COST ANALYSIS OF ENVIRONMENTAL
CONTROL SYSTEMS APPLICABLE TO
GEOTHERMAL ENERGY DEVELOPMENT

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SUMMARY

This document compares and evaluates the cost of various environmental control systems applicable for the control of air emissions, wastewater discharge, and solid wastes generated from geothermal power plant operations. Only near-term technologies are considered because cost estimates for state-of-the-art technologies are more accurate, permitting meaningful cost comparison.

Since many variables and different assumptions are used in the development of cost estimates and cost functions, a hypothetical 50 MWe power plant is used throughout this document as a base case for cost comparisons. After the baseline conditions have been established, sensitivity analyses are performed to identify which variables and plant operational parameters are most likely to affect the overall cost of the environmental control systems. All costs in this report are annualized and presented in cents per kilowatt hour.

Four H₂S abatement systems were selected for detailed cost comparison.

- Iron catalyst process
- Stretford process
- EIC process
- Dow oxygenation process.

Other systems were not included because they are still in relatively preliminary development stages and associated cost figures lack reliable data derived from field experience. The results of our analyses show that the iron catalyst and Stretford processes are the least costly options for H₂S abatement. The total cost of H₂S abatement systems are directly dependent upon H₂S concentration and

indirectly dependent upon resource temperature for the same unit of power output.

Four wastewater treatment and disposal systems were included for detailed analysis:

- Chemical precipitation
- Evaporation ponds
- Injection without pretreatment
- Injection with pretreatment.

Other advanced treatment processes, particularly desalination, were not considered because most of them are applicable only to brackish waters and not to the high-salinity fluids commonly found in geothermal systems. The results of our analyses indicate that injection is the least costly option. Further, the cost of wastewater treatment is very much dependent upon resource temperature, which indirectly determines the flow rate required to produce a specified amount of power. For chemical precipitation systems, the cost of wastewater treatment is also sensitive to the amount of suspended and dissolved solids in the fluid.

The major sources of geothermal solid wastes are H_2S abatement and wastewater treatment sludges. The cost of sludge treatment, handling, transport, and disposal were evaluated for each of the H_2S abatement and wastewater treatment systems. Cost estimates were based upon disposal of sludge to a landfill site approximately 50 miles away from the power plant. The result of our cost analysis revealed that sludge disposal for both chemical precipitation and injection-with-pretreatment systems is the most costly item in the wastewater treatment process.

Because of the variability of geothermal resource characteristics and power plant configurations, the following three power plant scenarios were established for the purposes of environmental control cost comparisons:

- "Best Case" 50 MWe plant, characterized by
 - high resource temperature ($\geq 270^{\circ}\text{C}$)
 - low total dissolved solids ($\leq 5,000$ ppm)
 - extremely low H_2S concentration (≈ 0 ppm)
- "Most Probable Case" 50 MWe plant, characterized by
 - medium resource temperature ($\approx 200^{\circ}\text{C}$)
 - medium total dissolved solids ($\approx 10,000$ ppm)
 - low H_2S concentration (≈ 40 ppm)
- "Worst Case" 50 MWe plant, characterized by
 - low resource temperature ($\leq 170^{\circ}\text{C}$)
 - high total dissolved solids ($\geq 100,000$ ppm)
 - medium to high H_2S concentration (≈ 200 ppm).

The cost of environmental control for these three power plant scenario is presented in Exhibit 5.5 and repeated here as Exhibit S.1. Costs associated with sludge disposal are included in the air abatement and wastewater treatment systems costs. This cost information reveals that, for these three power plant scenarios:

- The iron catalyst and Stretford processes are the least costly H_2S abatement systems.
- Injection and injection-with-pretreatment are the least costly wastewater treatment systems.
- Sludge disposal for chemical precipitation is a very costly item.
- The cost of H_2S abatement is generally much less than that of wastewater treatment.

EXHIBIT S.1*

COST SUMMARY FOR THE H₂S ABATEMENT AND WASTEWATER
TREATMENT SYSTEMS FOR THE THREE DIFFERENT
HYPOTHETIC 50 MWe PLANT (CENTS/KILOWATT-HOUR)

*Same as Exhibit 5.5.

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1.0 INTRODUCTION

1.1 Background

Attempts by industry to commercialize geothermal energy and efforts by the Federal government to promote this alternative energy source over the last few years have encountered a number of environmental-related problems. The expanded use of geothermal energy, especially for power production, has been constrained by these problems. Major environmental concerns include:

- Air pollution (primarily H₂S)
- Disposal of large volumes of used geothermal brine
- Disposal of sludges and other solid wastes associated with geothermal operations.

Environmental controls for these and other problems are required by law. Although the government has been responding to the need to develop geothermal environmental controls, significant technical progress is still needed.

