatures. This can be either an advantage or a disadvantage for geothermal disposal. At higher temperatures, certain types of scale and precipitates ($BaSO_4$) are more soluble while others ($CaSO_4$) are less soluble. Individual assessment of the impacts of the higher temperature will have to be done for each location and brine chemistry.

In conclusion, the oil field experiences indicates that clean-up system will be required to facilitate injection of high salinity (>725,000 ppm TDS) geothermal liquids. Exceptions may be made if the receiving formation is highly fractured.

7.0 LEGAL AND INSTITUTIONAL ASPECTS OF GEOTHERMAL WASTE DISPOSAL

The objective of this section is to identify existing and proposed laws and regulations that govern geothermal waste disposal. A complete discussion of all applicable federal and state laws and regulations would be impractical here, but an overview of the basic rules and their gaps, overlaps, and contradictions will illustrate the complexity of the current situation. This section consists of three parts: 1) a review of federal regulations, 2) a review of state regulations and 3) conclusions.

Legislation and regulation for all phases of the geothermal industry have often been adopted from legal precedents established for other resources such as water, minerals, oil and gas. The most effective legislation, however, takes into account the unique properties of each resource. A recent publication by Weinstein et al. supports this premise: "The legal structure for regulation of geothermal energy development should be logically and explicitly related to the nature of the resource and the institutional arrangements most appropriate to its development."(76)

7.1 FEDERAL GOVERNMENT REGULATIONS

The surface disposal of wastes into navigable waters is regulated by the Federal Water Pollution Control Act (FWPCA), as amended by the Clean Water Act of 1977.(77) Surface disposal is controlled through the enforcement of effluent limitations, which are written into individual discharge permits. These effluent guidelines are promulgated by the Environmental Protection Agency (EPA), and permits are issued either by the EPA or by states that have an approved National Pollution Discharge Elimination System (NPDES). The basic objective of the Act is "to restore and maintain the chemical, physical, and biological integrity of the Nation's waters." To achieve this objective, the following goals are cited:

1. It is the national goal that the discharge of pollutants into navigable waters be eliminated by 1985.

2. It is the national goal that, wherever attainable, an interim goal of water quality, which provides for the protection and propagation of fish, shellfish, and wildlife and provides for recreation in and on the water, be achieved by July 1, 1983.

3. It is the national policy that the discharge of toxic pollutants in toxic amounts be prohibited.

Even though the Act does not specifically address the disposal of geothermal effluents, it refers to planning for the control of salt water intrusion into surface water-bodies and control of pollutant disposal on land and in subsurface excavations in order to protect the quality of ground and surface waters. Any user of geothermal waters who wishes to perform effluent disposal in these ways must still acquire an NPDES permit for point-source discharges. Regulation of these discharges will be handled either by the state or the EPA, and guidelines or limitations will be established based on the "best engineering judgement."[78] For most large-scale disposal programs, the character of the geothermal effluents and the implications in the Act point to deep injection as the most acceptable technique. After 1985, when the planned zero-discharge goal is realized, injection may be the only viable method for large-scale developments.

Part C of the Safe Drinking Water Act (42 USC 300 h) instructed EPA to develop minimum requirements for state programs to protect underground drinking water sources from contamination by underground injection.[79] EPA first issued proposed regulations for this purpose on August 31, 1976 (41 FR 36730).[80] In response to public comments, EPA has issued new regulations (April 20, 1979; 44 FR 23738.)[81] These rules establish the technical criteria and standards to be used in implementing the underground injection control (UIC) programs. Once the UIC regulations are promulgated, the states will be required to develop and implement programs to comply with the minimum requirements established by the EPA. For most states, barring any complications and/or noncompliance of the state's programs, implementation should occur in the spring of 1981.

Geothermal energy production and the disposal of geothermal wastes will be affected by the proposed regulations. The particular permitting and substantive standards that apply depend on the classification of a particular well. The regulations establish five classes of injection wells. Since the classifications depend partly on the relationship of the well to an underground drinking water source, the definition of such sources is important. According to the proposed regulations, a "source" includes all aquifers that currently provide drinking water or that contain fewer than 10,000 parts per million of total dissolved solids. The Safe Drinking Water Act allows, but does not require, states to exclude portions of aquifers that produce geothermal energy. A state may also exclude aquifers that cannot be reasonably expected to supply drinking water (Proposed 40 CFR 146.04, 44 FR 23758).[81]

The EPA has divided injection well practices into five different catagories, of which geothermal wells are designated Class III:[81]

> Class III includes all special process injection wells, for example, those involved in the solution mining of minerals, in situ gasification of oil shale, coal, etc., and the recovery of geothermal energy.

To operate a new Class III well, a party must obtain a permit prior to startup; and old wells must be certified within 5 years of the effective date of the Underground Injection Control program. Class III injection wells that pass through a surficial aquifer must meet casing and cementing standards designed to protect the aquifer. It must be demonstrated through specific tests or construction records that the wells are mechanically sound. This substantiation must be provided at the time the well is initially set in operation, and once every 5 years thereafter. If a geothermal field contains several wells of the same design and age, the proof-of-integrity requirement may be waived for all but a certain percentage of the similarly-patterned wells.

The Geothermal Supervisor, a representative of the Secretary of the Interior, has the authority to "prescribe rules and regulations" on operations conducted under a geothermal lease granted pursuant to the Geothermal Steam Act. This authority is granted under 30 CFR Part 270 of Title 30 - Mineral Resources. The essence of these regulations with respect to waste disposal can be summarized in the following three quotations:

> 30 CFR, Part 270.30 (b). "The lessee shall take all reasonable precautions to prevent: 1) waste; 2) damage to any natural resource . . .; 3) injury or damage to persons, real or personal property; and 4) any environmental pollution or damage."

> 30 CFT, Part 270.35. "After completion of all operations authorized under any previously approved notice or plan, the lessee shall not . . . use any information or well for brine or fluid injection until he has submitted to the Supervisor in writing a new plan of operations and has received written approval from him."

> With respect to pollution, 30 CFR, Part 270.41 states: "Plans for disposal of well effluents must take into account effects on surface and subsurface waters, plants, fish and wildlife and their habitats, atmosphere, or any other effects which may cause or contribute to pollution, and such plans must be approved by the Supervisor . . ."

Geothermal Resources Operational Orders 1-7 will be carried out by the U.S. Geological Survey. These Geothermal Resources Operational Orders (GRO) under the authorization of 30 CFR, Part 270 are titled as follows:

GRO Order 1: Exploratory Operations
2: Drilling, Completion and Spacing of Geothermal Wells
3: Plugging and Abandonment of Wells
4: General Environmental Protection Requirements
5: Plans of Operation, Permits, Reports, Records and Forms (Proposed)
6: Pipelines and Surface Production Facilities
7: Production and Royalty Measurement Equipment and Testing Procedures

GRO Orders 1-3 do not pertain to liquid waste disposal.

GRO Order 4 states the requirements to maintain aesthetics, control land use and reclamation, maintain public access, protect recreational values, maintain slope stability and control erosion, protect biota, and preserve cultural resources. These categories are addressed in a nonspecific sense, and liquid waste disposal is not mentioned. Section 8 of GRO Order 4 addresses the control of subsidence and seismicity. "If subsidence is determined . . . to present a significant hazard to operations or adjoining land use, . . . increased injection of waste or other fluids" may be required. This requirement may also be placed on the lessee if seismicity is determined to be hazardous. Section 9.A. (1) specifically addresses pollution control from liquid disposal.

> "Liquid well effluent or the liquid residue thereof containing substances, including heat, which may be harmful or injurious and cannot otherwise be disposed of in conformance with Federal, state, and regional standards, shall be injected into the geothermal resource zone or such other formation as is approved by the Supervisor. Toxic drilling fluids shall be disposed of in a manner approved by the Supervisor and in conformance with applicable Federal, state, and regional standards."

Section 9.A. (4) of Order 4 regulates the use of pits and sumps, requiring the use of impervious liners and the purging of harmful materials prior to backfilling after useful life is ended. Section 9.C (1) - (5) in GRO Order 4 specifies that the permitee must supply the following materials if injection wells are to be used:

(1) Plan of Injection
(2) Monthly Injection Report
(3) Periodic Inspection
(4) Application for New Injection Wells
(5) Well Conversion Requirements

If liquid waste disposal other than injection is proposed by the lessee, the Plan of Development must include the following elements from <u>GRO Order 5</u>:

". . . (a) A statement of proposed surface facilities (equipment with flow-line drawings)
(b) Specification of the volume of waste and a proposed method of disposal
(c) Account of the compatibility of waste liquids with surface and ground waters of the area
(d) A proposed method of maintaining separation of waste from the natural water systems (taking into account the proximity and quality of surface and ground waters)
(e) A calculation of the permeability of the proposed impoundment or the proposed method of maintaining separation of waste from the natural water systems

(f) A proposal for the treatment of waste liquids
(g) A plan for monitoring and keeping records.

If injection is the proposed disposal method, the Plan of Injection mentioned in GRO Order 4, Section 9.C. (1) is expanded in GRO Order 5, Section 1.F. (1) - (9), to include the following requirements:

(1) a map of the area
(2) a listing of the injection fluid characteristics
(3) disposal zone characteristics
(4) subsurface maps and cross sections
(5) available logs or histories of area wells
(6) description of a representative injection well drilling program
(7) proposed downhole and surface injection equipment
(8) proposed injectivity surveys
(9) a study of hydrology of the area.

GRO Order 6 involves design and construction requirements for pipeline and surface facilities. Under general design, this Order regulates the protection of pipelines from thermal expansion, specifies anchoring requirements, and specifies design requirements for two-phase flow. Under Safety Control Devices, this Order specifies injection well design for maximum injection pressures and methods for sensing and control of injection pressures.

GRO Order 7 specifies that a waste heat measurement to within 2 percent must be recorded for royalty metering.

In sum, the GRO Orders consist of rather general requirements for the design of waste disposal systems and the protection of the environment. Detailed requirements for plans, reports, inspections, and approved mechanisms are not included. Considerable latitude exists because of the general nature of the requirements and the Geothermal Supervisor's freedom to determine courses of operation. The specific nature of systems design and the enforcement of environmental protections are somewhat subject to supervisory discretion.

Another law that could potentially affect the disposal of geothermal wastes is the Resource Conservation and Recovery Act of 1976 (RCRA), PL94-580.[82] RCRA substantially amends and completely replaces the previous language of the Solid-Waste Disposal Act. The law requires EPA to define hazardous waste and to publish standards so that wastes defined as hazardous can be disposed of, treated, or stored at the place of generation or at an off-site facility in a manner to protect public health and the environment. Title II (Solid Waste Disposal) of RCRA provides statutory authority for the EPA to develop hazardous waste guidelines and regulations. To facilitate the requirments of RCRA, the Environmental Protection Agency proposed hazardous waste guidelines and regulations on December 18, 978 (43 FR 58946).[83] Revisions to the proposed guidelines and regulations are currently being made by the EPA and should be completed in 1980.

The main objective of the hazardous waste management program is to insure that hazardous wastes are identified and competently controlled from the point of their generation, during their transportation and to their ultimate disposition at a permitted treatment, storage, or disposal facility. The applicability of these regulations to both temporary disposal of geothermal wastes in ponds and permanent disposal of wastes at the geothermal power-plant site depends on the identification of geothermal wastes as a hazardous substance. The most important aspects of the hazardous waste management program are identification and inclusion of hazardous wastes in the control system. Responsibility to identify hazardous wastes and to insure proper control of the waste is assumed by the generator of the waste. Wastes are defined to be hazardous if they meet the EPA-established criteria of ignitability, corrosivity, reactivity, toxicity, radioactivity, infectiousness, phytotoxicity or teratogenicity and mutagenicity. Since the chemical content and hazardous nature of geothermal wastes may vary from site to site, specific wastes from individual facilities must be tested to determine their hazardous qualities. Specific test procedures are described in the proposed regulations. The operation of a geothermal power plant and disposal facility requires compliance with 40 CFR Part 250 Subparts B, D and E of the proposed regulations.[83] These subparts establish standards applicable to generators of hazardous wastes and to owners and operators of hazardous-waste treatment, storage, and disposal facilities.

These standards specifically set requirements for record keeping, reporting, site location and design, operating methods, contingency plans, continuity of operations, personnel training, financial responsibility, monitoring, inspection, and compliance with a manifest and permit systems.

It is too early to discern whether the geothermal industry will be affected by the Toxic Subtances Control Act.[84] This act, which will be implemented by the EPA, gives the federal government blanket authority to regulate any substance that may present an unreasonable risk of injury to the health or the environment. The wording of the law implies that controls are desired over the manufacture, processing, distribution in commerce, use, and disposal of many chemical substances and mixtures. Possibly, the controls will be aimed at manufactured chemicals rather than substances produced from geothermal reservoirs (except those that are commercially produced). The definitions are not only unclear, but there also exists a potential for conflicting legislation among the Toxic Substances Control Act, the FWPCA Amendments, the SDWA, and the Conservation and Recovery Act. If geothermal disposal gets entangled in this web of overlapping jurisdiction, delays in obtaining permits will inevitably result.

One final act on the federal level will affect the disposal of geothermal effluents. The Geothermal Steam Act states in Section 9:

> If the production, use or conversion of geothermal steam is susceptible of producing a valuable byproduct or byproducts, including commercially demineralized water for beneficial uses in accordance with applicable state water laws, the Secretary (of the Interior) shall require substantial beneficial production or use thereof unless, in individual circumstances, he modifies or waives this requirement in the interest of conservation of natural resources or for other reasons satisfactory to him. However, the production or use of such byproducts shall be subject to the rights of the holder of preexisting leases, claims or permits covering the same land or the same minerals, if any.[85]

One additional section of the Steam Act may affect the disposal of geothermal effluents. Section 23 states that the lessee, in all stages of geothermal development, should "use all reasonable precautions to prevent waste of geothermal steam and associated geothermal resources." Eventual impact of Section 23 on effluent disposal is unknown.

In summary, the laws passed by the Congress that affect geothermal disposal have concentrated mostly on protecting the environment and not so much on promoting geothermal development per se. Moreover, the lack of definition in existing regulations, the complex requirements for permits, and the potential for overlapping jurisdiction will continue to hamper the development and utilization of geothermal energy.

The organizaton most involved in the regulation of geothermal effluent disposal is the EPA, which has been charged with responsibility of administering FWPCA, the SDWA, the Resource Conservation and Recovery Act, and the Toxic Substances Control Act. Permits issued for disposal activities and the enforcement of regulations are taken care of either by the EPA or by those states that have EPA-approved plans.

The EPA is planning to issue a series of documents leading to the establishment of regulatory standards for the geothermal industry. EPA's regulatory approach has the following objectives:

(a) to establish point-source emission and discharge limitations for all environmentally damaging constituents

(b) to provide guidelines on anticipated limitations to development

(c) to minimize environmental constraints caused by uncertainties in emission and discharge requirements

(d) to evaluate information on guidance throughout precommercialization stages

(e) to regulate pollution through permit systems.

Other agencies involved in disposal are the Bureau of Land Management and the U.S. Forest Service. The Bureau of Land Management is the administrative agency for lands owned by the federal government, and the U.S. Forest Service administers national forest lands. These agencies may issue permits for disposal, but any action taken is subject to compliance with state and federal water quality requirements. With respect to environmental matters, it is expected that the EPA will maintain regulatory powers, but it is unclear whether or not the Department of Interior will assume general supervisory powers over the broader aspects of geothermal disposal.

The Department of Energy (DOE) will also play a role in geothermal energy development. Although not a regulatory agency, DOE promotes favorable policies for the development of geothermal resources, assists in planning for future exploration and development, and supports research activities aimed at solving both technical and institutional barriers to rapid geothermal development.

7.2 STATE REGULATIONS

7.2.1 California

The state of California possesses the only electrical generating power plants that use geothermal energy in the U.S. In addition, exploration of other areas within the state indicates that California may have the nation's largest potential supply of geothermal energy. As a result, the level of regulation and legislation of geothermal activities is more advanced in this state than in any other.

The Geothermal Resources Act of 1967 identifies the means by which state-owned lands can be leased from the State Lands Commission for geothermal development.(86) The activities that take place after the lease is secured are governed by Title 14 of the California Administrative Code.(87) Chapter 4 of the Natural Resources Section of the Code deals with the rules and regulations governing oil and gas operations within the state, to be administered by the Division of Oil and Gas within the Department of Conservation. Subchapter 4 contains the state-wide geothermal regulations. Numerous sections of this subchapter deal with geothermal disposal as it relates to injection of effluents back into the geothermal formation.

According to Section 1931.2, the geothermal operator is required to give notice and receive approval to convert an existing well into an injection well. Sections 1935, 1935.2, and 1935.4 establish casing requirements for geothermal wells. Under these regulations, operators are required to file monthly injection reports in accordance with Section 1937.1(3). Article 6 (Section 1960-1967) deals specifically with injection, and regulates the approval of projects, surveillance of the wells, injection reporting, and the abandonment of the injection well.

The environmental aspects of the disposal of geothermal effluents are presently regulated by the State Water Resources Control Board, established in the Porter-Cologne Water Quality Control Act of July 1976.[88] This Act was passed in conjunction with the Federal Water Pollution Control Act Amendments of 1972. Chapter 1 of this Act declares that regulation over the "conservation, control, and utilization of the water resources of the state" will be maintained to "attain the highest water quality which is reasonable, considering all demands being made and to be made on those waters. . ." With respect to waste discharge requirements, Chapter 4 states that "any person discharging waste or proposing to discharge waste wihin any region that could affect the quality of the waters of the state. . . shall file with the regional board (Regional Water Quality Control Board)." The Regional Board has the power to control the nature and extent of these discharges. Chapter 7 prohibits the injection of wastes into a domestic water supply source, in conjunction with the proposed rules of the Safe Drinking Water Act.

The California State Water Resources Control (WRC) Board has recently established state-wide guidelines for land disposal of wastes. These requirements generally cover the disposal of wastes from ponds or lagoons, and of wastes from heat rejection systems.[89] The jurisdictional scope of WRC regulations is unclear, because land-disposal permits are also required by the California Solid Waste Managements Board and the State Department of Health. The WRC amendments describe four different site classifications, ranging from absolute prohibition of runoff or overflow disposal (complete containment) to direct dumping of wastes into surface or ground waters. Three separate waste classifications have been established:

Group 1 Wastes - wastes that contain toxic substances or substances that could affect the quality of usable waters.

Group 2 Wastes - wastes that contain biologically or chemically decomposable material that will not damage water quality.

Group 3 Wastes - wastes that consist of nonwater-soluble or inert solids.

Article 3, Section 2520(b) catalogues wastes of industrial origin that fall into Group 1: "Brines from food processing, oil well production, water treatment, industrial processes, and geothermal plants." (The term brine is not defined, but is usually characterized as having 36,000 ppm TDS.) If all wastes from geothermal plants are Group 1 wastes, they can only be disposed of in Class I disposal sites (the most strict classification), or in rare instances, in Class II-1 disposal sites. In California, Class I and II-1 sites are presently used for the surface disposal of geothermal wastes. Some of the characteristics of each of these sites are listed below.

Site Characteristics

Class I	Class II-1
Complete isolation from waters.	Near complete isolation from waters.
Cannot overlay usable ground waters except under exceptional cases	May overlay ground waters with impermeable barriers; requirements lowered from Class I.
Stringent requirements for impermeable barriers	Washout or inundation protection from 100-year flooding.
No washout or overflow allowed.	Controls for minimum leachate production.

These three regulatory documents illustrate the extensive coverage that has been given to geothermal waste disposal with respect to injection engineering requirements, disposal to surface and ground waters, and land-site disposal. Experience with these regulations will be discussed later.

Three major organizations control disposal of geothermal effluents in California. The State Lands Commission controls the leasing of state-owned lands for geothermal development. The Division of Oil and Gas of the Department of Conservation regulates the day-to-day activities of geothermal operations, and is mostly concerned (in the context of this report) with the engineering aspects of disposal by injection. The California State Water Resources Control Board and Regional Water Quality Control Boards are responsible for maintaining the quality of California waters. The Board is responsible statewide for water pollution control, the maintenance of water quality, and the enforcement of water rights. Regional boards may adopt water quality control plans, prescribe waste discharge requirements, and perform other water quality functions within their respective regions with State Board approval. The State Solid Waste Management Board and the Department of Health require permits to allow land disposal of solid wastes.

Other agencies that may influence disposal of liquid wastes include the Fish and Game Department, the Air Resources Board, and the California Energy Commission (which was created by the Warren-Alquist Act). The Energy Commission has the primary responsibility of bringing electrical energy supply-and-demand into balance through resource conservation and development, especially geothermal and solar.[(86)] No direct interaction with disposal is anticipated.

Certain counties in California exercise considerable control over geothermal operations, a somewhat unique aspect mainly brought about by the extensive developments in the state. The counties interact on many levels, but perhaps the main aspect is that the counties are the lead agencies responsible for determining whether or not an Environmental Impact Report (EIR) is required prior to development in a manner described by the California Environmental Quality Act of 1970.[(90)]

The general attitude in California is pro geothermal, but increasingly closer regulation of activities has slowed the commercialization of geothermal resources. Major concerns have been voiced about certain permitting requirements, the implications of the SDWA, the preparation of EIRs, and the long-term protection of the environment. The need for energy in the state will most likely force a streamlining of the regulatory processes and a more diligent promotion of geothermal energy.

7.2.2 Oregon

Oregon has had a long history of nonelectric utilization of geothermal energy. The most highly developed geothermal area in Oregon is Klamath Falls, where geothermal heat has been used mainly for space heating since around the turn of the century.[91] Geothermal regulations are more advanced in Oregon than in most other states and are administered by three separate state agencies--the Department of Geology and Mineral Industries (DGMI), the Department of Water Resources (DWR), and the Department of Environmental Quality (DEQ).