Since many of the technical requirements for these controls are not known in detail and many of the controls are still at laboratory- or pilot-scale development stages, the costs associated with these systems are also uncertain. For example, the development and field-testing of the EIC Process for H₂S control at The Geysers has demonstrated that early estimates of the economics of the abatement system were unrealistically low. The economics of other types of environmental controls also currently involve high levels of uncertainty. Cost estimates have been made for a number of controls, but these are usually based on very preliminary technical data. More importantly, there is a lack of systematic comparison among different environment-

al control systems, taking costs and system efficiencies into consideration.

1.2 Purpose

The purpose of this document is to perform cost analysis and cost comparison of different environmental control systems applicable to geothermal energy development. Specifically, the following major types of emission control processes and waste treatment systems are examined in detail:

- Air pollution control systems, including the Stretford process, iron catalyst process, EIC process, Dow oxygenation process, and other potential H₂S removal processes.
- Water pollution control systems that include appropriate wastewater treatment and disposal technology.
- Sludge and solid waste treatment and disposal systems.

The results of this analysis will reveal which environmental control systems are the most cost-effective in controlling emissions or discharges from geothermal operations.

1.3 Scope

This study investigates the cost associated with environmental controls using DOE-funded studies as a base for cost comparison. In areas where there are not sufficient data or where baseline data are judged to be misleading or erroneous, other studies (particularly studies funded by the U.S. Environmental Protection Agency) are used to supplement the cost analysis.

To facilitate cost comparison, a hypothetical 50 MWe hydrothermal power plant, using a flashed-steam cycle, is used throughout the document. Sensitivity analyses are performed so as to identify the

sensitivity of each system to various operational parameters. All cost information presented is in 1977 - 1978 dollars. It would not be difficult to update these cost figures. However, most cost estimates published to date have a rather large margin of error. Updating them without verification against plant performance data would only increase this cost uncertainty. The 1977 cost data, however, are extremely useful as a basis for cost comparison.

2.0 AIR ABATEMENT SYSTEMS

2.1 Emission Characteristics

Non-condensable gases and particulate matter may be released to the atmosphere, together with geothermal steam, during different phases of the power plant operation. At sufficiently high concentrations, several of these substances can be the source of concern due to potential health and environmental effects. Hydrogen sulfide (H_2S) is a pollutant of special interest because of its toxicity at high levels and its pungent, "rotten egg", odor at extremely low concentrations.

Exhibit 2.1 compares air emission characteristics of several electric generating processes. Although H_2S emission is a problem mostly for certain geothermal power operations, it is not a criteria pollutant under the National Ambient Air Quality Standards. Nevertheless, a few states, including states in which hydrothermal development is occurring or is likely to occur, have promulgated regulations to control H_2S emission.

The following subsection describes several processes that have been demonstrated, or appear to be promising, for controlling H_2S emission for geothermal power plants. These processes include ones adapted from other industries and specially-modified or specially-designed technologies for geothermal applications.

2.2 Process Selection

There are two basic approaches to H_2S control:

- Upstream treatment, which removes H_2S and other associated pollutants before they reach the turbine in the power plant.

PROCESSES	PARTICULATES	SULFUR DIOXIDE	NITROGEN OXIDES	HYDROCARBONS	CARBON MONOXIDE	AMMONIA	HYDROGEN SULFIDE
Coal-Fired Conventional	10,900	2,000	1,575	26	87		
Coal-Fired MHD	36	600	360				
Oil-Fired Steam Electric	490	3,900	515	12	59		
Gas-Fired Steam Electric	26	1	1,200	2	27		
Synthetic Fuel Lurgi Process	N/A	31	32	N/A	N/A		
Geothermal Flashed Steam				690		120	23
Geothermal Vapor Dominated				15-1,800		19-2,150	6-1,800

EXHIBIT 2.1

COMPARISON OF AIR EMISSION OF 50 MWe EQUIVALENT ELECTRIC
POWER GENERATING FACILITIES (TONS PER YEAR)

- Downstream treatment, which removes H₂S after it leaves the turbine.

Exhibit 2.2 shows the location of several treatment processes for a flashed-steam plant. Based on the traditional "end-of-pipe" emission control concept, most of the control systems developed to date focus on downstream treatment. An obvious advantage of this system is that it provides minimal interference to the plant operation. On the other hand, upstream treatment offers two major advantages, including:

- Reduction of turbine blade stress corrosion cracking and sulfide scaling, caused by the presence of H₂S.
- H₂S emissions during stream stacking (when the plant is shut-down) can be controlled.

The status of development of H₂S abatement systems is summarized in Appendix A. Four major H₂S emission control processes have been selected for cost analysis in this report.

- EIC process
- Dow oxygenation process
- Stretford process
- Iron catalyst process.