Geothermal regulations were adopted by the Oregon Department of Geology and Mineral Industries (DGMI) in 1972, and placed in the Oregon Administrative Rules Compilation.[92] The DGMI - the main geothermal regulatory agency in Oregon - is authorized to "control the drilling, redrilling, and deepening of wells for the discovery and production of geothermal resources so that such wells will be constructed, operated, maintained and abandoned in the manner necessary to safeguard the life, health, property and welfare of the people of this state and to encourage the maximum exonomic recovery of geothermal resources therefrom" (Section 20-005-1). In these regulations, geothermal resources include heat, contained minerals and fluids, but exclude oil, hydrocarbons, and waters less than 250°F (Section 20-010-5). Waters from wells deeper than 2000 feet are automatically classified as geothermal. By this definition, the Klamath Falls development is not controlled by DGMI regulations.

Fluids outside the DGMI classification are regulated by the Department of Water Resources (DWR), which regulates ground-water supply and water rights. The DWR classifies geothermal fluids as ground water, and attempts to regulate the supply and appropriation of this resource as such. A third agency, the

State Department of Environmental Quality (DEQ), is charged with the responsibility of maintaining the quality of surface prior to the disposal of any effluents from a geothermal site. To protect against any unforeseen environmental hazards, the DEQ regulations also state that the geothermal operator must not "pollute land, water or air. . ., and the operator must comply with Federal and state air and water quality standards." The DEQ has prepared a water quality management plan for the State of Oregon, based on the requirements of the FWPCA and Oregon Law (ORS Chapter 468).[7.20] The stated objectives of this plan are summarized below:

- to identify beneficial uses for public waters
- to establish water quality standards
- to protect existing water quality where qualities exceed established standards
- to guide waste treatment and controls for future growth
- to identify water quality deficiencies and noncompliance, and to propose and implement the necessary corrective action.

The plan addresses 19 separate drainage basins in Oregon, describes beneficial water uses, water quality standards, and minimum controls for waste treatment, and identifies needs and proposed actions. No mention is made of the geothermal activities in the Klamath Basin. It is certain that this DEQ water management plan, when implemented, will affect geothermal disposal by the enforcement of surface water quality standards.

Conflicts may arise between DEQ and DWR, since both agencies are partially responsible for regulating the use of ground water. At the present time, it appears that a permit from both departments will be necessary to use or dispose of ground waters. The basic policy of DWR at the present time centers around zero discharge and nonconsumptive uses of underground waters; this policy may force injection back into the original production zone. Since relatively little large-scale development has occurred in Oregon, the final resolution of these issues is not known. (One other agency, the Health Division, may become involved with geothermal disposal if existing or potential drinking water sources are involved.)

The overlapping jurisdictions of DEQ and DGMI will have to be addressed in the event that a large geothermal installation is proposed. The disposal of effluents from geothermal installations is not now considered to be a problem, mainly because of the low activity level. However, Oregon places a high value on the environment and will insist that new projects adhere strictly to regulations. The major concern with geothermal energy now appears to be the prevention of energy waste.

As in other states, there is some concern about the effect of the Safe Drinking-Water Act (SDWA) on geothermal development. In any case, it now appears that Oregon will choose not to administer a SDWA program, but will allow the EPA to do so.

7.2.3 Utah

Utah's experience with geothermal energy has been relatively short. The major development to date has been in the Roosevelt Hot Springs area in the southwestern part of the state. Utah has passed "Rules and Regulations for Wells Used for the Discovery and Production of Geothermal Energy," to be administered by the Division of Water Rights. To date, geothermal reservoirs have been handled as a water source. The Water Pollution Control Act of Utah, the major single piece of legislation applicable to geothermal effluent disposal,[93] is modeled after the Federal Water Pollution Control Act, and is more stringent than some of the federal requirements with respect to water quality. Some of the features of the Utah Act are listed below.

- The water quality of surface streams cannot be degraded by disposal of effluents. Many streams in Utah are less than 500 ppm in total dissolved solids.
- Injection into freshwater aquifers is not allowed.
- The salinity of the Colorado River cannot be increased.

- Design criteria for municipal and industrial waste treatment processes have been established.
- Temporary surface ponding is allowed with proper engineering and construction so as to restrict waste seepage through the walls of the ponding bed.
- Injection is the preferred method for large-volume disposal, but the wastes must be placed either back into the production formation or into some zone of equal or poorer quality.

Two organizations - the State Divison of Water Rights and the Water Quality Section of the Board of Health - are usually involved in regulating geothermal development in Utah. The State Engineer of the Division of Water Rights is responsible for protecting water rights and overseeing resource developments involving all state waters. The Water Quality Section of the Board of Health regulates Utah water quality in general.

The relative youth of Utah's geothermal industry and its short regulatory history make impacts on geothermal disposal difficult to pinpoint. Currently, there appears to be some confusion over the interface of water rights and geothermal fluids. If geothermal fluids brought to the surface become a part of the surface estate, then do the downstream users of water own that water and can they dictate its disposition? If zero-discharge is a requirement, injection is a must, but will the SDWA cause difficulties for producers who choose injection? How does the use of geothermal resources affect the ground water system?[94] These questions must be answered if citizens of Utah are going to utilize their new-found resource, and at the same time maintain an acceptable supply and quality of state waters.

Apart from this dilemma over water rights, Utah accepts injection as the preferred technique for disposal as long as the effluents are put back into their original formation or some equally impure zone. Discharge into streams, freshwater aquifers, or the Colorado River is unlikely without adequate treatment.

7.2.4 Nevada

Nevada has been the site of numerous geothermal exploration projects, including those at Beowawe, Brady Hot Springs, Leach Hot Springs, and Kyle Hot Springs. Some recent discoveries at Desert Peaks by Phillips Petroleum show a promising geothermal future for that area. A facility to directly use geothermal energy for vegetable dehydration is under construction at Brady Hot Springs by Geothermal Food Processors, Inc., and the Magma Power Company.

No geothermal regulations exist in the State of Nevada, but there appears to be some motivation to promulgate regulations similar to those for the oil and gas industry. Currently, permits are not required to drill geothermal wells, but approval is required from the State Division of Water Resources (DWR) to produce a well. A permit is also required from DWR for the use of a production or injection well; the process follows the usual path of filing an application, giving the public an opportunity to act, and then finally processing the permit at DWR.

The regulation of geothermal effluents is not specifically addressed in Nevada State regulations; however, the Division of Environmental Protection Services has jurisdiction over water quality and disposal of wastes to surface and ground waters. The State Water Pollution Control Regulations for Nevada were adopted by the State Environmental Commission in October 1973, and closely follow the guidelines established in the FWPCA. Nevada has an approved NPDES program, which is administered by the Division of Environmental Protection Services.

Even though some of the remote areas of Nevada may be considered as possible surface disposal sites, it is unclear whether these sites can be considered permanent or can be used extensively without the use of impermeable barriers. When the Resource Conservation and Recovery Act is promulgated, the requirements for surface disposal will be more stringent.

On the subject of adopting regulations for geothermal industry similar to those for the oil and gas industry, there is some feeling that such regulation would not greatly reduce conflicts over water rights, but would instead impose stricter standards for drilling operations. The access and supply issues over water rights are not amenable to solution through drilling regulations.

7.2.5 Idaho

Idaho has placed a great deal of positive emphasis on geothermal developments, largely through the efforts of state agencies, the Idaho National Engineering Laboratory, and the Department of Energy. The main developments are currently in the Raft River area and the City of Boise. The regulatory foundation for the development of geothermal resources has also been established.

In 1972, Idaho passed the Geothermal Resources Act.[95] In 1974, the Act was updated to reflect the reorganization of State agencies. The Act states that "it is the policy and purpose of this state to maximize the benefits to the entire state, which may be derived from the utilization of our geothermal resources, while minimizing the detriments and costs of all kinds which could result from their utilization." The Act defines geothermal resources to be "sui generis, being neither a mineral resource nor a water resource, but they are also found and hereby declared to be closely related to and possibly affecting and affected by water and mineral resources in many instances." The Act outlines the requirements for submitting production or injection well drilling permit applications to the State Department of Water Resources, which is the lead agency in Idaho for the exploration and development of geothermal resources. The Act also established abandonment procedures and provisions for utilization of geothermal reservoirs. As a supplement to the Act, the Department of Water Resources has prepared rules and regulations and minimum construction standards for geothermal wells.[96] Rule 7 of this document addresses injection wells. The permit application routinely requires information about existing reservoir conditions, the method of injection, the source of injection fluid, estimates of the amount of fluid to be injected daily, the zones or formations affected, and analysis of injected fluid and fluids already in the injection zone. The rules also list surveillance requirements.

Water quality standards and waste-water treatment requirements were established by the State in June 1973.[97] These regulations are enforced by the Division of Environment of the Department of Health and Welfare. The regulations cover both surface and ground waters, and adopt an antidegradation policy that states that "waters whose existing water quality is better than the established standards. . . will be maintained at their existing high level" Section III (D). This requirement goes beyond the normal requirement of adherence to minimum water quality standards. Specific regulation of disposal into injection wells is included, also, requiring adequate treatment of wastes so as to make the quality of the effluent equivalent to the existing underground water Section X (I). Minimum requirements are listed for land disposal of waste-waters, and are intended to prohibit "a public health hazard, a nuisance condition, or an air pollution problem" Section XI (B). Regulation of geothermal resource disposal in Idaho is aimed both at promoting development and minimizing deleterious effects.

The State's attitude toward geothermal disposal is still in the formative stage. Injection appears to be the preferred technique, for it is thought to conserve the resource and protect the State's waters. Surface disposal may be extremely difficult to implement in light of Idaho's antidegradation policy. One exception may be the use of geothermal effluents that are low in contaminants as irrigation water during periods of drought.

7.2.6 New Mexico

Geothermal investigations in New Mexico have been undertaken by Union Oil Company near Vallez Caldera and by Los Alamos Scientific Laboratory near Fenton Hill. Leasing of state geothermal lands is regulated by the State Lands Office according to the "Rules and Regulations Relating to Geothermal Resources Leases" (1971). The Oil Conservation Commission regulates geothermal drilling through the "Rules and Regulations of Geothermal Resources" (Order No. R-4860, 1974). Regulations for water quality are contained in the New Mexico Water Quality Act,[98] and are enforced by the State Water Quality Control Commission, which has delegated the responsibility of monitoring discharges from oil and gas facilities to the Oil Conservation Commission, and the remainder to the Environmental Improvement Agency (EIA).(99) New Mexico does not have an approved NPDES system; therefore, federal regulations under FWPCA are implements by the EPA. The water quality regulations profess the following purpose:

> The purpose of these regulations controlling discharges onto or below the surface of the ground is to protect all ground water of the state. . .which has an existing concentration of 10,000 mg/ or less TDS, for present and potential future use as domestic and agricultural water supply.

The regulations are meant to allow the degradation of existing ground waters up to the limit of the established standards. A separate antidegradation policy exists for streams in New Mexico.(100) The Water Quality Control Commission states:

> Degradation of waters, the quality of which is better than the stream standards established by the New Mexico Water Quality Control Commission, is not reasonable. . ., unless it is justifiable as a result of necessary economic and social development.

This passage points out two interesting aspects of the New Mexico regulations: (1) the distinction between surface and ground waters with respect to degradation, and (2) the practical notion that, at some time, limited degradation of surface waters may be necessary due to economic or social factors.

The remaining water quality regulations describe the permitting procedure in detail, and set standards for eight separate water basins in New Mexico. No specific mention of the disposal of geothermal wastes exists in the regulations or standards.

In summary, the New Mexico Water Quality Control Commission is the agency charged with the responsibility of regulating water quality within the State. Either the EIA or the Oil Conservation Commission is delegated the responsibility of administering the standards and regulations. The New Mexico Water Quality Act implies that the EIA will regulate all disposers of waste materials, with the exception of the oil and gas industry. It is not yet known whether the Commission will adhere to this interpretation, because geothermal resources can be classified as an energy source similar to oil and gas. The scope of the regulation may be resolved as the Vallez Caldera geothermal field nears completion.

The implemenation of the water quality control regulations with respect to injection and the utilization of geothermal resources are both at an early stage in New Mexico, and any conclusions concerning current State attitudes are premature. New Mexico is concerned about the quality of its waters, more so with surface than ground waters. New Mexico also recognizes the increasing need for energy, and has made provisions to promote development without unduly harming water quality.

7.2.7 Hawaii

Hawaii is enthusiastic about developing geothermal resources within its own borders, although it has only one geothermal well in place at this time. State planners are anxious to reduce the state's dependence on energy imports.

Currently, geothermal operations are approved or disapproved by the State Deparment of Land and Natural Resources through "Regulations on Leasing and Drilling of Geothermal Resources" (Reg. No. 8). (The DLNR is the lead agency for geothermal activity in Hawaii.) The legislation addresses:

- leasing of state lands
- permitting procedures for well drilling
- procedures for protection of Hawaii's freshwater lens
- a flexible design to encourage development and to handle future issues
- designs to complement all federal, state, and local laws concerning environmental protection.

Injection is considered to be the most desirable technique for large-scale disposal of effluents in Hawaii, although caution must be exercised to protect the freshwater lens. Emphasis has been placed on the promotion of geothermal development in regulations, and the general attitude is positive. The Department of Planning and Economic Development programatically encourages the development of geothermal resources.

7.2.8 <u>Texas</u>

Texas has not yet experienced extensive geothermal development, but is a prime state for the utilization for geopressured resources. Texas is also reasonably well prepared to handle geothermal waste disposal due to its long experience with oil brine and industrial waste disposal.

Texas' Geothermal Resources Act of 1975 is modeled closely after the Geothermal Steam Act, but does include "geopressured waters" in its definition of the resource.[101] The Act specifies the rules for leasing of State lands and the regulations for drilling on public and private lands. Leasing regulations are now pending, with final authority resting with the State Land Office. Drilling operations are controlled by the Texas Railroad Commission.[102] In the Act and in the Commission rules, the Railroad Commission has been given the responsibility of regulating the exploration and development of geothermal resources, and for protecting the environment and the public from hazards. Rule 8(A) states, "Freshwater whether above or below the surface, shall be protected from pollution. . ." Other rules associated with disposal and environmental protection are listed below.[103]

> <u>Rule 8(B)</u>: The operation of each ". . .geothermal resource well or well drilled for exploratory purposes. . .shall be carried on so that no pollution of any stream or water course of this state, or any subsurface waters, will occur as the result of the escape or release or injection of geothermal-resource or other mineralized waters from any well."

Rule 8(C): All operators conducting ". . .geothermal resources development and production are prohibited from using saltwater disposal pits for storage and evaporation of. . .geothermal resource waters. . ." (1)(b) "Impervious collecting pits may be approved for use in conjunction with approved saltwater disposal operations. . " (1)(C) "Discharge of. . .geothermal resource waters into a surface drainage watercourse, whether it be a dry creek, a flowing creek, or a river, except when permitted by the commission, it is not an acceptable disposal operation and is prohibited."

Rule 8(D): (1) "The operator shall not pollute the waters of Texas offshore and adjacent estuarine zones or damage the aquatic life therein." (2) ". . .geothermal resource well drilling and producing operations shall be conducted in such a manner to preclude the pollution of the waters of the Texas offshore and adjacent estuarine zones." (2)(a) "The disposal of liquid waste materials into the Texas offshore and adjacent estuarine zones shall be limited to saltwater and other materials which have been treated, when necessary for the removal of constituents that may be harmful to aquatic life or injurious to life or property."

Rule 9(A): "Salt water. . .unfit for domestic, stock, irrigation, or other general use may be disposed of. . .by injection into the following formations: (1) All nonproducing zones of oil, gas, or geothermal resources bearing formations that contain water mineralized by processes of nature to such a degree that the water is unfit for domestic, stock, irrigation or other general uses."

Permits for drilling or operation of wells may be obtained without notice of public hearing if all surrounding owners and offset operators do not object within ten days after the application is filed. Public hearings are held upon request.

Under the rules of the Texas Railroad Commission, the following aspects of disposal are indicated:

- Temporary saltwater collecting or storage pits are permitted if they have impermeable barriers.
- Saltwater treated to remove harmful constituents may be released into bays, estuaries, and the Gulf of Mexico.
- Under restricted conditions, saltwater disposal into natural water courses is permitted.
- The lowering of standards for some water bodies is permitted if sufficient justification exists.

Another law having great influence on the disposal of geothermal effluents is the Disposal Well Act, formerly known as the Injection Well Act.(104) The Disposal Well Act separates waste into two categories-- industrial and municipal waste, and oil and gas waste. Industrial and municipal waste includes that from the "development or recovery of natural resources other than oil or gas" [Section 22.002(4)].

The Disposal Well Act describes permitting procedures for injecting the two types of wastes. In Subchapter B, it states, "No person may begin drilling a disposal well or converting an existing well into a disposal well to dispose of industrial and municipal waste without first obtaining a permit from the Texas Water Quality Board." In Subchapter C, it states, "No person may begin drilling a disposal well or converting an existing well into a disposal well to dispose of oil and gas waste without first obtaining a permit from the Railroad Commission of Texas."

The Disposal Well Act is in direct conflict with the Texas Geothermal Resources Act, insofar as it assigns geothermal responsibilities to the Water Quality Board rather than to the Texas Railroad Commission. This issue has not yet been decided. Cooperation does exist between the agencies however, as exemplified by the enactment of the Disposal Well Act. Anyone requesting a waste injection permit from the Water Quality Board must obtain a letter from the Railroad Commission stating that the proposed well will not endanger oil and gas operations, and vice versa.

The Disposal Well Act does not adopt standards on well construction, but a double-cased well with packers and waste flow solely through the inner tube is the preferred technique.[105]

Water quality standards established by the Water Quality Board also affect the disposal of geothermal effluents.[106] These standards are basically in compliance with the FWPCA, but an approved NPDES permitting system is not yet in place. Currently, two permits are required for surface disposal, one from the Water Quality Board and one from the EPA.

One final observation concerning possible regulating problems in Texas. Permits for over 40,000 oil and gas waste disposal wells have been issued, the vast majority without public hearings. If the SDWA or other state legislation makes all permits subject to public hearing, and if geothermal well regulations reside with the Railroad Commission, tremendous delays in the development of geopressured resources could result.

At the present time, the Texas Railroad Commission appears to be the lead agency for geothermal regulations, in spite of the Disposal Well Act. Not only is the Commission given the authority in the Geothermal Resources Act, but the close association of geopressured resources with oil and gas is obvious. It is estimated that up to 50 percent of the energy content in some geopressured fluids is in the form of natural gas, creating a clear compatibility with oil and gas operations.

The second major agency in Texas that affects geothermal operations is the Water Quality Board. The Board is not only responsible for maintaining the quality of surface and ground waters, but is also given jurisdiction over geothermal injection wells under the Disposal Well Act. At the present time, the Water Quality Board is regulating 133 separate industrial and municipal waste wells in the State, and public hearings have taken place on each permit application.

Other agencies that peripherally will interface with geothermal development are listed below, with a short description of their roles.

- Texas Water Development Board--water planning, economic studies, brine desalination programs
- Department of Health--certification of water and wastewater treatment systems, monitoring of coastal waters
- Water Well Drillers Board--maintains expertise in well drilling for oil and gas
- State Land Office--leasing of State lands for geothermal exploration and development
- School Land Office--leasing of school lands
- Air Quality Board--regulation of air pollution.

The general atmosphere for the development of geothermal resources in Texas is positive, in spite of some concern over pollution of State waters by existing injection wells. The general feeling of confidence is enhanced by the long experience of the oil and gas industry, and the advanced state of regulation to protect the environment. Numerous problems and unanswered questions concerning geothermal disposal in Texas nevertheless remain.

1) The key regulating question is the division of responsibility between the Railroad Commission and the Water Quality Board. Conflicts here could delay developmental progress. Modification of the Disposal Well Act to classify geothermal resources with oil and gas would alleviate this problem.

2) Even though injection of wastes into saline aquifers is the preferred disposal technique, little is known about the suitability of these aquifers for large-scale, long-term liquid waste disposal.

3) Subsidence potential remains an unanswered question for geopressured resource utilization. It will be impractical to return the

extracted geothermal fluids to their original formation upon disposal. The geopressured mudstones containing the fluids have a high porosity, and extraction of large fluid volumes will cause an increase in mudstone density. Some of the compaction at depth may translate to the surface. One case in which subsidence did occur due to oil and gas production from geopressured sediments is the Chocolate Bayou field near Galveston. More than 0.3 m of subsidence has been experienced after deep production at 2400 to 3900 m. Subsidence may be minimized if numerous fault lines exist, or water influx occurs, or the formation is structurally isolated from the surface. Numerous questions remain to be answered, and they will most certainly affect the disposal of geothermal effluents in Texas.

4) Surface disposal to streams, rivers, or offshore areas is allowed in Texas under special conditions. With the strict requirements of state and federal regulations, and the questionable economics of wastewater treatment, surface disposal is not expected to become a widely used technique.

5) Ponding of effluents has caused environmental problems within the State. Shallow, unlined pits have allowed migration of oil brines into surrounding formations. Over 15,000 of these evaporation ponds have been leveled and covered along the Red River by order of the Red River Authority.[107] Liners are often used but have a short lifetime in contact with many geothermal effluents.[108] The Railroad Commission has expressly prohibited the use of these methods except in temporary situations during which approved impermeable liners are employed. It is likely that these types of ponding will continue to be used during drilling operations, and may be used for flow testing, emergency flow leaks, and as secondary systems for backup to the primary disposal system.

6) The economics of injection as a disposal technique is still in question, with the cost of drilling, the low flow rates, and high pumping pressures considered. It is estimated that several injection wells may be required for each producing geopressured well. The use of double-walled designs will also increase the cost of injection wells.

7.2.9 Louisiana

Louisiana, like Texas, has experienced little geothermal development but has great potential for geopressured resource utilization. The Office of Conservation has prepared regulations for geothermal resource development, largely based on oil and gas regulations.[109] The major revision to Louisiana Statewide Order 29-B concerns the disposal of wastes in Section 15. The following items were added:

1. All disposal of the geothermal/geopressured operation waste material into the surface waters of the state shall be done pursuant to and under the control of the regulations and procedures set forth by the Stream Control Commission or other appropriate state or federal agencies having control over such surface disposal.
2. Produced saltwater may be disposed of and/or stored in pits where such method and pits have been approved of by the Commissioner of Conservation.
3. Unless in conflict with a provision of these regulations, the provisions of Section XV - Pollution Control of State Wide Order 29-B of the Department of Conservation shall control the subsurface disposal of saltwater.

These proposed regulations are extremely general, and their direct impact on geothermal/geopressured disposal is unknown. Other key aspects of the existing rules are the issuance of permits without public hearing (with permission of offset operators), and the acceptability of annular disposal of saltwater for a one-year period with the proper permit.

Water quality controls of surface waters exist in the State Stream Control Commission, and the rules and regulations are in compliance with FWPCA.

In summary, the lead agency for geothermal regulation is the Office of Conservation, which will administer the exploration and development of geopressured resources. The Stream Control Commission is responsible for the quality of the surface waters. Other agencies with possible peripheral involvement are the Department of Public Works (freshwater wells) and the Department of Health (drinking water).

Injection of geothermal effluents into saline aquifers with greater than 10,000 mg/ℓ of total dissolved solids is currently considered to be the most desirable technique for waste disposal. The importance of water supplies and strict water pollution regulations will largely eliminate surface water disposal. Storage and evaporation ponds may be used for drilling operations.

7.2.10 Wyoming

Geothermal development in Wyoming has been slow, with only two known geothermal resource areas having been designated in Yellowstone Park and at Frazier. Four wells produce hot water.(110)

Geothermal resources in Wyoming are defined in the State statutes as water that is owned by the State.(111) The only reference to waste disposal is contained in the rules and regulations of the State Board of Land Commissions for geothermal leases.(112)

Under the section concerning land development, paragraph (f) states that: "Geothermal resources shall not be disposed of except in accordance with sales contracts or other methods which have first been approved of in writing by the State Engineer." Section 21, paragraph (d) of the rules addresses the protection of other resources: "Wastes shall be discharged in accordance with requirements and prohibitions prescribed by the Department of Environmental Quality (Water Control Board) which shall also approve the place, and manner of waste disposal." Paragraph (k) says, "Drilling mud shall be ponded in a safe manner and place, and where required by the state, posted with danger signs, and fenced to protect persons, domestic animals, and wildlife. Upon completion of drilling, the mud shall be disposed of, or after drying in place, covered with a protective layer of soil."

The State Engineer of Wyoming will regulate geothermal development in the State. The State Board of Land Commissioners will be responsible for leasing of lands for exploration and development. Water quality and waste disposal will be the responsibility of the Department of Environmental Quality.

Other States

Other western states that may have significant geothermal resources include Alaska, Arizona, Colorado, Montana, and Washington. These states have experienced minimal geothermal development, and have not addressed specifically the issue of geothermal liquid waste disposal. Existing regulations on geothermal development are listed below.[a]

Alaska

Statutes:	Geothermal Resources Act (1971) AK. Stat. 38.05.181
Leasing:	Div. of Lands - Regulations & Statutes Pertaining to Coal and other Leasable Minerals (1974) 11 A.A.C. 84.700...
Drilling:	Div. of Oil & Gas (1974) 11 A.A.C. 94.730...

Arizona

Statutes:	Geothermal Resources (1972); amed. HB 2257 (1977) A.R.S. 27-651...
Leasing:	Land Dept. - Geothermal Resources (1972) T.12C.5.A.21 under revision)
Drilling:	Oil & Gas Conservation Comm. - General Rules & Regulations Governing the Conservation of Geothermal Resources (1972) T. 27C.4.a.4

(a) Doug Sacrato, "State Geothermal Laws and Regulations," National Conference of State Legislatures, presented at the Geothermal Resources Council Short Course No. 7 - Geothermal Energy: A National Opportunity, May 17-18, 1978.

Colorado

Statutes: Geothermal Resources act (1974) C.R.S. 34-70-101...

Leasing: Board of Land Commissioner - Special Rules & Regulations Relating to Geothermal Resources Leases (1972) SLB #248-1

Drilling: Oil & Gas Conservation Comm. - Rules & Regulations for the Development & Production of Geothermal Resources (1976) G101...

Montana

Statutes: leasing - Lease of Geothermal Resources (1974) R.C.M. 81-2601...

siting - Major Facilities Siting Act (1975, as amed) R.C.M. 70-801...

filing bottom-hole temperatures - Act to Facilitate the Discovery of Geothermal Energy Sources (1975) R.C.M. 60-127, 144, 148

Leasing: Dept. of State Lands - Geothermal Rules & Regulations (1975) M.A.C. 26-2.6 (2)

Drilling: Dept. of Natural Resources & Conservation - Geothermal Investigation Reports (1975) M.A.C. 36-2.8 (14)

Washington

Statutes: Geothermal Resources Act (1974) T.79 R.C.W.

Leasing: Dept. of Natural Resources - Geothermal Leasing Policy (1978) DRAFT

Drilling: Dept. of Natural Resources - none

7.3 CONCLUSIONS

The major environmental concern of the federal government and state agencies arising from geothermal development is the proper disposal of geothermal effluents. In many state and federal laws, several restrictions have or will be placed on surface disposal and ponding. Other states have incomplete regulations concerning these disposal techniques. The regulatory review implies that injection either into the producing reservoir or into saline aquifers is the preferred technique, both from a resource conservation and an environmental point of view. The SDWA may impose stricter controls on injection, but its full impact is not yet known.

Although a number of problems and gaps exist in geothermal legislation (due to technical uncertainties concerning disposal), a number of legal unknowns can be identified.

1) Problems with the definition of the resource and its interaction with other natural resources have created numerous regulatory conflicts within state agencies and the federal government on regulatory control. A method of alleviating these difficulties is needed. As stated in a recent publication on legal problems of geothermal development,". . .the geothermal developer must secure approval from a bewildering array of governmental bodies before proceeding with any stage of geothermal development. In California, he must report to the county planning commission, the state Division of Oil and Gas, Regional Water Quality Control Board, Air Resources Board, Public Utilities Commission, Energy Resources Conservation and Development Commission, and possibly the Federal Power Commission. On public lands, the State Lands Commissioner or Bureau of Land Management and the U.S. Geological Survey must also be consulted. Each governmental unit is concerned with a different aspect of geothermal development, and there is no supervisory agency to protect developers from inconsistent procedures and requirements. . . ."[113]

2) The setting of standards on injection well design is not uniform, and it is currently unknown which techniques should be recommended, or whether any standards are necessary.

3) One of the greatest gaps in the knowledge of disposal is the transfer of information to those who create regulations. This transfer of information should include technical, institutional, legal, and historical data.

4) The standardization and normalization of regulations is needed to aid developers in responding to the legal requirements for disposal.

8.0 EVALUATION OF GEOTHERMAL WASTE DISPOSAL TECHNIQUES

In the utilization of geothermal energy, fluids and gases must be disposed of in adequately designed systems. These systems must be able to handle very large volumes of fluids that contain salts and toxic substances as well as residual thermal energy. The liquid volume of a 100-MWe flashed steam-type plant is 10^9 liters/day, which equals 28 million gallons/day.

In this chapter, we have identified seven disposal concepts that could be used at geothermal sites. Four are based on surface disposal and three are based on injection, as listed below.

Disposal Systems for Geothermal Liquids

Surface Discharge:	Direct release to surface waters
	Treatment and release to surface waters
	Closed-cycle ponding and evaporation
	Consumptive secondary use
Injection:	Injection at a producing horizon
	Injection at a nonproducing horizon
	Treatment and injection

Many other combinations of these concepts are possible, and other concepts could be developed (e.g., direct conversion of liquids into solids).

The actual choice of a disposal system depends on the chemical and physical properties of the liquid, the uses being made of the geothermal fluid, and the properties of the disposal sink. These factors are variable and highly dependent on each site so that identification of a general disposal method applicable to all sites is not possible. Our study provides the framework for comparing the various alternatives for disposal at a specific site.

To test the feasibility of the various disposal concepts against conditions likely to be encountered in the field, it is necessary to have a set of evaluation criteria. The evaluation criteria allow comparison of one disposal system against other systems, with emphasis on the strengths and weaknesses of each. Four groups of evaluation criteria were used: 1) technical, 2) economic, 3) legal, and 4) environmental and safety. Each of these four major groups includes subgroups, as shown below. Some standardization of the meanings of the criteria is necessary if the various disposal techniques are to be compared. A brief definition or description of each criterion is given in the following paragraphs.

Evaluation Criteria for Disposal Systems

1. Technical Criteria

   - Working experience
   - System components and materials availability
   - Geology and hydrology
   - Interactions of the utilization process and the disposal system
   - Useful by-products
   - Reliability

2. Economic Criteria

   - Direct cost of disposal
   - Costs

3. Legal Criteria

   - Geothermal laws
   - Environmental laws
   - Water rights laws
   - Land use laws

4. Environmental and Safety Criteria

- Safety and emergency preparedness
- Water pollution
- Air pollution
- Noise pollution
- Toxic substances disposal
- Solid waste disposal
- Induced seismic events
- Induced land subsidence

8.1 EVALUATION CRITERIA

8.1.1 Working Experience

Past experiences with disposal systems at geothermal sites and in related industries should be evaluated.

System Components and Materials Availability

The disposal system may require unusual materials, components, or machines to function properly. The extent to which off-the-shelf components and materials can be used should be assessed. Any new or critical items requiring additional research and development to make the system feasible should be identified. Similarly, those items that require unusually long procurement lead times should be identified.

Geology and Hydrology

Each site will have a unique geology and topography that will strongly affect the feasibility of the disposal system. For example, hilly surface terrain will make ponding difficult and may cause hillside stability problems, whereas relatively flat lands would limit the ability to transfer large volumes of water to secondary holding ponds. Knowledge of the subsurface geology, hydrology, and physical properties, and the chemical properties of the geothermal reservoir, will be essential in determining the feasibility of the various injection disposal systems.

Interaction of the Utilization Process and the Disposal System

The extent to which the choice of the disposal system limits and affects the operating policy of the utilization system must be evaluated. Some disposal systems, such as dumping into the ocean or a large body of water, will have very little interaction with the utilization system. However, other cases, such as injection, may have a direct and immediate effect on the utilization system. Similarly, the load-handling capability of the closed ponding and evaporation system under inclement weather conditions may affect the production capabilities of the entire system.

Useful By-products

The technical and economical feasibility of developing useful by-products (such as the utilization of CO_2 for dry ice or the extraction of valuable chemicals and minerals from the brines), should be considered for each disposal process. These products may be used to defer some of the costs of disposal.

Reliability

Reliability of the geothermal disposal system should be evaluated in terms of past working experience and knowledge of the system's components and materials. The effects of plugging, scaling, and corrosion are particularly critical.

8.1.2 Economic Criteria

The economic criteria used in this evaluation are: (1) the direct cost of the disposal system, and (2) how these costs affect the cost of power production. Site-specific cost data on some systems are presented whenever available, and a qualitative ranking for the different disposal systems is given. Data on disposal costs are limited due to the relatively recent evolution of many of the disposal options; areas in which additional technical costs information is needed will be identified.

8.1.3 Legal Criteria

Geothermal Laws

Legislation, laws, and regulations for the development of geothermal energy are applied at the federal, state, and local levels and, consequently, are quite specific by site. (Chapter 7 summarizes federal and state regulations.) The extent to which these regulations affect disposal systems should be evaluated and the differences between systems emphasized.

Of the federal regulations, the Geothermal Steam Act of 1970 (30USC-1001-25) and the Geothermal Energy Research Development and Demonstration Act of 1974 (Public Law 93-410) established broad guidelines that affect nearly all geothermal development. The regulations spawned by these legislative acts place further constraints and establish responsibilities for effective management of geothermal resources. Similar laws have been enacted in most western states and, consequently, some limitations and control at both the state and local levels will be exercised for most geothermal developments. The objectives of applying the evaluation criteria are to emphasize the differences between disposal systems in light of the geothermal laws.

Environmental Laws

The primary environmental laws affecting geothermal liquid disposal are: a) the Federal Water Pollution Control Acts Amendments of 1972 (PL-92-500); b) the Safe Drinking Water Act (PL-03-523, 1974); c) the Resource Conservation and Recovery Act (PL-94-469, 1976); and d) the Toxic Substances Control Act (PL-094-469, 1976). The regulations generated by this fairly extensive body of legislation have a significant impact on geothermal disposal systems and the options available to the developer. In some cases, the legislation may specifically prohibit the discharge of geothermal wastes to surface waters. In other cases, control of injected fluids to prevent contamination of freshwater acquifers will place constraints on injection. We will not attempt to itemize state and local environmental laws, but these may greatly affect the options available, and consequently must be considered at the specific site under development.

Water Rights Laws

Water rights are primarily controlled by state legislation and regulations (see Chapter 7). The specific effects that water rights have upon each disposal method must be determined for comparison purposes.

Land Use Laws

The uses of federal lands in the western states are controlled primarily by the Bureau of Land Management and the U.S. Forest Service. However, other agencies, such as the National Park Service and the Bureau of Reclamation, may be involved at certain sites. State regulations affect nearly all land use not covered by federal regulations for lands administration by federal agencies. The effects of these regulations for the specific sites should be evaluated for each disposal system.

8.1.4 Environmental and Safety Criteria

In this section we will compare from an environmental and safety standpoint only those systems that have passed the legal criteria.

Safety and Emergency Preparedness

The disposal systems will be evaluated with respect to their susceptibility to serious accidents such as fires, explosions, pipe ruptures, earthquakes, and the like. Backup systems for emergencies and unexpected breakdowns should exist for disposal systems, but some backup systems will be more effective than others in being responsive to disruptions from normal operations.

Water Pollution

Water pollution either on the surfce or subsurface level must be considered for most disposal systems and, assuming the legal criteria can be met, the systems will be compared to determine those that minimize both the planned and accidental releases.

Air Pollution

Some air pollution may occur in the development of geothermal resources, even for binary cycle plants and closed systems. Most systems require a period of well testing and periodic blowdown of wells, which will release major contaminants to the atmosphere in the form of noncondensible gases. Of course, accidental releases such as pipe ruptures can occur in any system, but some systems may be more susceptible than others to such accidents. Futhermore, planned releases will occur from ponds, cooling towers, separators, and silencers.

Noise Pollution

Noise pollution occurs primarily during the planned or accidental blowdown of wells, and during those conditions when the power plant is inactive and geothermal fluids are being discharged through the silencers. Noise levels for each disposal system should be compared.

Toxic Substances Disposal

The release of toxic substances such as arsenic and mercury may preclude the use of surface disposal systems in some cases because of inability to meet the legal criteria. However, assuming the legal criteria can be met, the disposal of toxic substances must be carefully evaluated because of the impact on plants, animals and humans, and because of the economic impact of implementing the disposal system.

Solid Waste Disposal

Some systems will neccessitate solid waste disposal, such as those involving treatment processes before disposal. Periodic removal of the solid wastes would be required, and an environmentally acceptable disposal site must be available.

Induced Seismic Events

The probability of inducing seismic events as a result of injection of fluids is expected to be low. Surface disposal techniques would be expected to incur an even lower risk of inducing seismic events. Even though these probabilities are low, they should not be ignored when considering specific sites.

Induced Land Subsidence

Land subsidence tends to occur in some geologic structures when geothermal fluids are extracted. Disposal systems using injection into the producing reservoir may mitigate land subsidence. This factor should be considered when comparing disposal systems.

8.2 DISPOSAL SYSTEM EVALUATION

8.2.1 Direct Release to Surface

This technique includes release to fresh waters such as rivers, streams or lakes, and to saline waters such as salt lakes or the oceans.

Technical Evaluation

Historically, geothermal operators used direct discharge to an available drainage system; but the downstream effects and the increased concern for the environment have brought on more stringent controls for environmental, health, and safety reasons. Although direct discharge is not now being used in the U.S., it was used at The Geysers until 1969. The trace impurities (e.g., boron, arsenic, and ammonia) in the waste fluid from The Geysers exceed allowable limits for direct discharge as established by the State Water Resources Control Board. In Iceland and at Klamath Falls, Oregon, a number of homes that use geothermal water for space heat discharge the waste fluids into the sewer system. This practice is being phased out, and heat exchangers are being used on most new installations.

Outside the U.S., direct discharge is still being used extensively. In New Zealand, waste fluids at Wairakei are being discharged directly into the Waikato River. The fluids represent about 1 percent of the total mean river flow, and have caused some downstream problems by reducing the number of fish and increasing the plant growth.[51] This disposal method appears to be technically acceptable for the present time, but new geothermal developments in this river basin will require other methods of disposal.

At Ahuachapan, El Salvador, a combination of disposal methods has been used. Initially, about 30% of the liquid waste was injected into the production reservoir, and the remainder was discharged into the Rio Paz River. El Salvador has since built an 86-km canal to the ocean and is still injecting about 30% of the liquids for pressure maintenance and routing the remaining 70% to the ocean. A study to follow the long-term effects of this discharge into the ocean would provide a good basis for assessing the potential for using this method in the U.S.

Direct discharge is the simplest method, technically, becuse it only requires a conduit from the plant to the receiving waters and a diffuser to disperse the liquids into the water. The conduit can be piping or an open channel and, in most instances, the materials used in the plant should be satisfactory in the disposal system. Since this disposal method requires minimal equipment, there should be little interaction with the remainder of the plant. Scale formation can occur, which will increase the maintenance costs slightly. Removal of the scale can be scheduled to coincide with normal plant shutdowns. The reliability of this sytem should be high. The geology of the area will not be important at most sites, although the topography will be important in deciding the type of conduit to be used and whether or not pumping is required to transport the liquid wastes. The hydrology of the area will be very important.

This disposal method is not expected to produce any useful by-products, except the water itself, which would increase the volume available downstream for other uses. Depletion of the reservoir can occur if the natural recharge is low.

Economic Evaluation

Three major costs determine the economic feasibility of a direct release disposal system:

- land acquisition
- system construction and installation
- piping, ducts, and complementary capital.

Although both capital and labor markets are fairly homogeneous over the western United States, construction costs and right-of-way acquisition expenses will vary significantly between localities.

Distance from the producing wellhead to the receiving disposal waters is a critical and limiting factor. As distance increases, an economic incentive is created to substitute other disposal methods for untreated discharge. It may prove less expensive to treat and release in local freshwater streams than to pipe to an ocean for disposal.

Operating expenses include repairs and maintenance of capital equipment, pumping expenses (if necessary), and removal of precipitates and scale from piping and ducts. These expenses are expected to be relatively low.

The arrangement at Wairakei is probably the simplest and most economical method of geothermal liquid waste disposal, although there is a small capital cost associated with the drainage canals that carry the liquid effluent from the wellhead steam separators to the Waikato River system. The cost of liquid waste disposal at Wairakei has not been reported in the literature.

A second alternative to direct surface release involves transport of liquid wastes to the ocean for disposal. Although both TRW(114) and Booth(115) indicated that this technique has severe economic limitations, it is currently being practiced at Ahuachapan, El Salvador as an alternative to disposal in the Rio Paz River. The 86-km canal that transports liquid waste from Ahuachapan to the Pacific Ocean cost $15.2 million to complete. Spreading this cost over the three power generation units (Unit 1 - 30 MWe, Unit 2 = 30 MWe and Unit 3 = 35 MWe), the canal cost $160/kW. The operating costs are assumed to be negligible, since the canal uses gravity flow and little equipment is involved.(126)

Legal and Institutional Evaluation

The Federal Water Pollution Control Act has three goals (see Chapter 7):

1) to eliminate discharge of pollutants to navigable waters by 1985
2) to protect fish, shellfish, and wildlife by 1983
3) to prohibit discharge of toxic pollutants in toxic amounts.

To meet these goals, direct discharge of geothermal waters from most sites with temperatures high enough for electric power application will not be allowed. The Puna site in Hawaii may have water that is clean enough for direct discharge. Sites that have lower temperature waters (which are useful enough for direct or process heating), may have water clean enough for direct discharge. This restriction could be temporarily lifted for marginal water in times of severe drought. Sites that are near the ocean, e.g., along the Gulf Coast, can still consider using this method to dispose of liquids.

Water rights laws will certainly be important if this disposal method is used. In Oregon, the Department of Water Resources considers geothermal fluids to be ground water, and regulates the supply and appropriation of that resource accordingly. Utah does not have specific regulations on geothermal fluids at this time, but there appears to be a potential for water rights problems within the state.

Environmental and Safety Evaluation

The assumption is made that as long as water quality standards are met, the chance for water pollution is low. Sampling will be required to insure that the water quality does not deteriorate with time. High flow rates could cause some erosion in the receiving waters, stream, or lake bed if the diffuser design is not adequate. Thermal pollution must be considered a potential problem unless the conduit is long enough to permit the waste to cool. The direct discharge method should provide the best occupational safety of the disposal techniques and will require little or no backup systems.

The release of toxic substances, except for undetected changes in fluids chemistry, isn't expected to be a problem because the wastes will have to meet the legal criteria before they can be considered for this method of disposal. Some solid wastes will be generated from scale removal and thus will have to be disposed of separately.

All of the surface disposal methods will result in near total release of dissolved gases. Therefore, a thorough analysis and evaluation of the noncondensible gases in the water must be made before direct surface disposal is considered. Large volumes of water vapor will be released to the atmosphere.

Noise polluton is possible with this method as with all surface disposal, but available silencers are adequate to reduce the noise to acceptable levels.

Inducing seismic events is not expected to be a problem; but the potential for land subsidence is very real. Experience in the oil industry and at some geothermal sites, such as Wairakei, indicates that, in many areas, continued removal of liquids from subsurface strata can cause subsidence of the land surface. At some geothermal areas, subsidence is occurring naturally and the potential added effect of liquid removal without injection is not known.

Conclusions

Direct discharge systems are simple to construct (i.e., they require no special equipment or materials), and would have low operating cost and high reliability. The unresolved problems include:

- meeting the legal requirements
- erosion and other damage from high-volume flow
- precipitation of undesirable solids (minor)
- thermal effects on the recipient waters and surroundings.

8.2.2 Treatment and Release of Surface Waters

Treatment involves the application of one or more processes that modify the properties of liquid waste. Processes may cause physical, chemical or biological changes in the fluids or some combination thereof. Simple treatments would be settling and filtration or flocculation. More advanced treatments, such as reverse osmosis, electrodialysis or ion exchange, are sometimes used on liquid wastes from industries other than geothermal.