These processes were selected because:

- The Stretford and iron-catalyst processes are being used at The Geysers power facility and, thus, cost figures will tend to be more valid than for other control systems.
- The EIC process is at a near-commercialization stage and its development was partially funded by DOE.
- Cost information is readily available for these four processes, allowing a more meaningful cost comparison to be made.

EXHIBIT 2.2

LOCATIONS OF H₂S ABATEMENT PROCESSES IN A
GEOTHERMAL FLASHED-STEAM POWER SYSTEM

2.3 Cost Estimate

Cost information for the H₂S abatement systems has been presented in several DOE-sponsored documents and has been summarized in a previous submission under this task. Comparison in this report of different H₂S abatement processes has been based on a hypothetical 50 MWe steam power plant with the following characteristics:

- Resource temperature --340°F or 170°C
- H₂S concentration in fluid -- 220ppm
- Flow rate -- 11,500,000 lbs per hour*
- Plant capacity factor --0.8

Exhibit 2.3 provides a cost comparison of the four systems based on the above mentioned assumptions. It appears that the Stretford process and the iron catalyst process are the least costly. However, other factors may influence the cost of H₂S abatement must be considered in order to establish more meaningful total-cost estimates. These factors are discussed in more detail in the next subsection.

2.4 Sensitivity Analysis

In order to arrive at a range of costs for each H₂S abatement system, a sensitivity analysis is performed on the basic costs. The variables chosen for this analysis are:

- H₂S concentration
- Resource temperature

* This amount will flash into 1,350,000 pounds of steam at a temperature of 230°F (110°C) and a pressure of 21 psi.

EXHIBIT 2.3. COST COMPARISON OF FOUR CANDIDATE
TECHNOLOGIES (1977 DOLLARS)

Processes	Annual Capital	O&M	Total	Cost Per Kilowatt-Hour
Iron Catalyst	\$156,000	\$137,000	\$293,000	0.084¢
Stretford	\$231,000	\$170,000	\$401,000	0.115¢
EIC	\$328,000	\$184,000	\$512,000	0.146¢
Dow Oxygenation (in-line)	\$1,150,000	\$2,630,000	\$3,780,000	0.180¢
Dow Oxygenation (packed column)	\$410,000	\$2,540,000	\$2,950,000	0.843¢

- Type of energy conversion system
- Size of power plant.

2.4.1 H₂S Concentration

The hypothetical 50 MWe plant is based on a H₂S concentration of 220 ppm, which is typical of the conditions at The Geysers a steam-dominated resource. For other sites, the H₂S concentrations are substantially less, ranging from 1 ppm to 61 ppm in the liquid phase (see Exhibit 2.4). For H₂S abatement systems, the capital cost items generally include the various types of holding tanks, scrubbing equipment, etc. They are one-time costs, but annualized to facilitate cost comparison. Operations and maintenance (O&M) costs include maintenance materials, maintenance labor, electric power, chemicals, oxygen and water as required. Exhibit 2.5 summarizes, qualitatively, the anticipated types of changes in capital and O&M costs due to changes in H₂S concentration (other parameters holding constant).

2.4.1.1 Iron Catalyst. This system involves adding ferric sulfate in solution to the cooling water, thus oxidizing the H₂S contained in the aqueous phase (see Appendix A). The capital cost includes the use of filterbed thickeners for sludge treatment and is more dependent upon flow rate than upon H₂S concentration. Capital cost for this system is found to be independent of H₂S concentration. In this system, the major O&M cost item that varies with H₂S concentration is the cost of treatment chemicals, which increases with increasing H₂S level in the steam phase. The total annual cost of the iron catalyst system as a function of H₂S concentration is illustrated as follows:

EXHIBIT 2.4

RANGES AND AVERAGE VALUES OF H₂S
 FOUND IN GEOTHERMAL FLUIDS FROM WELLS
 IN VARIOUS KGRA'S (ppm)

<u>KGRA</u>	<u>Range</u>	<u>Average</u>
The Geysers*	5-1600	222.
Salton Sea	1.6-6.0	3.2
East Mesa	0.12-1.6	0.54
Brawley	-	55.1
Heber	-	0.18
Baca	-	60.17

*Steam - dominated resources

EXHIBIT 2.5

TYPES OF VARIATIONS OF CAPITAL AND O&M COSTS
AS A FUNCTION OF H₂S CONCENTRATION

COST	IRON CATALYST	STRETFORD	EIC	DOW OXYGENATION
Capital Cost	Constant	Exponential	Exponential	Constant
O&M Cost Items				
Materials	Constant	Exponential	Exponential	Constant
Labor	Constant	Constant	Constant	Constant
Electric Power	Constant	Linear	Linear	Linear
Chemicals*	Linear	Linear	Linear	Not Required
Oxygen*	Not Required	Not Required	Not Required	Linear
Water*	Not Required	Not Required	Linear	Not Required

* Some quantity discounts may be available making it slightly deviated from linear.