Technical Evaluation

At this time no sites in the U.S. are using treatment and direct discharge, but the method is being considered in New Zealand. Rothbam and Anderton[116] report on a pilot plant at Wairakei, New Zealand that is designed to remove silica and arsenic from waste waters. In this process, waste fluid at 90°C is "aged" to allow silica to polymerize; addition of slaked lime to the waste fluid rapidly precipitates a flocculent-hydrated, calcium silica gel, which readily settles out in tanks. Simultanesously, if the arsenic has been preoxidized to its pentavalent state, it co-precipitates. The calcium-silicate precipitate is then dried with waste heat to produce a useful by-product for wallboards or insulants. The pilot plant operation showed that technically this is a viable option.

The waste fluids from a direct heating project in Idaho are clean enough to be discharged into the Boise river, except for a higher than allowable fluoride concentration. The allowable level is about 2 ppm, and the waste stream contains about 10 to 15 ppm. One method for removing the fluoride ions from water uses an activated alumina bed, which has been used for drinking-water supplies. This system works, but it is expensive.

Some typical treatments that are available for geothermal liquid wastes include: 1) exclusion of air and maintenance of CO_2 pressure to prevent calcite plugging, 2) sedimentation in holding ponds to prevent formation plugging, and 3) slaked lime addition to remove silica and arsenic.

Conventional waste-water treatments may be effective on some geothermal liquid wastes. These treatment systems remove suspended solids from waste water in a four-step process. The first three unit operations - rapid mixing, flocculation, and sedimentation - are typically performed in a single vessel. Chemicals are added to promote flocculation and settling. Step four in the conventional system is filtration of the liquid effluent to remove turbidity and fine suspended solids, which did not settle out. Special materials may be needed if the liquids are corrosive.

One of the following advance water treatments may be usable. These advanced treatments are used when conventional systems cannot achieve a desired water quality. These treatments include ion exchange, reverse osmosis, and electrodialysis. In the ion exchange process, undesirable ions are removed from a waste stream and replaced with other ions as the water flows through a special resin bed. The type of resin is chosen based on the ion to be removed.

In the reverse osmosis process, water is driven through a semi-permeable membrane from a solution of high dissolved solids concentration to solutions of lower concentration. The driving force is an applied pressure that is greater than the osmotic pressure of the solution. The membrane prevents the passage of the solids. Electrodialysis is similar to reverse osmosis in the respect that both are membrane desalting systems. However, electrodialysis is different in that: (1) the driving force is an electrical field rather than pressure, and (2) the ions, rather than the water, pass through the membrane. Membranes for these two processes are presently limited to about 27°C for reverse osmosis and 60°C for electrodialyses. Experimental membranes are being tested to higher temperatures.

The precipitated solids collected in any of the above treatment systems or left in the bottom of an evaporation pond create another waste source requiring disposal.[117] These solids can be disposed of in a number of ways, including landfilling, mineral recovery, and ocean dumping. The method and site for the disposal of the solids will depend on whether they are classified as hazardous or not. Classification will vary from site to site and will serve to further limit the disposal options available.

The general processes for treating liquid wastes to remove contaminants are known, but the individual nature of the liquids at each geothermal area requires that any treatment plant be tailored for each specific site. One problem in designing any treatment plant is the variability of fluid chemistry with time. This need to handle chemistry changes will increase the design complexity of plants.

The geology and hydrology of the site are as important to treatment systems as they are to direct discharge systems. Treatment methods will interact with the plant, since periodic equipment failure may occur or such things as plugging of filters can happen. To prevent plant shutdown, temporary backup systems, such as holding ponds, may be required. The increased amount of equipment and the complexity of the system will cause the reliability to be less than that of direct discharge methods. Useful by-products can be obtained from this method. At the Broadlands, an estimated 30,000 tons(M) of lime would be needed annually and would yield 80,000 tons(M) of calcium silicate. The calcium silicate can be used in building materials and cement, or as a soil conditioner if the arsenic content is sufficiently low.

Economic Evaluation

Conventional treatment system costs are dependent on flow rate, influent water composition, temperature, and desired product water quality. Costs reported by Christensen(118) are based on municipal waste treatment facilities and are probably lower than the costs will be for processing geothermal brines. Municipal waste treatment systems are designed to operate at ambient temperature. The high temperatures of the bines could increase costs due to the need for corrosionand heat-resistant materials. On the other hand, higher temperatures could also tend to decrease costs, because faster reaction rates would allow use of smaller units. As few of these costs are included, actual system designs and costs will have to be determined on a case-by-case basis.

The capital costs for an East Mesa and a Salton Sea treatment plant, using municipal waste treatment plants estimates, are estimated at 50 $/kW and $34/kW, respectively. The yearly operating costs for these two plants were an estimated $115,000 and $81,000 without sludge disposal.(118)

Sludge disposal costs can be higher if the solids content of the waste water is high.(118) Offsite disposal costs are $21.4 per ton of concentrated solids (50% water), which includes $11.4 per ton for transportation to a landfill 200 miles away, and $10 per ton for landfill costs.(114) A plant with a high level of dissolved solids could generate several thousand tons of sludge per day, constituting a major cost item. These costs do not include the cost of dewatering to 50% solids. If the sludge can be disposed of onsite, or near the site, substantial cost savings may be achieved. Ideally, generation of marketable residues would eliminate the need for solid waste disposal sites for the geothermal industry. Little work has been done in this area and to date the production of marketable commodities from residual sludges has not been shown to be cost effective for geothermal resources.

This disposal technique is economically unfeasible at Ahauchapan, El Salvador because (1) the abundant residue salts could not be profitably marketed; (2) the highly corrosive nature and the silica saturation of the residual fluid would require additional treatment; and (3) there is no market for the demineralized water. Therefore, other disposal techniques are being used.[119]

Legal and Institutional Evaluation

A waste-treatment disposal method should be able to meet the geothermal and environmental laws, since each facility must be designed for the individual site. The biggest problem would be to have enough flexibility in the plant to accommodate brine chemistry changes that may occur over the lifetime of the plant. This is necessary to insure that liquid-waste output meets the regulations for temperature and chemistry. Since this disposal method will also release nearly all dissolved gases, careful consideration must be given to releases to the atmosphere.

As with all surface disposal methods, water rights are a potential problem that will have to be addressed at each site. Since this disposal method will entail additional acreage for ponds, filters, or other treatment facilities, land-use laws will have to be considered.

Environmental and Safety Evaluation

This disposal method can be designed and built to be inherently safe. Settling ponds and filtration systems with proper guardrails have little susceptibility to serious accidents. Pond rupture and release of liquids due to earthquakes is a potential problem. Since many known geothermal resource areas are located in active earthquake zones, the pond containment structure must be designed to withstand seismic loading.

Unplanned water pollution could happen if chemistry changes in the liquid waste occurred and went undetected, or if treatment adjustments were not made to accommodate the changes. Normally these changes would be very gradual over an extended period, so any chance for significant pollution would be small.

Air pollution can occur because nearly all dissolved gases will be released from the liquids. If these gas releases exceed allowable limits for the specific fields, a significant amount of additional equipment and expense will be required. Noise pollution should be about the same as for all surface disposal methods, and can be reduced to acceptable limits by proper use of silencers.

Insofar as settling ponds or filtration systems collect solids, disposal of solid wastes will be a problem. The identification and evaluation of potential disposal sites near the geothermal sites will be very important to future development.

Induced seismicity should not be a problem, but as in all surface disposal methods, land subsidence may be a limiting factor in applying this method. This will depend on the potential damage that can occur in the site area or to the power plant.

Conclusions

The treatment-and-direct-discharge disposal method is technically feasible for many geothermal sites. Methods are available for treating many geothermal fluids to meet the discharge requirements, but the costs may be high. The solids that are generated by the treatment process can develop into a major disposal problem. The primary considerations will be the cost and the effect of depleting the producing reservoir by not returning the liquids.

8.2.3 Closed-Cycle Ponding and Evaporation

This method of disposal includes use of dry lake beds, single large ponds or multiple stage ponds as described by Morrison et al.[108]

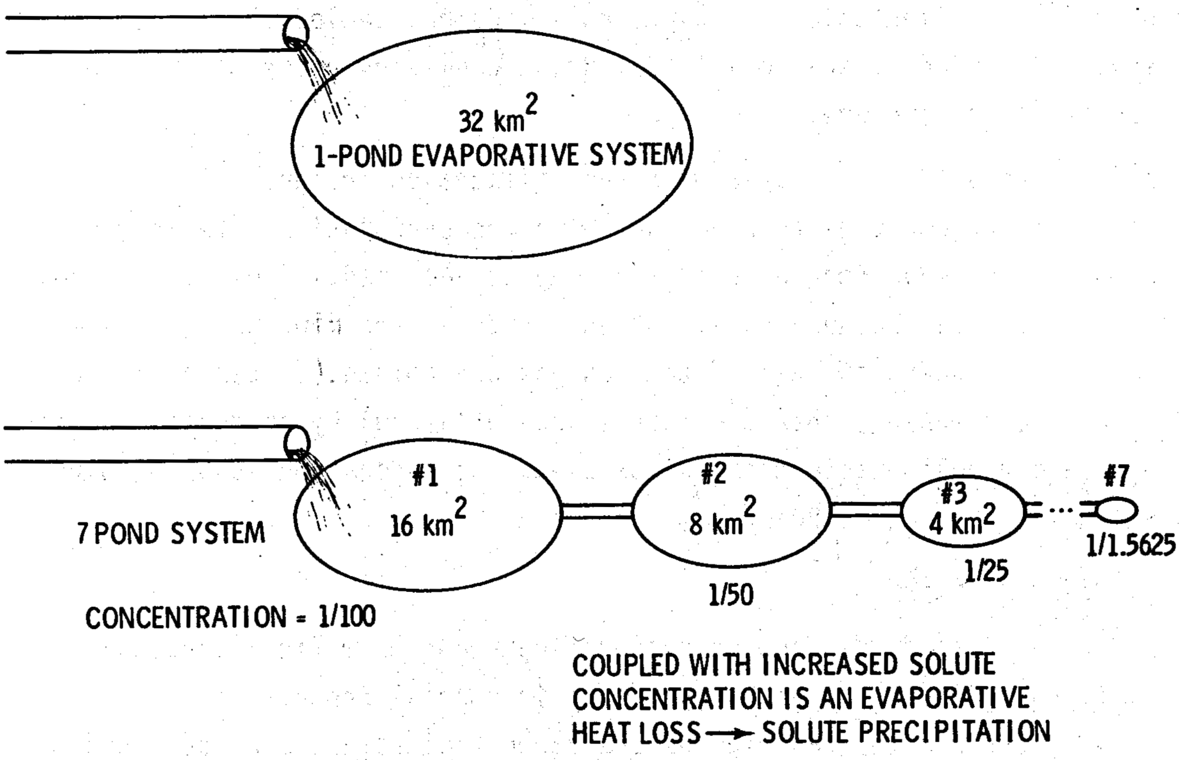
Technical Evaluation

Closed-cycle ponding is being used as the disposal technique at Cerro Prieto's first 75-MWe facility. Alternate methods are being considered for the plant for when additional turbines are installed. One method is to run the overflow from the pond through a canal to the Sea of Cortez or Laguna

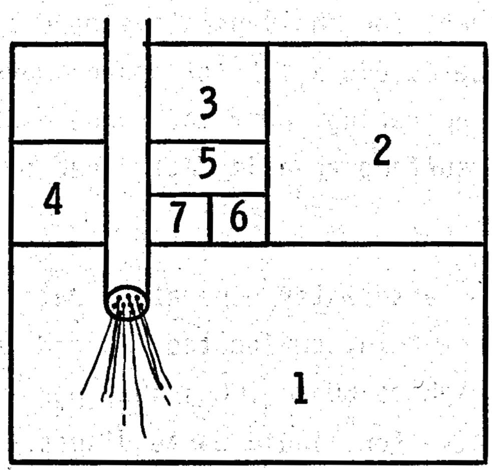
Salada.[120] Injection is also being considered for disposal. Morrison et al.[108] state: "Lagooning of brines, however, remains a viable alternative (to injection) as well as a temporary storage technique." They believe that any hazard to the environment can be controlled through careful design and management.

Salts can be concentrated by using several ponds in series rather than one large lagoon, as illustrated in Figure 8.1, Panel 1. Various salts can be expected to deposit in Ponds 1 through 7. Assuming that (1) the input concentration in the first pond is 1/100 of the satuation point, and (2) the concentration leaving a pond is double its inlet concentration, then the next pond in the series will require an area only one-half of the source pond. As a consequence of the temperature drop in each successive pond, the salt concentration will have reached its saturation point and will precipitate out by the seventh pond. An alternate design is shown in Figure 8.1, Panel 2. Here the flow from the last pond would be a saturated solution that could be evaporated by the heat from the inlet piping for Pond 1. Ponding was widely used in the oil industry, but since impermeable barriers were not required, some ground water contamination occurred. Presently, in Texas, ponding is not allowed for permanent disposal and old ponds are being dismantled (see Chapter 6). During initial well testing at most sites, ponding is the most widely used method for collecting the waste. The liquids may be allowed to evaporate or may be disposed of by one of the other means. Ponding is also considered a candidate for emergency backup to other disposal methods.

Two types of ponds, natural and man-made, are used for evaporation. A natural pond (e.g., a dry lake bed or a flat, depressed area) usually covers a large area because of the absence of barriers at its edges. Man-made ponds, on the other hand, contain an impermeable barrier at their sides and bottom made either of manufactured materials, such as PVC or butyl rubber, or natural materials, such as montmorillonite. The plastic liners are generally protected with a layer of sand or clay to exclude contact with the sun and air. Plastic liners have not been completely successful to date, and a number of them have failed after a few years, resulting in local contamination to the ground water.



PANEL 1



PANEL 2

FIGURE 8.1. Multi-Pond Surface Evaporation

At Cerro Prieto, sedimentation of suspended solids has sealed the lagoon and is preventing leaching of the soil.[108] Brine chemistry plays a major role in this self-sealing process.

Ponding interacts very little with the utilization process. If there are long periods of inclement weather during which the evaporation rate is much below normal, some reduction in waste flow may be required. The system should have high reliability, because equipment and controls are kept to a minimum. Evaporation will concentrate all of the non-gas contaminants. Since some ponds require periodic cleaning, they can be a source of useful by-products, though they may create a solid-waste disposal problem. Consideration is being given to mining the pond at Cerro Prieto.

Economic Evaluation

TRW[114] estimated the cost of evaporation ponds as a final disposal option based on research conducted by the Environmental Protection Agency.[121] Although the EPA figures are taken from actual project costs in average situations in the U.S. over a variety of conditions for 1971, the costs were restated to 1977 by TRW using the Marshall and Stevens Process Industries Average Equipment Cost Index.

Initial capital investment for an evaporative pond system of 100 surface acres[a] was calculated to be $\$1,646 \times 10^3$, or approximately \$16,460 per surface acre. Total annual operating and maintenance expenses were given as \$69 per acre. The required surface area is determined by:

$$A = Q/E$$

where A = area required, Q = waste water generation rate, and E = evaporation rate. Since geothermal sites are often located in arid regions, evaporation rates will typically be as high as 60 to 100 inches per year, making evaporation ponds a viable alternative for liquid waste disposal.

(a) The 8 km^2 (2000 acres) system at Cerro Prieto is sufficient to handle the fluid output of the 75-MWe facility. Assuming linear proportions, the 100 acre system would be sufficient to handle the output of a 4-MW facility. For the 2000-acre evaporation system at Cerro Prieto, the TRW cost correlations yield an estimated initial capital investment of $\$20.28 \times 10^6$ and annual operating and maintenance costs of \$40,000/year.

With respect to cost sensitivity to the total water surface area, TRW shows total annual costs for systems of 10 acres to 10^5 acres ranging from \$32,000 to \$75 x 10^6, respectively. TRW expects that average total annual costs per acre will range from approximately \$3200 to \$750 over the interval, as summarized in Table 8.1.

One of the major capital cost components is the pond liner required to prevent leakage from containment lagoons used for surface disposal. Liners were estimated in 1977 dollars to range from an installed cost of \$1.17 per square yard for 10 mil PVC up to \$3.78 for 1/16-inch Butyl rubber. Self-sealing by precipitation is expected to be significantly less costly than the installation of synthetic or natural liners, but is not likely to be technically feasible at every potential site. Brine chemistry is the major determinant of potential self-sealing by precipitation.

Surface ponding appears to be an economically viable option for geothermal liquid waste disposal. However, the following site-specific parameters must be considered before choosing this option:

1) evaporation rate
2) effluent temperature
3) liner requirements
4) plant size
5) land costs
6) local, state, and federal regulations.

TABLE 8.1. Surface Ponding for Evaporative Disposal: Total Annual Costs[(a)]

Acres	Capital Investment, \$	Annual Capital Recovery, \$/Yr	Annual Operating, \$/Yr	Annual Total, \$/Yr	\$/Acre per Year
10	338,000	30,000	2,000	32,000	3,200
100	1,690,000	150,000	60,000	210,000	2,100
100,000	8.37 x 10^8	74,300,000	700,000	75 x 10^6	750

(a) 30 years at 8%. All figures are in 1977 dollars.

Legal and Institutional Evaluation

Both the Federal Water Pollution Control Act and the Safe Drinking Water Act could affect the ponding disposal method, insofar as improper pond construction, ruptured ponds, or leaking ponds could contaminate either navigable surface water, or potable ground water. Ponds will have to be well engineered, because most known geothermal resource areas are located in areas of high-seismic activity. California requires that ponds be designed by licensed civil engineers.

Utah will allow temporary ponding contingent upon proper pond engineering and the installation of impermeable lining. Nevada has permitted the waste from one well test to flow into a dry lake bed. This was in a desert area where the total dissolved solids of the local waters closely matched that of the waste.

Water rights will affect the use of ponding just like it affects the use of all surface disposal methods. Land-use laws could greatly affect ponding, since pond size for a full-sized plant could be large.

Environmental and Safety Evaluation

From an occupational standpoint, ponding will be a very safe disposal method. Little or no operating activity is required. Occasionally the pond may be cleaned out to allow recovery and/or disposal of solids. Like all surface disposal methods, the noncondensible gases are released, and consideration must be given to high local concentrations of H_2S. Earthquakes can be a potential problem and good design must be applied.

Water pollution potentially exists, since plastic liner materials have been known to fail after a few years of service. Presently, there are no known economical and reliable methods for early detection of pond leakage. Detection usually occurs after contamination appears in nearby wells or other ground water. Bank erosion from heavy rains or flash floods should be considered during the site selection and pond design. Air pollution will occur due to the release of noncondensible gases and large volumes of water vapor.

Toxic substance and solid waste disposal will be required if the pond needs periodic cleaning. Amounts and type of materials to be disposed of will depend on the chemistry of the liquids and the type of saleable products removed.

Induced seismic activity should have a low probability, but land subsidence can occur. In some arid regions, a large pond or lake created by the geothermal liquid wastes could attract waterfowl and may be capable of sustaining aquatic life.

Conclusions

Closed-cycle ponding may be an acceptable disposal method in arid areas where land costs are low. The creation of a large pond or lake could be an added attraction in those areas that have no aquatic environment. Technically, this disposal method can be applied if the environmental issues can be satisfied.

8.2.4 Consumptive Secondary Use

This method of disposal includes both full use of the liquid wastes for application in agriculture or industry, and use of part of the wastes (e.g., the condensate from the flashed-steam plants).

Technical Evaluation

The geology, hydrology, and topography of an individual site will greatly influence the potential secondary uses of liquid wastes. Utilization of 100 percent of the geothermal wastes is most likely to occur at those sites with low total dissolved solids (TDS), such as Raft River in Idaho or some of the Oregon or Nevada locations, and where there is a need for additional water supplies.

No geothermal sites are making secondary use of disposal wastes at this time. Experiments are being run at Raft River[8] to determine the capability of using the geothermal wastes to irrigate agricultural crops. The early tests were considered a success since the yields and crop composition were comparable to freshwater, and there was no apparent increase in heavy metal pick-up. Additional testing is planned. The use of part of the geothermal wastes may be possible at several sites. The flashed steam at the Niland site is scrubbed with condensate. This scrubbed steam is generally less than 20 ppm TDS, and has reached a level less than 5ppm. This waste fluid could then be considered for secondary uses if it is not needed for plant cooling.

The Bureau of Reclamation completed a study for using geothermal water for power production and/or desalination. The study was followed with pilot plant testing. The tests were considered technically successful, although at the present time the desalted water is too expensive. Disposal of the remaining wastes after extraction of water for secondary use may be more difficult because of the increased concentration of TDS.

Another potential secondary use would be the growth of algae. The algae could be used as feed for fish or shellfish. The growth of the algae could result in water clean enough to be disposed of by one of the less costly methods. Tests are needed to determine if traces of heavy metals accummulate in fish that are grown on these algae.

For the low-salinity sites, standard components and materials can be used. The sites that will use part of the liquid wastes, such as condensate, can use ordinary equipment and materials once higher purity is obtained. If the purification system, such as a desalting plant, is part of the disposal system, care will be required in the selection of materials and components that can withstand the chemistry of the liquid waste.

Consumptive disposal methods will interact with the site's utilization and secondary disposal systems, and temporary holding ponds might be necessary to prevent plant shutdown. Those sites that use the liquids for irrigation will require another use or disposal method for off-season. The use of low-salinity water should be a very reliable system, since standard components and materials can be used. A system using part of higher saline wastes will be less reliable depending on the chemistry of the starting liquid and the complexity of the treatment system. The major by-product will be usable warm water.

Economic Evaluation

Consumptive secondary uses that require little or no treatment are highly desirable since capital outlay and land costs will be low. If minimal treatment is required, this disposal method could result in a net income by combining the sale of process heat to reduce the temperature of the fluids, and the sale of water for irrigation. The use of the water for irrigation can be an attractive feature in several locations in the arid west.