<u>H₂S Concentration</u>	<u>Total Annual Cost</u>
40 ppm	\$242,600
220 ppm	\$293,000
830 ppm	\$464,000
1600 ppm	\$680,000

2.4.1.2 Stretford Process. This process scrubs non-condensable gas from the condenser ejector with an aqueous solution of sodium carbonate, sodium metavanadate, and ADA. A surface-contact condenser must be used with this process so as to eliminate direct contact of the cooling water with the steam condensate, thus avoiding carry-over of H₂S into the cooling water. Capital cost includes the differential investment required for a surface-contact condenser in lieu of a direct-contact condenser. Other factors, such as materials, electric power, and chemical requirements also vary with H₂S concentration. Total annual costs as related to H₂S concentration are shown as follows:

<u>H₂S Concentration</u>	<u>Total Annual Cost</u>
40 ppm	Insufficient data to extrapolate
220 ppm	\$420,000
830 ppm	\$590,000
1600 ppm	\$780,000

2.4.1.3 EIC Process. This is an upstream process that removes H₂S from geothermal steam by scrubbing it with a aqueous solution of copper sulfate. Capital cost items are scrubbers, reactors, tanks, vessels, heat exchangers, filter, pumps, and other associated process equipment. Other cost items vary linearly with H₂S concentration. The effect of H₂S concentration on total cost is shown below.

<u>H₂S Concentration</u>	<u>Total Annual Cost</u>
40 ppm	Insignificant data to extrapolate
220 ppm	\$ 512,000
830 ppm	\$1,051,000
1600 ppm	\$1,575,000

2.4.1.4 Dow Oxygenation. This system involves the introduction of oxygen to the geothermal fluid, causing the oxidation of H₂S to elemental sulfur or sulfate ion. Capital costs are more dependent upon flow rate than upon H₂S concentration. The major O&M cost items that vary with H₂S concentration are the cost of cryogenic oxygen and electric power required to inject oxygen into the system. The variation of total system cost with H₂S concentration is shown below.

<u>H₂S Concentration</u>	<u>Total Annual Cost</u>
40 ppm	\$ 982,000
220 ppm	\$2,950,000
800 ppm	\$9,810,000

Exhibit 2.6 is a summary of annualized cost estimates of the four abatement technologies at different H₂S concentrations.

2.4.2 Resource Temperature

The resource temperature chosen for the hypothetical 50 MWe flash-steam power plant is 340°F (170°C). However, for most resources in the U.S. that have a large electric generating potential, the resource temperature is generally greater than this. Exhibit 2.7 shows the geothermal areas that have a reservoir temperature greater than 150°C and an estimated electrical generating potential greater than 200 MWe for 30 years. It is apparent that most geothermal re-

EXHIBIT 2.6

SUMMARY OF ANNUALIZED COST ESTIMATES OF THE
 FOUR CANDIDATE TECHNOLOGIES AT DIFFERENT
 H₂S CONCENTRATIONS (1977 DOLLARS) FOR A 50 MWe
 FLASHED STEAM PLANT
 COST PER KILOWATT-HOUR IN PARENTHESIS

PROCESS	H ₂ S CONCENTRATIONS			
	40 ppm	220 ppm	800 ppm	1600 ppm
Iron Catalyst	\$242,600 (0.069¢)	\$293,000 (0.084¢)	\$464,000 (0.133¢)	\$680,000 (0.194¢)
Stretford	-	\$401,000 (0.115¢)	\$590,000 (0.169¢)	\$780,000 (0.223¢)
EIC	-	\$512,000 (0.146¢)	\$1,051,000 (0.300¢)	\$1,575,000 (0.450¢)
Dow Oxygenation* (packed column)	\$982,000 (0.281¢)	\$2,950,000 (0.843¢)	\$9,810,000 (2.803¢)	-

*Based on H₂S concentrations in the liquid phase.

EXHIBIT 2.7

HYDROTHERMAL RESOURCE AREAS WITH A SOURCE
TEMPERATURE HIGHER THAN 150°C AND ELECTRIC
GENERATING POTENTIAL GREATER THAN 200 MWe

sources suitable for power development have a temperature range of 150°C to 250°C.

For the same unit power output, the lower the temperature, the greater the volume of fluid required for power generation. Exhibit 2.8 summarizes the effects of temperature and flow rate on electric power production. For a 50 MWe plant with resource temperatures of 150°C, 200°C, 250°C and 300°C, the mass flow rates required would be about 130,000, 60,000, 35,000 and 22,000 lbs per hour, respectively.

Three temperatures (170°C, 210°C, and 270°C) have been selected in order to illustrate the dependence of total H₂S abatement cost on resource temperature. For three out of the four control technologies, H₂S removal occurs in the steam phase. Consequently, steam flow rate is a more important parameter than fluid flow rate. Exhibit 2.9 summarizes the brine and steam flow rates for these three different temperatures. For the higher temperature resources, a two-stage flash system is assumed. Exhibit 2.10 summarizes the types of changes in capital and O&M costs anticipated due to changes in resource temperature. More detailed discussions of these changes are presented below.

2.4.2.1 Iron Catalyst. This system treats the noncondensable gases in the cooling tower after they come out of the gas ejection system. Thus capital cost is very much dependent upon steam flow rate, as larger-capacity filter beds and sludge thickeners will be required, due to the increased amount of sludge generated. O&M costs, particularly for the chemical feed system, is dependent upon flow rate. The total annual cost of the iron catalyst system as a

EXHIBIT 2.8

ELECTRIC POWER AS A FUNCTION OF MASS FLOW
FOR VARIOUS TEMPERATURES OF HOT-WATER AND
VAPOR-DOMINATED SYSTEMS

EXHIBIT 2.9

BRINE AND STEAM FLOW RATES USED IN ESTIMATING CHANGES
IN CONTROL COSTS AT DIFFERENT TEMPERATURE RESOURCES

Resource Temperature (°C)	Brine Flow Rate (Pounds Per Hour)	Steam Flow Rate (After Flash Tanks) (Pounds Per Hour)		
		First Stage	Second Stage	Total
170	11,400,000	1,350,000	-	1,350,000
210	6,050,000	750,000	450,000	1,200,000
270	3,100,000	620,000	330,000	950,000

EXHIBIT 2.10

TYPES OF VARIATIONS OF CAPITAL AND O&M COSTS
AS A FUNCTION OF RESOURCE TEMPERATURE

	IRON CATALYST	STRETFORD	EIC	DOW OXYGENATION
Capital Cost	Exponential	Exponential	Exponential	Linear/Exponential**
O&M Cost Items				
Materials	Exponential	Exponential	Exponential	Linear/Exponential**
Labor	Constant	Constant	Constant	Constant
Electric Power	Linear	Linear	Linear	Linear
Chemicals*	Linear	Linear	Linear	Not Required
Oxygen*	Not Required	Not Required	Not Required	Linear
Water*	Not Required	Not Required	Linear	Not Required

* Some quantity discounts may be available making it slightly deviated from linear.

** Linear for in-line systems
Exponential for packed columns

function of resource temperature is illustrated as follows:

<u>Resource Temperature</u>	<u>Total Annual Cost</u>
170°C	\$293,000
210°C	\$279,000
270°C	\$247,000

2.4.2.2 Stretford Process. The major capital cost item for the Stretford process is the surface-contact condenser in lieu of the direct-contact condenser for eliminating the direct contact of the cooling water with the steam condensate. O&M cost items, such as chemicals and electric power, vary according to the steam flow rate. The total annual cost as related to the resource temperature is presented below.

<u>Resource Temperature</u>	<u>Total Annual Cost</u>
170°C	\$401,000
210°C	\$382,000
270°C	\$266,000

2.4.2.3 EIC Process. Cost information for EIC process does not allow meaningful extrapolation to different steam flow rate conditions.

2.4.2.4 Dow Oxygenation. This process involves the oxidation of H_2S in the fluid phase. For a packed-column system, capital costs increase incrementally with fluid flow rate because additional columns will be required when the capacity of the previous column is met. Most O&M cost items vary directly with fluid flow rate. The dependence of total annual cost and resource temperature are summarized as follows:

<u>Resource Temperature</u>	<u>Total Annual Cost</u>
170°C	\$2,950,000
210°C	\$2,000,000
270°C	\$1,290,000

Exhibit 2.11 summarizes the cost estimates of the four systems at three different resource temperatures. For the iron catalyst and Stretford processes, total annual costs are more sensitive to changes in H₂S concentration than to changes in resource temperature. The main reason of this situation is that, for higher-temperature resources, more steam can be flashed from the same volume of fluid. Thus, the decrease in steam flow rate for higher temperature resources is partially compensated for by the increase in steam produced.

2.4.3 Energy Conversion Systems

The amount of H₂S emitted from a flashed-steam plant and a binary-cycle plant would be significantly different. For a flashed-steam system, the major emission sources occur at the condenser ejector and the cooling tower. For a binary system, after the fluid has passed through the heat exchanger, it is sent to injection wells for disposal. This fluid still contains the noncondensable gas, including H₂S. Hence, in theory, it is possible to design a binary plant without any H₂S emissions from the energy conversion cycle.