Legal and Institutional Evaluation

As long as the trace impurity of heavy metals remains low, the sites that can use all of the waste for secondary uses will satisfy the federal environmental laws that pose problems for other disposal methods. Even the Resources Conservation and Recovery Act should not restrict use of this method. Those sites that use only part of the liquids will have all of the normal problems that are associated with the method chosen for disposal of the remaining wastes. If irrigation is the secondary use, the emergency disposal system and the system proposed to handle the wastes during the off-season, will be cause for some concern.

Water rights may be a problem in both Oregon and Utah. The secondary use would require adequate planning and would necessitate obtaining approval from the Department of Water Resources in Oregon and the Department of Water Rights in Utah. Wyoming water laws could affect this method, since the State statutes say geothermal water is owned by the State.

Land-use laws could affect this method if the proposed secondary use were in conflict with existing plans for the site location.

Environmental and Safety Evaluation

The occupational safety with this disposal method should be very good, since the salinities will be low and standard equipment can be used. Earthquakes and major accidents should not be a problem with proper design. A back-up system will be required for emergencies when the disposal equipment fails, and when the primary disposal is not used.

Air pollution may be a problem since most of the dissolved gases and some water vapor will be released. Noise should not present a problem during normal operation.

Total substances will have to remain low for this disposal method to be usable. If the secondary use is agriculture or aquaculture, monitoring should be done to insure that the trace amounts of toxic materials are not concentrated over a period of time. Little or no solid waste disposal should be involved with the method. The potential for land subsidence will be the same as for all surface disposal systems. This will depend on the geology of the area. Those sites that use only part of the liquid and inject the remainder should have less potential for subsidence.

Conclusions

Secondary uses of geothermal liquids are potentially useful in parts of the arid west where water supplies are short, or where the existing ground water is not potable. The disposal method is technically feasible and could find application in lower flow, nonelectrical situations.

8.2.5 Injection at the Producing Horizon

Technical Evaluation

From a technical standpoint, injection at the producing horizon appears to be a feasible form of disposal and is being used at some of the major power-producing sites around the world: Ahauchapan, Larderello, and The Geysers. Injection of cooler waste fluids can cause problems, such as occurred at Otake and Hatchobaru, where the enthalpy of some production wells was lowered. Injection has been tried at most other geothermal sites with varying degrees of success. The injection pump is the one new component that is required for this method, even though the fluid chemistry may require that corrosion resistant materials be used in the disposal system. The design of the injection well must be adequate to withstand the maximum injection pressure and consideration must be given to requirements for hydrofracturing and/or acid injection.

The geology and hydrology are probably the most important factors to be considered. Injection must be into formations that have sufficiently high permeability to handle very large volumes of water and also are far enough from producing wells to avoid early interaction with the production wells. The injected fluids will have a lower temperature and different chemistry than when they were extracted. These physical and chemical changes in the fluids usually increase the probability of scaling and plugging, conditions which tend to be more severe in some formations than others. At the present time, there is no test method that can accurately characterize the reactions between the injected fluids and the receiving formation. Mechanical scrapers are used sometimes to remove scale from injection wells. Acid injection is also used to extend the life of injection wells.

The primary interaction between the utilization process and the disposal system appears when the injection wells or pumps start to plug and cannot handle the required flow. Therefore, a temporary back-up system or standby injection well is required. Interaction can also occur when the injection takes place too close to the production regions and the injected water cools the production well. The minimum distance between production and injection wells at Otake is 150 meters, which does not appear to be adequate.[52] The appropirate distance will vary at each site. Bodvarsson[25] proposed a minimum distance of 600 to 900 meters in his study of the injection of liquid wastes in the Imperial Valley, California. Problems can also occur where fracture zones extend into other aquifers or surface waters. Contamination of other aquifers can also result from well casing failure. Careful monitoring of the injected fluid will be required to detect any unpredicted movement of the fluid.

Injection should be at as high a temperature as possible, consistent with an economic heat removal, to reduce the scaling and plugging potential. At Ahauchapan, El Salvador, for example, it was found that injection could take place without plugging if the injection temperatures were 150°C or greater.[119] In another case at Hatchobaru, Japan, injection fluid was at

$60^{o}C$ and plugging was causing a 6 percent decrease in flow per year. It was decided to use some of the heat in the water for space heating, and a heat exchanger was installed on the waste-fluid line from the main power plant. Consequently, the temperature of the injected water dropped from 60 to $40^{o}C$ and the plugging rate of the wells promptly increased from 6 to 25 percent per year.(52)

Useful by-products are possible using an injection process, either from the utilization of the concondensible gases or from the extraction of minerals from the fluids. Temporary storage in ponds or tanks where precipitation of the useful products can take place is required. However, extraction of useful by-products probably will also decrease with fluid temperature and may also result in a disposal problem from the unwanted solid wastes. The reliability of systems is determined primarily by the rate of plugging, scaling, and corrosion, which may occur relatively slowly but not always predictably. Consequently, high reliability may not be obtainable at many sites.

Economic Evaluation

Injection costs arise from two components:

1) piping and pumping system to deliver the liquids to the injection site, and

2) the injection wells and injection pump.

At The Geysers, injection costs were reported in 1977 to be 0.5 mills/kWh.(122) This cost results from a contractual agreement between Union Oil Company and PG&E and does not reflect actual production costs, but we assume that it is high enough to cover the actual disposal costs incurred. The injection cost at The Geysers is relatively low because the high energy content of the vapor-dominated resource makes it possible to generate power at very low steam flow rates, on the order of 9 kg/kWh. Assuming 75% of the steam is lost in the cooling towers, the costs are about 220 mills per 1000 liters. Flow rates required to generate electricity from liquid-dominated systems could be at least an order of magnitude higher, depending on the temperature of the resource.

Defferding and Walter[46] report the costs of injection disposal, without treatment, in 1976 dollars for the liquid waste from a 50-MWe hypothetical binary facility at Heber (182°C, 6.9 x 10^6 lb/hr brine flow) to be approximately 6.8 mills/kWh, or about 19% of the estimated total cost of power, based on estimates prepared by the Ben Holt Company.[123]

TRW[114] has also calculated injection costs for geothermal liquid waste disposal as a function of fluid injection rate per well, and total waste fluid flow rate. In 1977 dollars, their cost estimates ranged from $10 per 1000 liters on a small 590 kg/hr system with low injection rates, to 15 mills per 1000 liters on a large 60 x 10^6 kg/hr system with the injecton rates of approximately 8,000 liters per minute per well.

The GEOCOST[124] model was used to estimate the cost of an injection system for a 50-MWe flashed steam plant (4.2 x 10^6 kg/hr injected). The disposal cost (in 1977 dollars) was 11.49 mills/kWh, or about 25% of the estimated total cost of power. This cost estimate was based on brine produced at 190°C with no treatment prior to injection. Bodvarsson[25] calculated the injection costs versus injection pressure for a theoretical power plant at East Mesa. Assuming an injection pressure of 400 psig, the cost estimates varied from 11 to 16 mills/kWh (120 to 185 mills/1000 ℓ) depending on which reservoir model was used. One reservoir model requires 20 injection wells for a 50-MW plant, and the other required 10 injection wells. If the injection pressure increases to 800 psig, the costs raise to 21 and 28 mills/kWh (210 and 280 mills/1000 ℓ).

Legal and Institutional Evaluation

The need to satisfy certain legal criteria may be a prime motivator for the development of injection systems. In some areas, strict environmental and pollution laws may preclude any other form of disposal. However, injection is not without its legal problems. The primary problems are associated with the potential for contamination of freshwater aquifers and the possibility of communication of contaminants to surface springs or streams. The use of available well design procedures and the correct installation of the well casing should prevent contamination of freshwater aquifers and confine the injection to the producing horizons.

In Japan, there has been concern that the production of geothermal fluids without injection may cause local hot springs, which are often used as health resorts, to dry up. Similar problems do occur in the U.S. There is a great concern over the geysers and mud pots in Yellowstone Park, and deep drilling at the geothermal sites several miles outside of the park has been restricted. Injection into the producing formations tends to be the disposal technique that will cause the least legal impact.

Environmental and Safety Evaluation

With respect to safety and environmental considerations, disposal by injection is considered one of the better systems. Safety problems are possible since the water may need to be pressurized to greater than 400 psig for injection. The toxic contaminants, however, are returned to the geothermal reservoir. Although the system is subject to failures due to accidents, such as pipe rupture, the disposal system can be designed with back-up systems and alternate injection wells to achieve reliability and safe operation. Berms can be placed around plants to collect and divert any accidental spills.

Assuming that the fluids are returned to the producing horizon, no planned air or water pollution results from this form of disposal system. During those times when the power plant is shut down and flow from the production wells must be maintained, direct flow to the injection wells can be made via bypass lines, thereby allowing planned shutdown of production wells. The geothermal fluids may be taken directly from the silencer or from the temporary storage pond for injection at high temperatures.

Injection is not a source of noise pollution except during the drilling and clean-out of injection wells. The primary sources of noise pollution during production come from the production wells and the centrifugal separators.

Some concern has been expressed that injection may induce seismic events, as has occurred with liquid waste disposal in other industries. Since injection takes place at or near hydrostatic head pressures into formations that have high permeability and an existing convection of geothermal fluids, the probability of inducing significant seismic events is very low. In any case, seismic monitoring at all geothermal plants around the world is routinely being done and only minor disturbances have been reported to date.

Land subsidence can be induced by withdrawal of geothermal fluids in large quantities in certain formations. Injection of the waste fluids into the producing horizons will tend to prevent land subsidence by replacing a large proportion of the withdrawn fluids. However, natural land subsidence may occur in local regions and cause problems with piping and surface installations. Monitoring of land subsidence should be done routinely at all geothermal power installations.

Conclusions

Disposal by injection into a producing horizon is a popular method which is being used or considered at many sites. The method is technically feasible, and legally and environmentally acceptable. However, there are potential problems such as interference with production wells, plugging of injection wells, and contamination of surface or potable aquifers.

8.2.6 Injection at a Nonproducing Horizon

The legal, environmental and safety criteria are essentially the same as those discussed for injection at a producing horizon. Consequently, only the technical and economic evaluations are presented here for injection at a nonproducing horizon.

Technical Evaluation

Injection at a nonproducing horizon has been tested at several sites. In production reservoirs that are highly fractured, passage of the injection fluid to the production wells can easily occur. This inflow of liquid can quench the well or at least reduce the enthalpy of the fluid. At sites with fractured or highly faulted reservoirs, injection of liquids outside the producing reservoir should be considered. This disposal method is being proposed for the power plant installation at Roosevelt Hot Springs. A sixmonth test of a production well and injection in a nonproducing horizon was recently successfully completed at Roosevelt Hot Springs. Wells were drilled in the vicinity of the injection well to monitor the movement of the injection fluid. In El Salvador, the technique was tried but was not successful because of low permeability.[53]

The materials or system components that are required for this technique are similar to those required for injection into a producing formation. The primary technical distinction between injection at a producing horizon versus a nonproducing horizon is the need to insure a physical barrier between the production and the injection wells. Environmentally, injection into the nonproducing horizon will provide less subsidence control than injection into the producing horizon and there will be the problem of reservoir depletion.

Economic Evaluation

Injection into a nonproducing formation can be accomplished by laterally locating the injection wells outside the production zone or by injecting into a zone that is vertically separated from the production zone. The costs will be much less for the vertically separate zones, but problems may arise because impermeable zones are not always continuous. Those sites that require lateral separation will have both the added capital cost of the additional piping, which could be several mills/kWh, and the added operating cost for pumping the fluids.

Conclusions

This method is technically feasible, but is expected to be used primarily where the producing zone is highly fractured, and injection into that zone could degrade the resource.

8.2.7 Treatment and Injection

Technical Evaluation

Disposal systems that treat the waste water prior to injection have been considered at most sites. The two primary motivations for treatment are: 1) the removal of silica and other contaminants that tend to plug the injection well or receiving formation and reduce its useful lifetime; and 2) the removal of useful by-products. Little experience in the geothermal industry is available, but treatment of injected fluids is common in the oil industry. How much of this experience can be transferred to geothermal industry is unknown, because of the much larger volume of fluids to be handled at the geothermal sites, and because the geology of the oil basins is generally considerably different from that of the geothermal basins. These treatments have been discussed in the evaluation of treatment and discharge to surface water.

Economic Evaluation

Bodvarsson[25] estimated the cost of injection for a power plant in the Salton Sea Area, for both treated and untreated fluids from the upper reservoir. The estimates did not include the cost of treatment. For injection at 400 psig, the costs were 5 and 7.5 mills/kWh (90 and 130 mills/ 1000 liters) for treated and untreated, respectively. Quong[10] estimated that treatment of Salton Sea fluids would cost about 2 mills/kWh. These cost estimates are lower than the one for East Mesa, because of the higher permeability and the lower volume per kWh. Disposal of the solids from the treatment plant are not included, but could be substantial for high-TDS liquids.

Legal and Institutional Evaluation

Legal criteria are essentially the same for this system as for the previous two injection systems. Comparisons between the systems would exist only on a site-by-site basis.

Environmental and Safety Evaluation

Environmental and safety criteria are essentially the same for this system as for the previous two systems, unless the chemical treatment involves handling hazardous materials or the release of toxic gases or fluids. Since the system may be considerably more complex than the simple injection system, the safety and environmental criteria should be carefully considered on a site-by-site basis. Many of the treatments, such as sedimentation and filtration, will produce solid wastes that will have to be disposed of.

Conclusion

Treatment before injection may be necessary where scaling and plugging of the receiving formation is a problem. The big factor will be to keep the treatment cost low.

EVALUATION OF GEOTHERMAL LIQUID WASTE DISPOSAL TECHNIQUES

Disposal Method	TECHNICAL ASPECTS: Experience with method	Equipment	Importance of geology and underground hydrology	Interaction with processes	Useful by-products	Reliability	Cost	LEGAL ASPECTS: Geothermal laws	Environmental laws	Water rights laws	Land use laws	ENVIRONMENTAL AND SAFETY ASPECTS: Occupational Safety	Water pollution	Air pollution	Noise pollution	Toxic substance disposal	Solid waste disposal	Induced seismicity	Land subsidence	Comments
Direct Release to Surface Waters	In use (a)	Readily available	Minimal	Very low	No	High	Low	Yes	Yes	Yes	Minimal	Excellent	Moderate	Yes	Yes	No	No	No	Potential	Low cost, good potential for low-temp., direct-heat applications
Treatment and Release to Surface Water	Minimal	Special materials may be needed	Minimal	Moderate (1)	Possibly	Moderate	Moderate	Yes	Yes	Yes	Minimal	Good	Low	Yes	Low	Potential	Yes	No	Potential	Cost of treatment must be kept low
Closed-cycle Ponding	In use (b)	Special materials (pond Liners) needed	Minimal	Very low	Possibly	High	Low (3)	Yes	Yes	Yes	Yes	Good	Low potential	Yes	Yes (5)	Potential	Some	No	Potential	Needs reliable liners and low-cost land in arid regions
Consumptive Secondary Use	Experimental	Readily available	Minimal	Significant (1)	Yes	High	Low	Yes	Yes	Yes	Yes	Good	No	Low potential	Low	No	No	No	Potential	Shows potential for medium- to low-temperature waters
Injection into Producing Horizon	In use (c)	Special Equipment (pumps) needed	High	Significant (1)	Possibly	Moderate (2)	Moderate (4)	Yes	Yes	No	No	Good	Moderate potential	Low	Low	No	Low	Low potential	Low	Very popular, but potentially has some problems
Injection into Nonproducing Horizon	Experimental	Special equipment (pumps) needed	High	Significant (1)	Possibly	Moderate	Moderate (4)	Yes	Yes	No	No	Good	Moderate potential	Low	Low	No	Low	Low potential	Potential	Used primarily where producing zones are highly fractured
Treatment and Injection	Experimental	Special materials may be needed	Moderate (1)	Significant	Possibly	Moderate to high	Moderate	Yes	Yes	No	No	Good	Low	Yes	Low	Potential	Yes	Low potential	Low	Solid disposal may be a big problem

(a) Wairakei, New Zealand; Ahuachapan, El Salvador; Iceland; Klamath Falls, Oregon
(b) Cerro Prieto, Mexico
(c) Ahuachapan, El Salvador and Larderello, Italy

(1) Temporary backup systems needed
(2) Has shown moderate reliability except in highly permeable zones
(3) Depends on liner and land costs
(4) Depends on permeability of [illegible]ing zone (lower permeability increases cost)
(5) Good designs reduce noise output

9.0 RESEARCH NEEDS

During the review and evaluation of the various disposal methods for geothermal liquid wastes, several areas requiring additional research have been identified.[a] These areas include:

1) a more detailed cost analysis of disposal systems (especially treatment systems)
2) trace-impurity cleanup of waste waters from fluorides, arsenic, or boron
3) economical and reliable monitoring and detection of pond leakage
4) identification and evaluation of disposal areas for solid wastes generated during waste treatment
5) study of long-term effects of discharge into the ocean
6) development of a test to determine the compatibility of the waste fluids and the receiving reservoir
7) development of a method to monitor the flow patterns of injected fluids in the receiving reservoir.
8) Two long-range projects include:
   a. development of a method or probe to determine the integrity of the well cement
   b. development of methods (in the reservoir engineering program) to predict or identify formations that can accept large quantities of fluids over a long period of time.

(a) The research needs that are listed here are not intended to be all inclusive, but rather isolate a few projects that can have short-time impact on some of the geothermal sites that are under development. Other ongoing programs that will have an impact on the waste disposal systems programs are: materials research; well logging, stimulation and cementing; and subsidence and reservoir engineering.

9.1 COST ANALYSIS

Computer models can be used to predict some of the costs of liquid effluent disposal, such as piping runs and pumping costs. Other data are available to estimate pond sizes and costs. The treatment costs have been primarily estimated from municipal waste plants.

What is Needed

Researchers need to take site-specific data from a few geothermal sites (4-6) that are prime candidates for development in the next 10 years, and develop flow sheets for waste disposal systems. Using the above data, they must develop more detailed and accurate cost estimates and determine the effect of geothermal waste disposal on power costs.

9.2 TRACE IMPURITY CLEAN-UP

A number of the lower-temperature geothermal reservoirs are usable for direct heating or process heating and are clean enough for discharge to surface waters except for one or more trace impurities. These impurities can include fluorides, arsenic or boron. The reduction or removal of these impurities would permit the use of less expensive disposal methods.

What is Needed

Researchers must develop low-cost methods to remove trace impurities from low-saline geothermal liquids.

9.3 MONITOR FOR POND LEAKAGE

Ponds are used at almost all geothermal installations for holding drilling muds during well testing, and many times as emergency back-up systems. The use of ponds for disposal could increase if there were a better method to detect leaks before they damage the nearby ground or surface waters.

What is Needed

Geothermal operators need a low cost, reliable method for early detection of leaks from holding or evaporation ponds.

9.4 SOLID WASTE DISPOSAL SITES

Injection of high salinity fluids will most likely require some waste treatment. This treatment will probably generate solid wastes. The volume of these solids will depend on the fluid, but can be very significant. Long-range trucking of the wastes to a disposal dump is expensive.

What is Needed

A study is needed to identify and evaluate potential solid waste disposal sites near the geothermal areas that might be developed in the next 10 years.

9.5 EFFECTS OF OCEAN DISCHARGE

Discharge of geothermal liquids into the ocean is a potential disposal option, especially in the Gulf Coast area.

What is Needed

A study is needed on the long-term effects on discharging geothermal liquids into the ocean. A cooperative effort with El Salvador and Mexico could provide some of this information, since these countries are presently discharging into saltwater. Existing cooperative projects may need to be modified to provide this added information.

9.6 COMPATIBILITY TEST

Injection of fluids into a deep reservoir is sometimes restricted or blocked by reactions between the receiving formation or formation water and the injected water.

What is Needed

Scientists need to develop a small-scale test, maybe using core samples, that can determine disposal parameters, such as minimum injection temperatures or maximum delay time. The test can also be used to determine the extent of cleanup that is necessary for long-term injection.

9.7 INJECTED FLUID TRACER

Subsurface injection of large quantities of fluids is faced with the problem of not knowing where the fluid is going. Flow patterns will proceed out from the injection well in the path of least resistance, generally towards the production wells. Radioactive tracers are used on a limited basis, but they can create problems of their own.

What is Needed

A method to monitor the movement of the wave front or the injected fluids is needed. Nonradioactive tracers that are detectable at low levels may be usable.

9.8 LONGER RANGE PROJECTS

- We need to develop a method or a logging tool that can measure the integrity of the well cement. This is needed to prevent acquifer contamination caused by deterioration of the cement.
- Also, we need to include in the reservoir engineering program studies directed at developing surface measurements to locate acquifers, which will accept large injection flows for an extended period of time.

The geothermal industry is developing at an increasing pace. New power plants are under construction, new geothermal fields are being tested for potential production, and a number of processor direct-heat applications are under development. Also, changes are occurring at The Geysers, where waste disposal is affected by the H_2S treatments. With all of this activity, there is a need for a central laboratory to gather and periodically disseminate pertinent information on waste disposal at these sites. This information would be very useful to companies that have geothermal installations under design, development or modification. The laboratory could become an information source that would be available to potential users of geothermal energy.

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APPENDIX A

EQUIPMENT CORROSION AT GEOTHERMAL SITES

EQUIPMENT CORROSION AT GEOTHERMAL SITES

The severity of material corrosion processes at geothermal sites may be expected to be strongly site-specific in view of the wide range of geothermal primary fluid compositions likely to be encountered with extensive exploitation of this resource. Corrosion response also depends on equipment design details and the design accommodation to corrosion. When dealing with corrosion situations far less complicated than that presented by most geothermal fluids, theoretical assistance is weak for many critical material applications. This implies that onsite testing is crucial for successful selection of structural materials for geothermal plants and their disposal ancillaries.

This appendix summarizes a few materials equipment observations reported for the Cerro Prieto and Wairakei sites, where relatively comprehensive materials evaluation has been underway for some time. Tables A.1 through A.5 present some corrosion data for Cerro Prieto, Wairakei, Niland and Holtville (East Mesa).

CERRO PRIETO[A.1]

Well Casings

- No corrosion failure of casings has been proved.
- Pitting and general corrosion inside production casing has been insignificant due to low oxygen content of bore fluids; possibly also due to protective effect of SiO_2, deposits.
- External and internal corrosion has been observed close to the surface, where ground water level has fluctuated.
- Galvanic corrosion has been observed near surface where two or more casings have been coupled without adequate insulation; poor bonding between casings and cement can lead to galvanic corrosion at any depth.

TABLE A.1. Corrosion Observations in Cerro Prieto Steam Source: A. Manon (Reference A.1)

CORROSION IN NON-AERATED STEAM

Material	Corrosion rate mm/yr	Pitting rate mm/yr	Corrosion rate change (days) 30	60	90	120	150
12 Cr	0.0100	0.024	0.0041	0.0085	0.0089	0.0127	0.0102
12 Cr-Mo-W	0.0040	0.024	0.0080	0.0041	0.0048	0.0039	0.0042
1 Cr-Mo-0.25 V	0.0400	-	0.023	0.022	0.029	0.059	0.040
3.5 Ni-1.75 Cr-Mo-V	0.0160	0.120	0.017	0.014	0.011	0.012	0.016
12 Cr-0.2 Al	0.0190	-	0.0003	0.0051	0.0080	0.015	0.019
15 Cr-1.7 Mo	0.0046	0.150	-	0.0023	0.0049	0.0041	0.0046
1 Al-1.5 Cr-0.25 Mo	-	0.970	-	-	-	-	-
Aluminium	-	-	-	-	-	-	-
ASTM A285	0.0400	-	0.110	0.051	0.046	0.040	-

CORROSION IN AERATED STEAM

Material	Corrosion rate mm/yr	Pitting rate mm/yr	Corrosion rate change (days) 30	60	90	120	150
12 Cr	0.100	1.70	0.10	0.14	0.10	0.10	0.10
12 Cr-Mo-W	0.069	1.60	0.12	0.06	0.04	0.07	0.07
1 Cr-Mo-0.25 V	0.210	-	0.50	0.28	0.20	0.14	0.21
3.5 Ni-1.75 Cr-Mo-V	0.340	0.70	0.29	0.52	0.16	0.16	0.34
12 Cr-0.2 Al	0.110	-	0.06	0.15	0.09	0.10	0.11
15 Cr-1.7 Mo	0.014	1.20	0.00	0.02	0.01	0.01	0.01
1 Al-1.5 Cr-0.25 Mo	-	0.85	-	-	-	-	-
Aluminium	0.083	2.90	-	0.03	0.04	0.10	0.08
ASTM A285	0.065	-	0.18	0.12	-	0.10	0.06
Deoxidized copper	0.510	-	1.03	0.91	0.66	0.52	0.51
Stellite #6	0.057	2.70	0.18	0.12	-	0.10	0.06

Non-aerated steam
- Pressure = 4.3 kg/cm^2 (61 psig)
- Temperature = 147° C (296° F)
- CO_2 = 1.95% (Weight)
- H_2S = 0.20% (Weight)
- Cl^- = 13.3 ppm
- Moisture % = 0.7% (Weight)

Aerated steam
- Pressure = 1 atmosphere (14.7 lb/in^2 abs)
- Temperature = 70° C
- CO_2 = 1.6%
- H_2S = 0.16%
- Cl^- = 7 ppm
- Moisture % = 0.7%

TABLE A.2. Corrosion Observations in Cerro Prieto Condensate Source: A. Manon (Reference A.1)

CORROSION IN LOW VELOCITY CONDENSATE

Material	Corrosion rate mm/yr	Pitting rate mm/yr	Corrosion rate change (days) 30	60	90	120	150
Deoxidized copper	0.240	no pitting	0.16	0.19	0.20	0.22	0.24
Aluminium	0.004	1.16	0.04	0.13	0.02	0.08	0.00
Naval Brass	0.072	no pitting	0.14	0.12	0.11	0.08	0.07
AISI Type 304 (18-8)	0.0008	no pitting	0.02	0.00	0.00	0.00	0.00
AISI Type 410 (12 Cr)	0.015	0.97	0.05	0.05	0.04	0.03	0.01
Low carbon steel	0.310	no pitting	0.62	0.42	0.34	0.33	0.31

CORROSION IN HIGH VELOCITY CONDENSATE

Material	Corrosion rate mm/yr	Pitting rate mm/yr	Corrosion rate change (days) 30	60	90	120	150
Deoxidized Copper	0.0640	*	0.19	0.83	0.73	0.64	-
Aluminium	0.370	3.65	0.06	0.12	0.29	0.35	0.37
Naval Brass	0.220	*	0.04	0.20	0.22	0.21	0.22
AISI Type 304 (18-8)	0.0003	no corrosion	0.00	0.00	0.00	0.00	0.00
AISI Type 410 (12 Cr)	0.080	0.85	0.00	0.02	0.09	0.20	0.08
Low carbon steel	0.700	*	-	1.14	0.90	0.88	0.70

*General Corrosion

Condensate, Low velocity
- Pressure = 1 atmosphere
- Temperature = 40° C
- Cl^- = 50 ppm
- pH = 6.8 - 7.0
- Velocity = 0.0005 m/sec

Condensate, High velocity
- Pressure = 1 atmosphere
- Temperature = 45° C
- Cl^- = 60 ppm
- pH = 6.4 - 7.3
- Velocity = 0.5 m/sec

TABLE A.3. Materials Tested at Cerro Prieto
Source: A. Manon (Reference A.1)

Material	Use on the Power Plant	Nominal Composition, %						
		C	Cr	Mo	Ni	V	W	Al
12Cr	Turbine buckets	0.12	12.0	0.13				
12Cr-Mo-W	Tubrine Buckets	0.22	11.7	1.00	0.7	0.25	1.0	
1Cr-Mo-0.25V	Rotor	0.30	1.25	1.10		0.25		
3.5Ni-Cr-Mo-V		0.25	1.75	0.40	3.5	0.11		
12Cr-0.2Al	Nozzle partition	0.04	13.0					0.2
15Cr-1.7Mo	Labyrinth strips	0.05	15.0	1.70				
1Al-1.5Cr-0.25Mo			1.50	0.25				1.0
Aluminum	Oil coolers							
ASTH A285	Outer and inner turbine casing	Maximum 0.06P, 0.06S						
Copper deoxidized		Pure copper						
Steilite #6	Sixth stage rotor blades (coat)	2.8Cr-4W-3Fe-Co Rem.						
Naval brass	Tube sheets Oil coolers	60Cu-39.25Zn-0.75Sn						
AISI Type 304 (18-8)	Gas ejector	0.08	19.0		9.0			
AISI Type 410 (12Cr)		0.15	12.5					

TABLE A.4. Surface Corrosion Rates in Wairakei Geothermal Media
Source: T. Marshall and W. R. Braithwaite (Reference A.2)

Metal[a]	Bore Water,[b] >200°C	Water,[c] ~125°C	Steam,[d] 100 - 200°C	Aerated Steam,[e] ~100°C	Condensate,[f] ~70°C	Condensate/ Fresh Water Mixture,[g] ~50°C	Highly Acid Thermal Water[h]
Titanium	0	0	0	0	--	--	0
Chromium (plating on steel)	0	--	0	0	--	--	--
Aluminum	I	0.8 - P	0 - P - I	0 - P	0.2	9	28
Zinc (coating on steel)	S[14]	1	0 - I - P	S	--	S	--
Austenitic stainless steels[i]	0.1	0	0	0	0	0	22
Ferritic stainless steels[j]	0 - 0.1	0.1 - P	0 - 0.3 - P	1 - P	0.1 - P	0 0.5	--
Carbon and low alloy steels	0.3 - 0.4	0.3 - 0.5	0.3 - 6	20	3	30 - 170	1,000
Grey cast iron	1	0.4	1 - 3	10	--	90	--
High silicon cast iron	--	--	0.5	1	--	--	8
Brasses[k]	5	0.3	0.3 - 0.6	40	0.2	--	--
Bronze	20	--	2	9	--	--	--
Aluminum bronzes	10	--	2 - 3	10	1	--	--
Silicon bronze	--	--	3	20	--	--	--
Cupronickel	9	--	2	--	--	--	--
Beryllium copper	10	--	4	--	--	--	--
Copper	20	10	2	40	5	--	--
Nickel	6	--	1	8	2	--	--
Monel and K Monel	8 - 10	1	2 - 4	10	4	--	14
Nomonic 75	0.3	--	0	--	--	--	--
Inconel	1	0	0 - 0.3	80	--	--	20
Lead, antimonial lead	--	--	0.5	2.5 - P	--	1	6

(a) 1 mil = 0.001 in.
(b) Tests in water at bottom of a closed geothermal bore.
(c) Water separated from wet geothermal steam at wellhead.
(d) Steam separated from discharging geothermal bore.
(e) Geothermal steam mixed with injected air.
(f) Geothermal steam separated and condensed under pressure.
(g) Geothermal steam condensed with freshwater to stimulate fluid in a jet condenser hot well.
(h) Natural water in a volcanic crater.
(i) 18/8 CrNi, 18/8/3 CrNiMo, and 18/12/2 CrNiMo varieties.
(j) 13Cr, 17Cr, 17/2 CrNi varieties.
(k) 60/40 CuZn, arsenical 70/30 CuZn varieties.
I = internal attack with embrittlement.
P = pitting.
S = zinc coating stripped.

TABLE A.5. Corrosion Observations in Synthetic Imperial Valley Brines
Source: J. P. Carter and S. D. Cramer (Reference A.3)

- Typical geothermal brine compositions, Imperial Valley, California

Constituents	Composition, ppm[1]	
	Niland brine (high-salt)	Holtville brine (low-salt)
Na	53,000	11,000
Ca	28,800	1,370
K	16,500	1,430
Fe	2,000	0.18
Mn	1,370	.9
Zn	500	.02
Sr	440	226
SiO_2	400	101
B	390	27.4
Ba	250	58
Li	210	55
Pb	80	0.26
Rb	70	1.7
Cs	20	4.0
Mg	10	21.8
Ge	---	1.5
As	---	1.0
Al	---	0.4
Cu	---	.05
Ag	---	.04
Ga	---	<.5
Mo	---	<.1
W	---	<.04
Cl	155,000	18,000
F	---	1.5
Br	---	35
S	30	<1
CO_2	500	---
NH_4	---	38.8
SO_4	---	16
H_2O	balance	balance
pH	Adjusted to 6.1 w/NaOH	Adjusted to 7.6 w/HCl

- Corrosion data at 105° C and 1 atm, 15 days[1]

	General corrosion, mpy				Crevice corrosion[2]			
	Air-aerated		Deaerated		Air-aerated		Deaerated	
	Holtville brine (3 w/o)	Niland brine (28 w/o)	Holtville brine (3 w/o)	Niland brine (28 w/o)	Holtville brine (3 w/o)	Niland brine (28 w/o)	Holtville brine (3 w/o)	Niland brine (28 w/o)
Iron Base:								
Carbon steel	40.9	5.8	17.3	4.2	--	--	--	--
4130 steel	10.7	--	0.2	--	1	--	1	--
Sandvik 3RE-60	0.1	0.9	.4	0.0	3	6	1	2
E-Brite 26-1	..0	3.6	.0	.0	1	1	1	1
Type 302 ss	.1	--	.0	--	2	--	1	--
Type 316L ss	.0	4.0	.0	0.0	2	6	2	2
Carpenter 20 ss	.2	2.2	.1	.0	1	5	1	2
Nickel Base:								
Monel 400	2.5	3.7	0.2	2.8	4	5	1	4
Inconel X-750	0.1	3.4	0.0	0.0	--	5	--	3
Inconel 625	.0	0.0	.0	.0	1	3	1	1
Hastelloy S	.1	.0	.1	.0	1	4	1	1
Hastelloy G	.1	.1	.1	.0	1	4	1	1
Hastelloy C-276	.1	.0	.1	.0	1	1	1	1
Copper Base:								
Copper	63.1	12.5	1.9	3.1	--	1	--	1
Copper-2Iron	11.6	13.3	3.7	2.7	--	--	--	--
90-10 brass	3.6	--	2.2	--	4	--	1	--
70-30 brass	4.3	--	1.2	--	4	--	1	--
90-10 Cupronickel	3.7	--	0.9	--	1	--	1	--
70-30 Cupronickel	17.9	5.8	5.7	0.6	--	4	--	3
Titanium Base:								
Titanium	0.0	0.0	0.0	0.0	2	2	1	1
Titanium-1.7W	.0	.0	.0	.0	1	1	1	1
Titanium-2Ni	.1	.0	.0	.0	--	1	--	1
Titanium-10V	.0	.0	.0	.0	--	1	--	1
Aluminum Base:								
2024-T3	[3]45.4	34.9	4.9	[3]1.3	--	6	--	6
6061-T6	2.1	56.6	2.1	[3]30.4	--	1	--	1
Molybdenum Base:								
TZM	3.0	1.4	0.2	0.0	--	5	--	1

[1]Dashes (--) indicate that metal was not tested.
[2]Numbers indicate extent of corrosion as follows:
1. Not detected.
2. Very slight (< 0.1 mpy)
3. Slight (> 0.1 mpy but < 1 mpy)
4. Moderate (> 1 mpy but < 5 mpy)
5. Severe (> 5 mpy but < 50 mpy)
6. Very severe (> 50 mpy).

[3]Pits 60 mils deep.

- Casing steels (e.g., H40 and K55) are sensitive to SCC in low temperature H_2S environments (a condition which can be obtained during a repair stage).
- Erosion has been observed in surface piping sections where there was a high-velocity flow of water/steam mixtures carrying sand.
- Rupture and collapse of casing has been encountered on several occasions; the extent of corrosion involvement in this action is unknown.
- Carbon steel can be used for casing and surface piping conduction of non-aerated steam.

Turbine

- After two years operation, two inspections of turbines have shown no corrosion or cracks on buckets; stellite facing on the sixth turbine stage was in good conditon; the main problem has been SiO_2 deposition on first-stage nozzles and buckets due to poor water separation from steam; 12Cr steel is used for buckets.

Cooling Water System

- Pitting and corrosion in cooling water systems has been the main corrosion problem, particularly for oil and hydrogen coolers; pitting has been observed for both Al and 304 SS; Ti tubes have given good service to date.
- High corrosion penetration rates have been observed on unprotected inside surfaces of C steel valves and pipes; epoxy coating has been used with good success in barometric condensers, although there have been instances of epoxy damage due to erosion.
- C steel pipes carrying discharge from condensers have shown severe corrosion and were replaced by fiber glass-epoxy pipes.
- Upper part of concrete canal conducting water from hot well to cooling tower pumps showed deterioration.

WAIRAKEI[A.2]

Bore and Wellhead Equipment

- Low strength steels (e.g., API grades H40, J55) have generally given good service; aerated thermal groundwater near surface can cause corrosion at surface end casing (usually controlled by multiple casing, with grouting).
- High velocity steam/water/detritus steams can cause severe erosion and corrosion damage to casing and valves; during normal operation this presents no problem.
- Thermal stresses caused by intermittent flow can produce casing fracture and joint failures, possibly aggravated by chloride and sulfide cracking; the French steel APS-10M4 is specially designed to resist sulfide cracking and hydrogen induced delayed failure; casing failure can be minimized by keeping bores discharging after intial "blowing in" period.
- Low strength C steel usually used for wellhead equipment, with SS for valve trim; Cu-based alloys are to be avoided; leakage to air can cause valve stems and packing to corrode.
- Stressed stainless steel equipment must be protected from hot aerated steam and spray to minimize chloride cracking.
- High velocity steam can cause erosion of deflector plates in silencers; this effect is reduced by streamlining flow and use of nonmetallics.

Steam/Water Pipelines

- Low-strength C steels have given satisfactory service; main corrosion problems have arisen from design methods used to cope with expansion joints (special precautions must be taken with stainless steel bellows).
- Avoidance of standby corrosion is chief operating problem and is minimized by:
    - Avoiding oxidation of residual H_2S to produce acid condensate
    - Keeping piping full of steam to avoid oxygen entry
    - Designing pipline to meet the standby corrosion problem.

Turbines

- Use lowest strength steel practicable; lowest blade tip speeds.
- Good joint sealing to minimize oxygen in-leakage.
- With above precautions, conventional turbine materials (cast steel castings, C steel rotors 13% Cr blades, shrouds and lacings) have given excellent service.
- Higher pressure geothermal turbines may require medium strength steels in final stages plus erosion shields to cope with erosion at higher tip speeds; considerable research and development is needed to develop geothermal turbines with a higher power density.

Condensers

- The condensers present probably the maximum corrosion severity conditions in the geothermal plant due to inevitable air in-leakage with surface condensers or dissolved oxygen in cooling water for jet condensers; condenser corrosion control measures include:
  - Use of mild steel, with epoxy and other surface coatings
  - Lead-coated steel
  - 13% Cr steel at only moderately severe corrosion sites
  - Al, austenitic SS's, PVC, polyester, fibreglass and other plastics, and use of wood for highly corrosive conditions where temperature and pressure are low
  - Use of pyrex glass tubing in some applications at low temperature and pressure
  - Use of Ni-resist iron for pumps
  - Concrete for water discharge ducts; concrete may require surfacing with coal tar to prevent "sulfate attack" in vapor spaces above water
  - Centrifugal compressors for gas extraction from condensers operate in highly corrosive mixture of wet gases and air; one corrosion control expediency is to limit interstage cooling so that gases remain relatively hot, dry during passage through compressor.

Cooling Towers

- Some of the abnormal conditions for geothermal cooling towers include:
  - H_2S in circulating water and subsequent oxidation to S, H_2SO_4 and other sulfer compounds
  - Corrosiveness of circulating water appears to depend largely on amount of NH_3 (or ratio of NH_3 to H_2S), since NH_3 tends to neutralize the acid
- Corrosion control measures include use of wood, concrete, austenitic SS's, Al, asbestos board, plastics and nonmetallic protective coatings.

Auxiliary Equipment

- Piping buried in thermal ground for transport of geothermal fluids is susceptible to sulfide SCC; use of metal, asbestos-cement, or piping protected with carefully applied nonmetallic coating is recommended.
- Spring materials used in instrumentation and control equipment pose SCC problems; Cu bearing alloys are to be avoided (e.g., Be-Cu); austentitic SS?'s, K-Monel are recommended for this application together with use of isolating fluids where possible.
- Atmosphere exposed equipment may suffer attach from H_2S (e.g., tarnishing of Ag contacts can render electronic equipment inoperable).
- Preventative measures include:
  - Gas discharge through remote and/or high vents
  - Good maintenance program
  - Use of resistant materials (e.g., Al) for overhead conductors, building sheathing; Cr plating of various components resists tarnishing; Pt, Au and other rare metals used for contact points of electrical equipment.
- General atmosphereic corrosion around geothermal plants is, in practice, one of the most troublesome corrosion areas and warrants full consideration in plant design.

APPENDIX A - REFERENCES

A.1 A. Manon, "Corrosion Problems at the Cerro Prieto Geothermal Project." Proceedings of Second Workshop on Materials Problems for Geothermal Energy Systems, El Centro, CA, May 16, 1975.

A.2 T. Marshall and W. R. Braithwaite, "Corrosion Control in Geothermal Systems." Geothermal Energy, Earth Sciences 12, UNESCO, p. 151, 1973.

A.3 J. P. Carter and S. D. Cramer, "Corrosion Resistance of Some Commercially Available Metals and Alloys to Geothermal Brines." Symposium on Corrosion Problems in Energy Conversion and Generation, New York, NY, October 15, 1974.