If, on the other hand, steam condensate from the fluid is used as a source of cooling water for the turbine exhaust, a cooling tower will be needed. In this system, the H₂S emission will be at the cooling tower and the ejector, similar to the case of a flashed-steam system.

EXHIBIT 2.11

SUMMARY OF ANNUALIZED COST ESTIMATES OF THE
FOUR CANDIDATE TECHNOLOGIES AT DIFFERENT RESOURCE
TEMPERATURES FOR A 50 MWe FLASHED STEAM PLANT
COST PER KILOWATT-HOUR IN PARENTHESIS

Process	Resource Temperature °C		
	170	210	270
Iron Catalyst	\$293,000 (0.084¢)	\$279,000 (0.080¢)	\$247,000 (0.071¢)
Stretford	\$401,000 (0.115¢)	\$382,000 (0.109¢)	\$266,000 (0.076¢)
EIC	\$512,000 (0.146¢)	-	-
Dow Oxygenation	\$2,950,000 (0.843¢)	\$2,000,000 (0.571¢)	\$1,290,000 (0.369¢)

In summary, the choice of energy conversion system will affect the amount and location of H_2S emission. Specific plant design parameters need to be known before more definitive statements concerning their effects on H_2S abatement can be made.

2.4.4 Size of Power Plant

The cost of most H_2S abatement systems on a per-unit-power-output basis is expected to decrease as the plant capacity increases. This cost reduction is mainly due to economies of scale. However, many other operational parameters, such as resource temperature and flow rate of fluid at the wellhead, are more important in determining the optimal size of a power plant.

2.5 Evaluation of H_2S Abatement Systems

Based on the systems performance and cost, it is apparent that the most cost-effective systems are the iron catalyst and Stretford processes. The EIC process has been field tests at The Geysers with some conflicting results. Cost figures for the Dow oxygenation process are questionable as they are derived from extrapolating laboratory test data.

3.0 WASTEWATER TREATMENT

3.1 Waste Characterization

Two factors are particularly important in the design of wastewater treatment facilities: the quantity and quality of the wastewater to be treated. Many factors and variables will affect the quantity and quality of wastewater to be disposed of. To facilitate cost comparison, the same "typical" 50 MWe plant as described in Section 2.3 is used for cost estimating purposes in this section.

The largest source of wastewater from a geothermal power plant is the geothermal fluid itself. A pumping rate of 11,500,000 pounds per hour is equal to approximately 33 million gallons of fluid per day. The cooling tower blowdown and the wastewater generated from H₂S abatement amount to a relatively small quantity (about 0.5 mgd) compared to the spent geothermal fluid. A volume of 33 mgd of wastewater is equivalent to the amount of domestic wastewater generated by a small-to-medium size city with a population of 150,000. The disposal of wastewater has become a special problem for the geothermal energy industry.

Chemical constituents present in geothermal fluids vary from site to site. The quality of geothermal fluid ranges from drinking water quality (as those found in Boise, Idaho) to fluids that are more saline than seawater (as those found in the Salton Sea resource area). Exhibit 3.1 illustrates the most common chemical species found in geothermal fluids and their concentrations. To date, there are no widely published data on the chemical characteristics of spent geothermal fluid. Exhibit 3.1 does, however, provide some indication of the wide range of values of chemical species found in the fluids.

EXHIBIT 3.1

COMMON CHEMICAL SPECIES FOUND IN GEOTHERMAL
FLUIDS AND THEIR CONCENTRATION (ppm)

Cooling tower blowdown is often combined with spent geothermal fluid and disposed of together. The major types of contaminants present in cooling tower blowdown are residual chlorine and corrosion products. The latter include heavy metal ions such as copper, chromium, and nickel.

3.2 Process Selection

Unlike H_2S abatement, there are no treatment and disposal technologies developed specifically for spent geothermal fluids. This is partly because injection of spent fluid is the most widely accepted option for the disposal of spent fluids. However, cost functions developed for wastewater treatment technologies for other industries and for municipal waste treatment will allow estimates to be made for geothermal waste treatment costs.

In general, there are three different types of wastewater treatment technologies that have potential application in the geothermal system. They are:

- Domestic waste treatment
- Industrial waste treatment
- Desalination.

Because of the high organic-matter content of domestic wastewater, biological treatment processes are most commonly used to biodegrade the organic contaminants in water. For industrial wastes, biological processes are generally used in industries that produce organic waste products. Food processing and the pulp and paper industries are examples of biological waste producers. Industries that produce

inorganic wastes, such as inorganic chemicals and metal finishing and electroplating, use a combination of chemical treatment and physical treatment processes for waste reduction. Desalination is used for the treatment of brackish water mainly through evaporation or reverse osmosis. Wastewater treatment processes that have potential application to geothermal systems are described in Appendix B.