APPENDIX B

VALUE OF MINERALS IN BRINE

TABLE B.1. Analyses of Some Disposal Brines, Seawater, and a Proven Economic Brine[a]

Brine	State	County	Formation	Sp. gr.	Na	Ca	Mg	K	Li	B	NH_4	Cl	Br	I	SO_4	HCO_3	DS
					Constituents (mg/l)												
1	Seawater	--	--	1.025	10,500	400	1,350	380	0.17	4.6	--	19,000	65	0.06	3,468	140	35,308
2	Okla.	Kingfisher	Oswego	1.124	56,250	8,300	260	180	14	18	300	98,300	1,500	1,300	180	50	166,652
3	Ark.	Columbia	Smackover	1.230	74,000	44,440	4,340	4,410	370	200	--	202,050	5,725	15	220	95	335,865
4	Kans.	Pawnee	Arbuckle	1.036	14,430	2,480	700	260	20	10	20	32,850	60	10	2,000	450	53,290
5	Kans.	Barton	Arbuckle	1.025	9,850	1,450	490	75	3	10	30	19,460	50	5	2,350	350	34,123
6	Kans.	Butler	Hunton	1.012	5,900	760	260	70	3	0	0	10,380	20	2	1,400	60	18,855
7	Kans.	Ellis	Arbuckle	1.034	16,800	2,630	690	190	10	5	0	30,500	50	2	2,880	315	54,072
8	Kans.	Pratt	LKC-Arb	1.020	9,400	1,200	320	105	5	3	0	17,900	50	3	1,100	250	30,332
9	Kans.	Barton	LKC-Arb	1.050	23,300	4,300	1,300	160	5	12	30	45,100	150	10	2,270	260	76,895
10	Ark.	Palm	Graves	1.046	19,900	3,500	900	200	5	10	45	42,200	500	10	0	170	67,439
11	Ark.	Ouachita	L. Graves	1.048	21,100	3,800	1,030	160	5	16	40	43,100	400	10	0	160	69,819
12	Ark.	Ouachita	L. Graves	1.046	20,500	3,800	930	140	5	12	40	42,400	600	10	0	60	68,495
13	Ark.	Union	Smackover	1.192	64,200	34,500	3,950	1,845	160	140	320	178,100	2,450	5	650	100	286,420
14	Ark.	Union	Smackover	1.192	63,900	38,500	3,850	1,945	180	150	260	180,800	2,340	5	440	190	292,560
15	Ark.	Union	Smackover	1.199	63,300	36,300	4,040	1,370	170	140	260	197,600	4,800	5	350	200	345,235
16	Ark.	Union	Smackover	1.191	64,500	37,300	3,895	2,000	165	140	100	182,600	3,390	10	255	600	295,955
17	Ark.	Columbia	Smackover	1.162	54,500	27,600	1,315	3,500	230	160	50	150,000	3,500	5	190	200	241,250
18	N.M.	Lea	San Andres	1.020	9,150	1,500	500	245	5	10	70	17,800	50	3	2,000	1,000	32,329
19	N.M.	Lea	Devonian	1.036	18,200	1,850	500	370	10	0	60	32,650	30	0	2,260	500	56,428
20	N.M.	Lea	Devonian	1.028	13,900	1,500	340	20	2	0	0	24,300	25	0	2,000	600	42,687
21	N.M.	Lea	Penn	1.043	21,600	2,840	770	150	10	40	90	42,600	210	5	360	380	69,055
22	N.M.	Lea	Devonian	1.039	19,350	2,400	410	560	10	5	0	37,240	40	2	1,630	490	62,137
23	Texas	Gaines	Devonian	1.025	12,380	1,970	365	400	5	5	100	22,400	40	0	610	590	38,865
24	Texas	Cherokee	Woodbine	1.056	30,000	8,650	345	105	2	40	50	49,100	270	30	240	400	89,232
25	Texas	Rusk	Petit	1.153	58,700	10,320	1,130	790	35	10	50	135,500	210	30	270	0	207,045
26	Texas	Cherokee	Woodbine	1.070	36,200	3,300	690	860	2	0	40	61,300	400	35	30	300	103,157
27	Texas	Wood	Woodbine	1.065	34,000	10,530	110	550	5	5	10	57,100	370	30	90	400	103,200
28	Texas	Wood	SubClarkville	1.037	21,200	840	205	360	2	10	25	31,800	180	35	0	450	55,107
29	Texas	Wood	Paluxey	1.076	34,600	6,750	970	250	10	20	40	68,700	100	25	420	300	112,185
30	Texas	Hopkins	Paluxey	1.010	5,640	630	40	50	2	10	0	8,350	70	5	120	500	15,417
31	Ala.	Mobile	Rodessa	1.031	12,180	5,630	480	400	5	0	90	29,400	40	10	710	190	49,135
32	Ala.	Mobile	Rodessa	1.039	14,500	6,750	550	320	10	12	80	37,000	50	10	300	160	59,742
33	Ala.	Mobile	Rodessa	1.052	18,400	8,860	680	460	10	30	90	47,540	30	12	400	140	76,652
34	La.	LaSalle	Wilcox	1.064	35,600	1,650	600	310	5	25	250	62,500	70	20	0	380	101,410
35	La.	Calcasieu	--	1.084	44,800	3,960	230	300	5	10	25	74,600	25	20	0	140	124,115
36	La.	Cameron	Miocene	1.076	42,600	2,335	135	200	5	12	12	68,900	30	20	0	300	114,549
37	Calif.	Fresno	--	1.026	13,600	1,855	780	200	1	5	0	28,870	15	20	0	240	45,616
38	Calif.	Kern	Kern	1.000	210	70	5	15	1	0	0	330	2	0	40	130	803
39	Ariz.	Apache	L. Hermosa	1.012	7,760	1,520	50	20	1	0	12	11,600	20	12	0	170	21,165
40	Okla.	Woods	Hunton	1.123	57,600	10,120	1,640	1,000	10	40	260	115,500	326	150	350	120	187,096
41	Okla.	Oklahoma	Wilcox	1.151	68,750	13,270	2,460	980	10	0	140	138,600	540	10	520	85	225,365
42	Miss.	Wayne	Wilcox	1.003	2,880	50	10	10	0	0	0	3,861	3	0	410	255	7,479

TABLE B.2. Formulas for Calculating Maximum Worth, Brine Worth, and Brine Value

Maximum worth = (X_i) (market value of compound i)[a]
Brine worth = M.W. - (market cost + fixed charges)

Assume:
brine worth = M.W. - 0.75 (M.W.)
Also assume:
brine value = M.W. x 0.1

(a) X = amount of compound, and i = number of compounds.

TABLE B.3. Value of Assumed Recoverable Compounds Used in Calculating Brine Value

Cation	Compound	Cation ($/ton[a])	Compound ($/ton)
Na	NaCl (rock)	18.09	7.11
Mg	$MgCl_2$ (99%)	259.38	66.14
	$MgSO_4$	346.99	69.22
Li	LiCl (technical)	11,515.10	1,873.91
Sr	$SrCl_3$	518.89	286.60
K	KCl	58.88	30.86
Ba	$BaCl_2$ (technical)	284.29	187.39
Ca	$CaCl_2$	120.64	43.54
NH_4	NH_4Cl	412.26	138.89

Anion	Compound	Anion ($/ton)	Compound ($/ton)
B	$Na_2B_4O_7 \cdot 10H_2O$	519.72	55.39
Cl	NaCl (rock)	11.72	7.11
SO_4	Na_2SO_4 (salt cake)	45.64	30.86
	$MgSO_4$	86.75	69.22
Br	NaBr	1,135.69	881.84
I	NaI (U.S.P.)	9,114.61	7,716.10
HCO_3	$NaHCO_3$	81.24	59.03
CO_3	$CaCO_3$	26.20	15.71

(a) Metric tons.

TABLE B.4. Value of Brine Constituents[a]

Assumed Brine Composition (kg/m^3 of brine):

Calcium	23.36
Magnesium	2.25
Potassium	5.27
Lithium	0.34
Boron	0.31
Sodium	57.65
Bromide	1.95
Iodide	0.04
Sulfate	0.11
Bicarbonate	145.60

Assumed Products (kg):

NaCl	146.01	at $	7.11/ton[b]	= 1.04
$CaCl_2$	64.73	at $	43.54/ton	= 2.82
$MgCl_2$	8.75	at $	66.14/ton	= 0.58
KCl	10.06	at $	30.86/ton	= 0.31
LiCl	2.05	at $	1,873.91/ton	= 3.84
$Na_2B_4O_7 \cdot 10H_2O$	2.97	at $	55.39/ton	= 0.16
NaBr	2.52	at $	881.84/ton	= 2.22
NaI	0.04	at $	7,716.10/ton	= 0.31
$MgSO_4$	0.13	at $	69.22/ton	= 0.01
$NaHCO_3$	0.10	at $	59.03/ton	= 0.01
			Maximum worth	= $11.30

Brine worth = $11.30 - 3/4 (11.30) = $2.82/$m^3$

Brine value = $11.30 x 0.1 = $1.13

(a) Assuming 75% of market cost is operating and fixed charges.
(b) Metric tons.

TABLE B.5. Brine Worth, Brine Value, and Ratio Commercial Brine Value/Disposal Brine Value

Brine	Brine Worth ($/m^3)	Brine Value ($/m^3)	Ratio	State
1	0.19	0.08	19.38	Seawater
2	3.69	1.45	1.07	Okla.
3	3.86	1.55	1.00	Ark.
4	0.28	0.11	14.09	Kans.
5	0.17	0.07	22.14	Kans.
6	0.10	0.04	38.75	Kans.
7	0.28	0.12	12.92	Kans.
8	0.14	0.06	25.83	Kans.
9	0.39	0.16	9.69	Kans.
10	0.41	0.17	9.12	Ark.
11	0.41	0.17	9.12	Ark.
12	0.82	0.33	4.70	Ark.
13	2.38	0.95	1.63	Ark.
14	2.50	1.00	1.55	Ark.
15	2.99	1.19	1.30	Ark.
16	2.61	1.04	1.49	Ark.
17	2.48	0.99	1.57	Ark.
18	0.18	0.07	22.14	N.M.
19	0.22	0.09	17.22	N.M.
20	0.16	0.07	22.14	N.M.
21	0.33	0.13	11.92	N.M.
22	0.25	0.10	15.50	N.M.
23	0.19	0.08	19.37	Texas
24	0.52	0.21	7.38	Texas
25	1.11	0.33	4.70	Texas
26	0.48	0.19	8.16	Texas
27	0.64	0.25	6.20	Texas
28	0.26	0.11	14.09	Texas
29	0.51	0.05	31.00	Texas
30	0.10	0.04	38.75	Texas
31	0.32	0.13	11.92	Ala.
32	0.37	0.15	10.33	Ala.
33	0.53	0.21	7.38	Ala.
34	0.34	0.14	11.07	La.
35	0.38	0.15	10.33	La.
36	0.33	0.13	11.92	La.
37	0.23	0.09	17.22	Calif.
38	0.01	0.01	155.00	Calif.
39	0.17	0.07	22.14	Ariz.
40	1.06	0.42	3.69	Okla.
41	0.96	0.39	3.97	Okla.
42	0.02	0.01	155.00	Miss.

APPENDIX C

ENVIRONMENTAL CHARACTERISTICS OF SPECIFIC U.S. GEOTHERMAL SITES

ENVIRONMENTAL CHARACTERISTICS OF SPECIFIC U.S. GEOTHERMAL SITES

CLEAR LAKE-THE GEYSERS, CALIFORNIA

The Clear Lake-The Geysers geothermal area is in northcentral California in Sonoma and Lake Counties, about 120 km north of San Francisco and 140 km northwest of Sacramento.

Environmental Setting

The Clear Lake-The Geysers geothermal area lies in the interior portion of the California Coastal Range, bordering the Sacramento Valley on the east. The topography is flat to rolling around Clear Lake to mountainous and narrow valleys with steep side slopes in the surrounding area. Elevations range from 366 to 1440 m (1200 to 4722 ft) above mean sea level. The area has a Mediterranean-type climate with warm summers and mild winters. Average monthly temperatures range from 5°C (41°F) (December) to 24°C (76°F) (July), and extremes of -13°C (9°F) and 47°C (116°F) have been recorded. The average annual precipitation ranges from 63 cm (25 in.) in lower areas to 203 cm (80 in.) in some mountain areas. The average number of continuous frost-free days ranges from 160 to 280 days.[C.1]

The most prominent water feature is Clear Lake, the largest freshwater lake entirely within California. Streams are small, exhibiting very low flows during the summer. Drainage in the western part of the area is toward the Russian River; Clear Lake and the eastern part of the area drain toward the Sacramento River.

Chapparal is the predominant native vegatative cover; the major species are California scrub oak, manzanita, western mountain mahogany and chamise. Woodlands include interior live oak, black oak, California buckey, Douglas fir, yellow pine, knobcone pine and Sargent cypress. The numerous springs, streams and varied vegetation provide good to excellent habitat for wildlife. Black-tailed deer is the most important game animal. Other mammals include the mountain lion, bobcat, gray fox, blacktailed jackrabbit, brush rabbit (cottontail), striped and spotted skunk, ringtailed cat, raccoon, and western grey squirrel. Game birds include the mourning dove, bandtailed pidgeon, and mountain and valley quail. Nongame wildlife species are also abundant, including 1 turtle, 13 snake, 17 amphibian, 6 lizard, 54 mammal and 200 bird species.

Clear Lake has an excellent warm-water fishery of largemouth bass, catfish, bluegill and crappie. Cold-water species in the streams include resident and migratory rainbow trout and resident brown trout. Big Sulphur Creek is the only drainage in the area supporting an anadromous steelhead fishery. Late fall stream flows, however, often become marginal for fish.

The area's economy is supported by agriculture, resorts, recreation services, land subdivision and geothermal power. The permanent population in the area is about 10,000, most of them living in a strip about Clear Lake and in the adjacent valleys. The actual population fluctuates widely due to tourism, primarily in the Clear Lake area in the summer. The largest community is Clear Lake Highlands with a 1970 population of 2,836. The largest business sector is services, much of it oriented toward tourists and retired people. Agriculture is second, including fruit and nut orchards, vineyards, dry pasture, and limited irrigated cropland. Forests are generally of poor commercial quality and only minor harvesting occurs. Mercury was mined until 1973, when the mines were shut down due to a depressed market.

Tourism has become one of the area's major industries, due to its scenic lakes and mountains, and its proximity to the populous San Francisco Bay and Sacramento Valley area. Resort development started more than a century ago with health spas at natural hot springs. The popularity of these resorts has declined, however, with mostly day use remaining. On the other hand, retirement communities and water sports oriented activities have increased. Most of the recreational use occurs during the summer. Clear Lake State Park was used by nearly 84,000 people in 1972.

It is a pleasing sight to view Clear Lake from a distance to observe its bluish-green waters and the brown and green-colored vegetation of the surrounding hills and mountains. The aesthetic values of Clear Lake are enhanced by the wildlife seen along its shores and on its waters. Piecemeal construction, however, of low-cost residences, motels, resorts, and trailer parks greatly detract from the natural setting of the lake and adjoining countryside. The use of septic tanks adjacent to Clear Lake has led to a sewage problem which has contributed to the eutrophication of the lake waters. Normally by July the lake's high nutrient content results in a large green algae bloom that persists for the rest of the summer and detracts from water contact sports.

In the summer the quiet and cool woods in the mountains are a welcome relief to travelers coming from the hotter, lower-elevation areas. The chapparal hills have their own aesthetic appeal through the variety of dark green and brown colors, although the contrast with light-colored soils in areas disturbed by surface mining and fire breaks distracts from the scenic quality.

Geothermal Fluid Characteristics

Both liquid- and vapor-dominated geothermal systems have been identified in the Clear Lake-The Geysers geothermal area. The present development for electric power production at The Geysers is from vapor-dominated systems. Thermal springs, however, are plentiful in the area and were the basis for numerous health resorts starting more than a century ago. Siegler Springs in the eastern part flows in excess of 15 gal/min at a maximum temperature of about 50°C (125°F). The Sulpher Bank area to the northeast contains springs delivering minor flows at temperatures near 80°C (180°F). Hot water was found in the deep wells drilled in the Sulpher Bank mine area east of Clear Lake, with maximum temperatures exceeding 175°C (350°F) and containing problem amounts of boron and CO_2.[C.2]

About 100 wells have been drilled at The Geysers for electric power generation, some of which have been converted to injection wells. All penetrate a vapor-dominated system which essentially contains freshwater steam at less than hydrostatic pressure with about one volume percent of gases and reservoir temperatures of about 250°C (480°F). Typical chemical analyses of steam condensate from three production wells are listed in Table C.1. The composition of gases associated with the geothermal steam produced at The Geysers is listed in Tables C.2 and C.3. The principal component of the steam condensate is ammonium bicarbonate (NH_3HCO_3). The principal chemical constituent in the steam is carbon dioxide (CO_2), but hydrogen sulfide (H_2S) is of highest environmental concern. The H_2S concentration is 16 times the human toxic level in the undiluted geothermal steam and ammonia (NH_3) is 5 times the human toxic level. A rotten egg odor is noticeable in and around the developed area.[C.1]

Average well production is about 100,000 lb of steam/hr with a maximum production of about 360,000 lb/hr. Waste water from the condensed steam was dumped into Big Sulphur Creek from the beginning of power generation in 1960 until 1971, when injection of waste water into the ground began.[C.3]

Environmental Effects of Liquid Waste Disposal

Principal environmental concerns at The Geysers geothermal development are related to gaseous emissions, principally H_2S. At The Geysers power plants, approximately 80 percent of the steam is used for condenser cooling and evaporated to the atmosphere. The remaining 20 percent, containing natural contaminants, principally NH_3HCO_3 and chemicals added to the cooling water, must be disposed of otherwise.

Starting with the first electric power development in 1960, liquid effluents were discharged into Big Sulphur Creek until 1971. Since 1969, however, waste water is being injected into the ground without significant technical or environmental problems.

Potentially harmful effects could result on fish and wildlife from improperly planned or executed handling of geothermal fluids. If uncontrolled releases, spills, seepage or well blowouts would occur, adverse impacts on soils and water quality could result from the addition of toxic substances. The potential failure of sump ponds containing drill muds and associated chemicals is of concern. Once these ponds have dried, they are covered with soil. Poorly built ponds could permit leaching of these chemicals into the

TABLE C.1. Composition of Steam Condensate from Typical Wells in The Geysers Field. Source: U.S. Department of the Interior[(C.1)] Analyst: I. Barnes, U.S. Geologic Survey

Constituent	Well, ppm by Weight Thermal #7	DX State 3395-1	Sulfur Bank 14
Silica (field)	0.50	0.20	0.50
Calcium	0.20	0.02	0.16
Magnesium	0.06	0.01	0.04
Strontium	0.10	0.05	0.10
Sodium	0.12	0.10	0.12
Potassium	0.10	0.10	0.10
Lithium	0.002	0.003	0.003
Ammonium	236.00	84.00	354.00
Bicarbonate	775.00	267.00	1153.00
Carbonate	0.06	--	1.05
Sulfate	7.10	24.00	11.00
Chloride	20 ±3	1.6 ±1	17 ±2
Fluoride	0.10	0.10	0.10
Boron	0.01	5.00	0.02
pH (field)	6.21	5.32	6.03
Specific conductance (micromhos at 25°C)	1430.00	546.00	2090.00
Date collected	10/28/70	10/29/70	10/28/70

TABLE C.2. Composition of Gases in the Geothermal Steam of The Geysers Field

Constituent	Symbol	Volume %
Water vapor	H_2O	98.045
Carbon dioxide	CO_2	1.242
Hydrogen	H_2	0.287
Methane	CH_4	0.299
Nitrogen	N_2	0.069
Hydrogen sulfide	H_2S	0.033
Ammonia	NH_3	0.025
Boric acid	H_3BO_3	0.0018

TABLE C.3. Constituents Carried in the Steam from Wells at The Geysers Field[a]
Source: Pacific Gas and Electric Company

Constituent	Symbol	Concentration, ppm by Weight		
		Low	Average	High
Carbon dioxide	CO_2	290	3260	30,600
Hydrogen sulfide	H_2S	5	222	1,600
Methane	CH_4	13	194	1,447
Ammonia	NH_3	9.4	194	1,060
Boric acid	H_3BO_3	12	91	223
Nitrogen	N_2	6	52	638
Hydrogen	H_2	11	56	218
Ethane	C_2H_6	3	8	19
Arsenic	As	0.002	0.019	0.05
Mercury	Hg	0.00031	0.005	0.018

(a) Measurements of 61 steam wells from 1972 through 1974.

surrounding ground and surface waters during the winter rain period. To date, no noticeable effect on the local groundwater resources has been noticed, although increased production in the future may affect the flow rate, temperature and chemical composition of thermal springs in the area.(C.1)

The construction of roads and waste handling facilities, including pipelines, would require vegetation clearing, diking and grading, resulting in loss of vegetation and wildlife habitat, and potentially causing soil erosion and surface water quality impairment. This is of particular concern due to the steep slopes in The Geysers area.

The fishery of the area would be the most severely affected by liquid effluents. The addition of hot water could increase stream temperatures deleterious to fish and stimulate undesirable aquatic weed growth. Adverse impacts on aquatic life in Big Sulphur Creek were observed during the routine release of geothermal effluents in the 1960's.(C.1)

Recreational activities, including fishing and hunting, could be affected by the disturbance of wildlife, damage to aquatic life, and impairment of scenic qualities, odor and noise. Scenic quality impairment would be noticeable mainly in areas with steep slopes and low vegetation. In flat areas, such as around Clear Lake, and in the forested regions, the developments would be less visible.

Only a small amount of land subsidence is expected in The Geysers area due to the local geology and the nature and use of the geothermal resource. Some seismic effects may occur as a result of the steam withdrawal and waste water injection, but no significant detrimental consequences are foreseen due to the low development of this area for other purposes. Damages may occur from future geothermal developments in other parts of the Clear Lake geothermal area having higher population densities and more diverse economic development.

The Geysers development has had a significant impact on the local and regional economy due to the electric power produced, tax revenues to local and state government, land royalty payments to the state government, and the increase of nearby land values. The method and success of the selected method for disposing of geothermal liquid wastes will have a direct influence on future expansion of The Geysers development and new developments in other parts of the Clear Lake geothermal area and, consequently, an indirect effect on the local and regional economy. The establishment of secondary by-product industries in conjunction with the dry-steam development is not anticipated because the steam is fairly pure.(C.1)

IMPERIAL VALLEY, CALIFORNIA

The Imperial Valley geothermal area, including the Salton Sea, Heber and East Mesa sites, is located in southwestern California in Imperial County, about 160 km east of San Diego. Imperial County borders Arizoña to the east and Mexico to the south.

Environmental Setting

The Imperial Valley occupies the lowest part of the Colorado Desert, with elevations ranging from 85 m (278 ft) below sea level in the Salton Sea to about 610 m (several thousand feet) in the surrounding mountains. The area has a characteristic desert climate, with hot, dry summers and mild winters. Temperatures over 38°C (100°F) typically occur more than 100 days each year, and the average annual precipitation is less than 7.6 cm (3 in.) There are about 12 days of frost each year. There is little fog and there are few thunderstorms. Stable atmosphereic conditions, westerly winds, and nighttime inversions are important meteorological features. Considerable smog is generated locally from burning stubble fields and smog drifts also in from the Los Angeles area. Suspended particulate concentrations generally exceed national air quality standards.(C.1,C.4)

The Imperial Valley is an interior basin with all surface drainage to the Salton Sea. The area is rather flat, but surrounded by ragged mountains. The Salton Sea is about 58 km (36 mi) long and 19 km (12 mi) wide. Its present water surface elevation is 71 m (232 ft) below sea level. The Sea is shallow, its greatest depth is 14 m (46 ft). The Salton Sea was formed by natural flooding from the Colorado River from 1905 to 1907. Since then the Sea has been maintained by natural runoff and irrigation return flows. Surface streams are very small and highly ephemeral. Nearly 3 million acre-feet of Colorado River water are diverted to the Valley each year to irrigate about 475,000 acreas. Extensive drainage systems exist to control soil salinity resulting from native occurrences and introduced by the irrigation water. Total dissolved solids concentrations range from 900 ppm in the irrigation water to almost 39,000 ppm in Salton Sea. An extensive groundwater system exists, which is primarily recharged from irrigation seepage. Total dissolved solids concentrations ranging from 500 ppm to 15,700 ppm have been measured in well water.[C.4]

The Imperial Valley includes an extensive irrigated agricultural region, a quasi-marine inland saltern ecosystem, state and federal game reserves, freshwater and riparian ecosystems, and extensive desert communities. Agricultural production, in order of importance, includes field crops, livestock and dairy products, and vegetable crops. The unique climate is such that most vegetable crops grow in the winter months and most field crops in the spring and summer months. The Salton Sea area has extensive shoebird (35 species) and waterfowl (47 species), including large migratory populations (Pacific Flyway) and five endangered species of birds. Wildlife composition varies widely as a function of local hydrologic and vegetative variations. Mammals include the coyote, desert fox, raccoon, bobcat, skunk, badger, muskrat, cottontail, jackrabbit, ground squirrel, valley pocket gopher, desert pocket mouse, and desert kangaroo rat. Typical desert plant communities include creosote brush, sage, mesquite, ironwood and desert willow. Extensive dunes exist in some areas with shifting, sandy soil and very sparse vegetation. There are 8 fish and 7 invertebrate species in the Salton Sea. The orangemouth corvina, sargo and gulf croacker provide the largest inland fishery in California. Striped bass, black crappie, channel catfish, bluegills, largemouth bass and various nongame fish exist in the main canal system. The lake is eutrophic with high water temperatures (to 36°C or 97°F during the summer), high concentrations of nutrients (nitrogen and phosphorus) and extensive algal blooms.