Surface wastewater treatment processes have to be designed to meet the National Pollutant Discharge Elimination System (NPDES), promulgated under the Clean Water Act. Subsurface disposal activities must comply with the Underground Injection Control (UIC) program under the Safe Drinking Water Act. Thus, three disposal systems have been selected for cost comparison here. They are chemical precipitation, evaporation ponding, and injection. These processes have been selected because they have the potential for meeting the above mentioned environmental regulations.

Ocean disposal is not considered a viable option because, with the exception of The Geysers, there are no hydrothermal sites on the west coast that are reasonably close (i.e. less than 100 miles) to the ocean. Many desalination processes, such as reverse osmosis and electrodialysis, are not being considered because 1) they are in the earlier stages of development and there is a higher uncertainty associated with their cost estimates, and 2) a preliminary examination of cost information revealed that they would cost more than conventional treatment processes and simultaneously achieve a lower removal efficiency.

3.3 Cost Estimates

To facilitate the comparison of wastewater treatment and disposal cost, a hypothetical 50 MWe flashed-steam plant, similar to the one described in Section 2, is used. Annualized capital costs, O&M costs and total costs, are presented in Exhibit 3.2.

For a chemical precipitation system, several unit processes are required to complete the treatment process. Exhibit 3.3 is a simplified flow diagram of such a system. Sedimentation is followed by chemical addition and finally filtration to remove precipitated solids. Cost estimates in Exhibit 3.2 do not include sludge treatment and disposal, which will be discussed in Section 4.0. In addition, it does not include items such as building cost, pumping between processes, special site preparation, automated control and monitoring systems, and engineering design cost. Thus the real costs for chemical treatment will be higher than those presented in Exhibit 3.2.

For injection disposal, an injection rate of about 1,500,000 gallons per day per well is assumed. The injection pressure is estimated to be about 200 psi.

For evaporation ponds, the major capital cost item is the cost of land, which can vary extensively throughout the nation.

3.4 Sensitivity Analysis

A sensitivity analysis was performed on the costs associated with fluid treatment and disposal. The following parameters were selected:

EXHIBIT 3.2 . COST COMPARISON OF SURFACE AND SUBSURFACE
DISPOSAL FOR A 50 MWe PLANT (1977 DOLLARS)

PROCESSES	ANNUAL CAPITAL	O & M	TOTAL	COST PER KWH
Chemical Precipitation				
• Sedimentation	\$ 160,000	\$ 120,000	\$ 280,000	0.080¢
• Lime Addition	\$ 280,000	\$ 280,000	\$ 560,000	0.160¢
• Alum Addition	\$ 240,000	\$ 881,000	\$1,121,000	0.320¢
• Filtration	\$ 320,000	\$ 441,000	\$ 761,000	0.217¢
Total	\$1,000,000	\$1,722,000	\$2,722,000	0.778¢
Evaporation Ponds *	\$7,840,000	\$ 160,000	\$8,000,000	2.286¢
Injection	\$1,100,000	\$1,545,000	\$2,645,000	0.756¢

*Based on an annual evaporation rate of 60 inches per year.

EXHIBIT 3.3
SIMPLIFIED PROCESS FLOW DIAGRAM FOR THE REMOVAL OF SOLIDS

- Dissolved solids content in brine
- Resource temperature
- Energy conversion system
- Size of power plant.

3.4.1 Dissolved Solids Content

The chemical composition of geothermal fluid is known to vary extensively from site to site. For heavy metal ions, which are priority pollutants under NPDES, a concentration range of 0.01 ppm to approximately 50 ppm of total metal ion concentration appears to be reasonable (see Exhibit 3.1).

3.4.1.1 Chemical Precipitation. The capital cost of a chemical treatment facility is generally independent of the total dissolved solids content in the wastewater. With the exception of the cost of chemicals and other O&M cost items, such as labor, materials and electric power, would not vary significantly with changes in total solids content.

Cost of chemicals, particularly chemicals used for the control of heavy metals, will vary linearly with the concentration of the heavy metal ions, primarily because of added chemical requirements as the heavy metal ion concentration increases. In order to have effective metal ion removal, 2 to 4 times of stoichiometric reagent is needed. Exhibit 3.4 illustrates the cost ranges of two common reagents used in chemical treatment processes. This exhibit assumes the cost of lime (CaO) and alum ($\text{Al}_2(\text{SO}_4)_3$) to be approximately \$40 and \$160 per ton, respectively. A linear relationship is also

EXHIBIT 3.4

COST OF CHEMICALS FOR THE PRECIPITATION OF METAL IONS

assumed.

Thus, if the geothermal fluid has a high metal ion content, the O&M cost could increase substantially. For the typical 50 MWe plant, the additional cost for chemicals is over \$2,000,000 if the total metal ions content is 50 ppm.