The Imperial County economy is dominated by agriculture, its associated support services and product processing. The county's economy is weak in manufacturing and construction activity compared to the state as a whole. There are no significant known mineral resources in the area besides rock, sand and gravel for construction purposes and the geothermal resource. The 1970 population of Imperial County was 74,492. Major urban centers and their 1970 populations are El Centro (19,272), Brawley (13,746) and Calexico (10,652).[C.4]

The Salton Sea and the dunes areas are a major recreational attraction in southern California, primarily for the Los Angeles-San Diego metropolitan population. The Sea is popular for fishing and hunting, boating, water skiing, swimming, etc. About 357,000 visitor days per year have been estimated for fishing alone.[C.1] The dunes and other desert areas are primarily popular for off-road vehicle use, and about 1.5 million visitor days per year have been estimated for the Imperial Sand Dunes. As many as 8,000 vehicles and 32,000 people have been estimated for a single weekend.

Aesthetically, the Salton Sea is a startling and pleasant contrast to the surrounding landscape, togther with the two rivers flowing into it and their abundant shore vegetation and bird populations. The water quality of the Sea, however, and frequent haze detract from these qualities. Some desert areas with flat mesas, deeply eroded stream channels, and sand dunes are attractive in their own way with their varying soil and rock colors and periodical wildflower and cactus blooms. The East Mesa area, however, is monotonous, characterized by flat topography, minimal color and texture variations, and sparse vegetation. The desert air is generally clear and dry.

Geothermal Resource and Development

As early as 1972, efforts were made to develop the geothermal resources in the Imperial Valley.[C.4] Mineral extraction, carbon dioxide recover, and power production have all been attempted, but with limited success. Some of the current geothermal activities are electric power production research, impact studies of proposed geothermal projects, baseline environmental studies, and exploratory drilling. Of the six known geothermal fields in the Valley, on the Salton Sea, Heber, East Mesa, and Brawley areas are expected to be developed. Estimates of their total electrical potential are under 5000 MW for 30 years. The Salton Sea area has the greatest energy potential because of its high down-hole temperatures (average of 286°C), yet it may be the hardest to develop since the geothermal fluids found there are high in total dissolved solids (TDS).

Geothermal Fluid Characteristics

All the geothermal systems in the Imperial Valley identified so far are liquid-dominated. The geothermal fluids are 10 to 30 percent water vapor by weight when produced, with the remained in the liquid state.[C.4]

Most of the information on the geothermal fluid characteristics in the Valley has been collected in the Salton Sea and East Mesa areas. Palmer[C.6] and Hoffman[C.7] each present the characteristics of about 20 geothermal wells located in the Salton Sea area. The characteristics of 6 geothermal wells in the East Mesa area are given in a U.S. Bureau of Reclamation status report.[C.5]

Representative temperatures for each of the geothermal areas in the Imperial Valley are listed in Table C.4; they range from 135 to 340°C.[C.6] Palmer[C.6] and Hoffman[C.7] give an average well bottom temperature of 286 ± 45°C for 16 Salton Sea wells, which is the hottest for the Valley. The average temperature of 6 East Mesa wells is given as 180 ± 13°C.

Flow rates for wells in the Salton Sea area are quite high, with an average flow rate of 435,000 lb/hr at an average pressure of 215 psi and average 19 percent steam by weight for 10 wells.[C.6]

The geothermal fluids in the Imperial Valley are generally quite saline. The salinity increases in a northwesterly direction, from the East Mesa area towards the Salton Sea. Total dissolved solids (TDS) concentrations average about 2,100 ppm in the East Mesa area, about 20,000 ppm in the Heber area, and about 210,000 ppm in the Salton Sea area. For comparison, the TDS content of seawater is about 33,000 ppm and of the Salton Sea about 39,000 ppm. Table C.5 summarizes the chemical composition data for geothermal fluids from wells in the East Mesa and Salton Sea areas.[C.4] For some constituents, the standard deviation is as large as or larger than the average concentration, indicating a large variance from well to well. In addition, the concentrations in a single well often varied by 25 to 50 percent when measured at different times. One East Mesa well with a TDS content 10 times higher than the others is not listed since it was not considered representative of the field.[C.4]

The fraction of noncondensable gases in the Imperial Valley geothermal fluids is estimated to be about 1 percent.[C.10] While the composition of this gas fraction is highly variable, CO_2 is always the major fraction with lesser amounts of H_2S, H_2, CH_4, NH_3 and N_2.[C.11]

Environmental Effects of Geothermal Liquids Wastes

Environmental effects of geothermal liquid wastes in the Imperial Valley will depend largely on the method selected for waste disposal. At present, injection into the ground is the method that is required by the county regulations. Regardless of the disposal method used, environmental effects will vary from site to site due to differences in geothermal fluid composition and local environments.

Extraction and disposal of geothermal fluids in the Imperial Valley, including brines with TDS contents up to five times of seawater, pose a threat of contamination to the soil, groundwater and Salton Sea. In 1962, for instance, a single geothermal well discharged brines containing about 250,000 T of salt to the Salton Sea during a 90-day period. This salt inflow represented 4.5 percent of the total salt inflow during 1962.[C.1]

The local groundwater system is complex, consisting of several layers, including artesian, and consisting of highly varying quality with respect to salinity and temperature. Injection of geothermal fluids could adversely

TABLE C.4. Average Geothermal Fluid Temperatures In Imperial Valley, °C. Sources: D. Layton and D. Ermak[C.4] M. Mathenson and L. P. J. Muffler[C.8]

Area	Temperature
Salton Sea	340
Heber	190
East Mesa	180
Brawley	200
Glamis/Dunes/E. Brawley	135

TABLE C.5. Average and Standard Deviation of Geothermal Brine Compositon of 4 Salton Sea and 9 East Mesa Wells, ppm. Sources: D. Layton and D. Ermak[C.4] T. D. Palmer[C.7] M. R. Hoffman[C.9] U.S. Bureau of Reclamation[C.5]

Constituent	East Mesa		Salton Sea	
TDS	2,120	336	214,000	98,000
Na	701	68	46,000	18,000
K	41	17	13,000	6,500
Ca	39	36	21,000	9,800
Mg	1.2	0.8	374	634
HCO_3	532	141	2,500	2,600
Cl	541	80	124,000	54,000
SO_4	172	45	180	230
B	2.8	0.6	317	199

affect the groundwater quality and restrict current and future uses, including use for cooling of geothermal power plants. Groundwater aquifers may also become contaminated from subsurface casing failures of both production and injection wells.

Injection may have a beneficial effect by limiting land subsidence which could result from the extraction of geothermal fluids. Land slope changes would affect the flow of water in irrigation and drainage canals, in subsurface drainage systems, and on surface irrigated farm land. Ruptures of the canals and drain tiles could interrupt the supply of irrigation water and the leaching of saline drainage water. This could have a severe impact on the productivity of the land and the region's economy.

All forms of surface disposal have been ruled out so far because of the large amounts of salts involved and the solid waste disposal problem if treatment or evaporation is used. Brines may be spilled accidentally to the land, however, from well blowouts, pipe and storage tank failures, and temporary holding pond failures. This would increase the salinity of the soils, thus affecting desert vegetation, wildlife, and agricultural productivity. Damage to the natural fauna and flora and to agricultrual crops may also result from the release of other substances such as boron, arsenic, fluoride and zinc to the land, water and air. Leaching of the added salts from desert soils, and consequently, vegetative recovery, could take many years due to the low natural precipitation. Spills to the land may also seep into the ground, affecting groundwater quality and use. Geothermal wells may be drilled in the Salton Sea itself, increasing the hazards from accidental spills. Subsidence of the lake bed, however, may be less serious than in onshore agricultural areas.

The Salton Sea ecosystem has been in a state of flux as a result of increasing irrigation return flows ever since the creation of the Sea in 1905 through 1907. These increased the size of the Sea and its salinity and nutrient levels. Many aquatic species were introduced by man, and some survived only for short periods. The salinity of the Salton Sea is only slightly higher than that of seawater, but its chemical composition is quite different. Consequently, it developed a very unique aquatic ecosystem characterized by a sparsity of species. This results in a rather unstable condition, where the disturbance of a single species in the food chain may have far-reaching effects on the entire system. Minor changes in the salinity or water temperature resulting from geothermal brine inflows could, therefore, cause significant aquatic ecological changes. Increased Salton Sea salinity would also affect the marsh vegetation and associated wildlife. Some of these changes will probably occur without geothermal development from salinity increases expected form normal irrigation drainage.

The concentrations of noncondensible gases in the Imperial Valley geothermal fluids are so low that CO_2 emissions from a geothermal power plant would be only 1/20th of the emissions from an equivalent fossil-fuel plant.[C.2] Sufficient measurements are not available to determine whether the emission of H_2S, and possibly also NH_3, may cause objectionable odor. Water vapor vented from cooling towers is not expected to be of much concern in the Valley's dry atmosphere.

Changes in the Salton Sea and desert ecosystem and land use would also influence the attractiveness of the area for recreational pursuits, primarily fishing and other water sports, hunting and off-road recreational vehicle use. Social-economic impacts may change significantly if injection of geothermal wastes, for instance, changes in the future to the recovery of by-products and freshwater. Human activity related to geothermal waste disposal may affect the desirability of some locations for wildlife, although the incremental effect of geothermal developments may be small in relation to disturbances by present recreational users.

The appearance of well rigs, pipelines, treatment plants, evaporation ponds and solid waste piles may be aesthetically unattractive in the natural desert and Salton Sea setting. Some people, however, may consider the geothermal development a unique attraction and an addition to the scenic and interest point qualities of the area, particularly in the more monotonous desert areas. The appearance of geothermal steam appears attractive to some, although objectionable odors may detract from the enjoyment of the development.

RAFT RIVER VALLEY, IDAHO

The Raft River Valley geothermal area is located in southcentral Idaho in Cassia County, about 97 km (60 mi) southeast of Twin Falls. The Valley borders Utah to the south, and the three-state intersection of the borders of Utah, Idaho and Nevada is about 48 km (30 mi) to the southwest.

Environmental Setting

Two environmental assessment reports are available for the Raft River Valley geothermal area,[C.13, C.4] but they were not received in time for consideration in this report. A summary of environmental conditions in the valley is contained in "Study of Geothermal Prospects in the Western United States."[C.2]

The Raft River is a southern tributary of the Snake River. The geothermal area lies in the southern part of the Valley a few miles north of the Utah border. The valley is generally flat with small gullies and ridges. There are many permanent and intermittent streams in the Valley. Shallow groundwater has been used for irrigation for many years, but drilling of shallow wells is not permitted anymore due to declining reservoir pressure.[C.2]

The air quality in the area is generally excellent although windblown dust occurs often. Ambient noise is very low.[C.2]

The vegetation in the Valley is of the sage subclimax type with sagebrush, greasewood and juniper being dominant. The Valley abounds in wildlife (rabbit, deer, coyote, squirrels, snakes and many birds). Trout, suckers and minnows are found in the streams. The region has four endangered species of birds, two of which nest in the area.[C.2]

Cassia County has a population of about 20,000. Burley, located about 64 km (40 mi) north of the geothermal area, is the largest town, with a population of about 8,300. Oakley, the nearest population center, has a population of about 650. The population density in the geothermal area is less than one person per square mile.(C.2)

The area is rural with some light industry focusing on potato processing. The general economy is based upon both irrigated and dryland agriculture. The natural environment has been altered extensively by farm activities. There are two historical sites in the Valley, the City of Rocks Indian burial ground and a stagecoach station on the Kelton Road trail. The area is not considered aesthetically extraordinary.(C.2)

Geothermal Fluid Characteristics

The geothermal system identified in the Raft River Valley is liquid-dominated. Maximum water temperatures of 140 to 150°C (284 to 302°F) are expected.(C.15) Table C.6 lists the water temperature and quality of three wells drilled as part of the geothermal research program conducted by the Idaho National Engineering Laboratory, and compares them with irrigation wells in the area and the Raft River.

The three geothermal wells have water ranging from 148 to 149°C (295 to 298°F) and flowed at 38 ℓ/sec (600 gal/min) and higher under artesian pressure.(C.15)

The quality of the geothermal water is quite good in two of the wells, with total dissolved solids concentrations about 2000 ppm. In the third well, the TDS content is about 4600 ppm.(C.16) For comparison, local irrigation wells have TDS contents ranging from 550 to 2120 ppm. Research in progress indicates that the geothermal water is suitable for irrigating agricultural crops and for aquaculture (raising warmwater fish).

Previous analyses of wells #1 and #2 also listed 350 to 389 ppm sodium (Na) and 5.4 to 7.6 ppm fluoride (F). Noncondensible gases, in order of volume percentage, included N_2, CO_2, H_2, Ar, O_2 and He.(C.17)

Environmental Effects of Geothermal Liquid Wastes

Environmental effects of geothermal wastes in the Raft River Valley will depend largely on the method selected for waste disposal. At present, injection into the ground is being mentioned as the most feasible

TABLE C.6. Average of Water Analysis in Raft River Area
Source: Idaho National Engineering Laboratory[C.16]

	Geothermal Production Wells 1 & 2	Geothermal Production Wells 3	Intermediate Hot Wells	Irrigation Wells	Raft River
Temperature, °C (°F)	146 (295)	148 (298)	93 (200)	21 (70+)	Seasonal Variance
TDS, ppm	2000	4592	2600	550 - 2120	507
Conductivity	2700	9870	4555	1720 - 3600	
Cl	816	1626	1435	738 210 - 1267[a]	117
Si	52	69	94	35	19
Fe	m	--	<0.02	m	m
Mg	0.23	0.6	0.25	48	59
K	39	95	26	13	7.5
Ca	29	200	88	191 53 - 320[a]	76
SO_4	54	34	64	35	46
HCO_3	30 to m	51	41	174	159 - m
SiO_2	--	--	87	--	--
Organic	0	0	0	<10/100 ml	318/100 ml

(a) Stewart's well is high TDS value.

alternative. Feasibility of nonelectric uses of the geothermal resource is being investigated due to the low-temperature, low-salinity characteristics of the geothermal water. Consequently, environmental effects of the liquid waste disposal will also depend on the utilization of the fluids.

An environmental assessment prepared by the Idaho National Engineering Laboratory[C.17] covering electrical developments was not available for this report.

ROOSEVELT HOT SPRINGS, UTAH

The Roosevelt Hot Springs geothermal area is located in southwestern Utah in Beaver County about 274 km (170 mi) southwest of Salt Lake City, 332 km (20 mi) northwest of Beaver and 19 km (12 mi) northwest of Milford. Beaver County borders Nevada to the west.

Environmental Setting

An environmental assessment report is available for the Roosevelt geothermal area (U.S. Bureau of Land Management, 1975), but it was not received in time for consideration in this report. A summary of environmental conditions in the area is contained in "A Study of Geothermal Prospects in the Western United States."[C.2]

The geothermal area lies in the Basin-and-Range province on the western flank of the Mineral Mountains.

No air quality measurements have been reported, but the air is relatively clean with the exception of windblown dust. Ambient noise levels are low.[C.2]

Only one permanent stream flows through the area, the other streams are intermittent. Shallow groundwater exists but irrigation pumping in the Milford area has led to up to 1.8 m (6 ft) of surface subsidence, the only instance of subsidence caused by groundwater withdrawal in the State of Utah.[C.2]

Four vegetation associations are found in the vicinity of the thermal area: desert scrub (shadscale, greasewood), sagebrush (Great Basin sage, cheat grass, halogeton), pinon-juniper (rabbit brush, bluebench wheat grass) and pinon-juniper pine (ponderosa pine, mountain mahogony). Many animals roam the area, the dominant being mule deer, bobcat, coyote, golden and bald eagle, and the Great Basin rattlesnake. Two rare or endangered species of birds may be in the area, but no nesting sites are known. There are no aquatic plants and the only known aquatic animal is the Great Basin spadefoot toad.[C.2]

The area is sparsely populated. The present population of Beaver Center is about 4000. The two nearest population centers are Milford and Beaver, with populations of 1300 and 1500, respectively.[C.2]

The thermal area is not inhabited but is visible from State Highway 257 which does not carry much traffic. Interstate Highway 15 connecting Las Vegas and Salt Lake City runs through Beaver.

Government and trade employ the largest number of workers. Transportation, mining, agriculture and tourism are also important to the local economy. Some mining-related industry exists at Milford. Private land (12.6 percent of County area) in Beaver County are used primarily for agriculture. The Roosevelt area is being used for grazing and mining.[C.2]

Twelve historic and pre-historic inhabited sites are known in the area. One of them is a chipping area with an associated Clovis fluted projectile point that is regarded as one of the most significant archelogical finds in the State of Utah.[C.2]

The general landscape is desert. The mountainous, southeastern part of the area affords moderate to highly scenic areas. The natural environment has been altered by grazing and cultural features such as mines, roads, and fences.[C.2]

Geothermal Fluid Characteristics

Present indications are that the geothermal system of the Roosevelt Hot Springs area is probably liquid-dominated. The original main hot spring was discharging 10 gal/min at 88°C (190°F), but the discharge decreased until the spring went dry in 1966. In 1957, analysis of the spring water showed a total dissolved solids concentration of 7800 ppm and a silica concentration of 313 ppm. The spring once served a resort.[C.2]

Information was available on two wells. A shallow well drilled in 1968 blew out at 84 m (275 ft) and had water temperatures in excess of 132°C (270°F). During drilling of a deep well (800 to 850 m) in 1975, 200,000 lb/hr of steam at 204°C (400°F) was recovered; this changed to a sustained hot water flow after a control valve was installed.[C.2] No other information on the characteristics of the geothermal fluids of this area was available.

Environmental Effects of Geothermal Liquid Wastes

Environmental effects of geothermal liquid wastes in the Roosevelt Hot Springs geothermal area cannot be assessed for this report since sufficient information on the magnitude of the geothermal resource, the physical and chemical characteristics of the geothermal fluids, the potential geothermal resource, and the environmental setting of this area was not available. An environmental assessment prepared by the U.S. Bureau of Land Management[C.18] covering the exploration and development of the geothermal resources on Federal lands in the vicinity of the Roosevelt Hot Springs in Beaver and Millard Counties was not available for consideration in this report.

VALLES CALDERA, NEW MEXICO

The Valles Caldera geothermal area is located in northcentral New Mexico in Sandoval County, about 97 km (60 mi) north of Albuquerque, 64 km (40 mi) northeast of Santa Fe, and 16 km (10 mi) west of Los Alamos.

Environmental Setting

An environmental report was not available to summarize the environmental setting of the Valles Caldera geothermal area without a comprehensive literature survey.

Geothermal Fluid Characteristics

Hot springs near the western edge of the Valles Caldera indicate the existence of a liquid-dominated system. Relatively high heat-flow values obtained just outside the caldera indicate the potential of extracting energy from dry hot rock.[C.19] Information was not available on the characteristics of the geothermal fluids in the liquid-dominated system and on the characteristics of effluents resulting from potential dry hot rock developments.

Environmental Effects of Geothermal Liquid Wastes

Environmental effects of geothermal liquid wastes in the Valles Caldera geothermal area cannot be assessed for this report since sufficient information on the magnitude of the geothermal resource, the physical and chemical characteristics of geothermal effluents, the potential geothermal resource use, and the enviornmental setting of this area was not available. There are no liquid geothermal fluids in a dry hot rock system. Environmental effects may arise, however, from the disposal of effluents arising from the injection and withdrawal of water for extracting the heat from dry rock. The nature of the disposal problem will depend on the magnitude of the development; the original quality of the injected water; the chemical composition, solubility and permeability of the hot rock (consequently, the quality of the water returned from the hot rock); the utilization of the heated water and the environmental setting of the site.

Some preliminary observations of Valles Caldera area are given by Smith.[C.20] Waste heat would be discharged to the environment from electric energy developments. Subsidence and seismic activity is not expected from the competent, granite rock of this area, but it may occur if hot rock systems with more permeable or fractured formations are developed in other areas.

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16. Abstract This report reviews the state of the art of geothermal liquid waste disposal and evaluates surface and subsurface disposal methods with respect to technical, economic, legal, and environmental factors.

The disposal of geothermal liquid effluents could affect the environment in an adverse manner. Disposal is not only complicated by the wide variability of waste fluid properties (e.g., temperature, pH, and chemical constituency), but also by the large volumetric flows involved. The task of waste disposal is also affected by such site-specific variables as geology and environmental setting and by legal requirements and unknown economic factors.

Three disposal techniques are currently in use at numerous geothermal sites around the world: direct discharge into surface waters; deep-well injection; and ponding for evaporation.

This report also reviews disposal techniques used in related industries. The oil industry's efforts at disposal of large quantities of liquid effluents have been quite successful as long as the effluents have been treated prior to injection.

This study has determined that seven liquid disposal methods--four surface and three subsurface--are viable options for use in the geothermal energy industry. However, additional research and development is needed to reduce the uncertainties and to minimize the adverse environmental impacts of disposal. These recommendations include areas of detailed cost analysis, trace impurity cleanup, monitoring of pond leakage, identification of disposal areas, discharge into the ocean, compatibility of wastewater and reservoirs, monitoring flow patterns, integrity of well cement, and reservoir modeling.

17. Key Words Liquid waste, geothermal brine, environment, water quality

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