3.4.1.2 Evaporation Pond. The total solids content would not affect the capital or O&M cost of an evaporation pond for the first few years of operation. High salinity brines may, however, require more frequent cleaning of the pond. Heavy metal ions constitute a very small portion of the total dissolved solids in the fluid and would not have any noticeable effect on the operation of the pond.

3.4.1.3 Injection. Total solids content of the fluid may affect the operation of an injection system, particularly in terms of plugging the well or geological formation with suspended solids. The cost is difficult to estimate since the speed and extent of well plugging tend to be unpredictable. Sometimes pre-treatment to remove suspended solids may be required to minimize well plugging. If a pre-treatment system is required, which is the worst-case example, the annualized cost of injection will be increased by \$840,000.

Exhibit 3.5 summarizes the annualized costs of the three base-case disposal systems with high salinity fluid.

3.4.2 Resource Temperature

As with H₂S abatement systems, a high resource temperature implies a lower flow rate for the same amount of power output.

EXHIBIT 3.5

SUMMARY OF ANNUALIZED COST ESTIMATES COST PER KILOWATT-HOUR IN PARENTHESIS

PROCESS	BASE CASE	HIGH SALINITY FLUID
Chemical Precipitation	\$2,722,000 (0.776¢)	\$4,820,000 (1.377¢)
Evaporation Pond	\$8,000,000 (2.286¢)	\$8,000,000 (2.286¢)
Injection	\$2,645,000 (0.756¢)	\$3,485,000* (0.996¢)

* Including pretreatment cost.

Exhibit 3.6 presents the flow rate at three different resource temperatures. Since units for wastewater flows have not been standardized, three sets of units (pounds per hour, liters per minute and gallons per day) are presented in the exhibit.

3.4.2.1 Chemical Precipitation. The capital cost of the treatment system is very much affected by flow rate. Most reaction tanks used in treatment plants are cylindrical in shape so as to minimize the amount of material used per unit volume. The scale of the plant is important: the cost per gallon for a 1-mgd facility might be twice as high as that for a 100-mgd facility. However, economies of scale are not as important as the plant size increases.

O&M costs are affected indirectly by flow rate. Higher flow rates require more chemicals for treatment as well as more electric power for pumping, aeration, and mixing. The annualized total costs for chemical treatment at the three resource temperature are:

<u>Resource Temperature</u>	<u>Total Annual Cost</u>
170°C	\$2,722,000
210°C	\$1,691,000
270°C	\$1,156,000

3.4.2.2 Evaporation Ponds. Capital costs for evaporation ponds are directly related to the amount of fluid to be disposed of. The relationship should be relatively linear. O&M cost is a small percentage of capital cost, with the major cost item being the cost of pumping. The annualized costs are:

<u>Resource Temperature</u>	<u>Total Annual Cost</u>
170°C	\$8,000,000
210°C	\$4,000,000
270°C	\$2,400,000

EXHIBIT 3.6

BRINE FLOW RATE REQUIRED TO PRODUCE 50 MWe
OF POWER AT THREE DIFFERENT RESOURCE TEMPERATURES

RESOURCE TEMPERATURES (°C)	BRINE FLOW RATE		
	Pounds/Hour	Liters/Minutes	Gallons/Days
170	11,400,000	76,200	32,800,000
210	6,050,000	37,800	17,400,000
270	3,100,000	22,600	8,900,000

3.4.2.3 Injection. Capital cost of injection will be affected incrementally by flow rate, because at high flow rates, more injection wells will be required. Construction of injection wells is a major cost item.

The major O&M cost item for injection is the cost of electric power required to pump the fluid into the injection well, although at certain sites (e.g., The Geysers) pump assist may not be required. The cost is independent of pump rate but is linearly dependent upon the volume of fluid to be pumped and wellhead pressure. Annualized total costs are summarized as follows:

<u>Resource Temperature</u>	<u>Total Annual Cost</u>
170°C	\$2,645,000
210°C	\$1,320,000
270°C	\$ 790,000

Exhibit 3.7 summarizes the total cost of different wastewater treatment/disposal systems under these three different resource temperatures.

3.4.3 Energy Conversion System

The amount of waste fluid generated from a flashed-steam plant and binary plant is not significantly different. Therefore, the selection of wastewater disposal options is generally not an important factor influencing the type of energy conversion system desired.

3.4.4 Size of Power Plant

Economies of scale are extremely important in chemical precipitation. The cost of wastewater treatment on a per-power-output basis would be less for large plants.

EXHIBIT 3.7

SUMMARY OF ANNUALIZED COST ESTIMATES OF TREATMENT/DISPOSAL TECHNOLOGIES AT DIFFERENT RESOURCE TEMPERATURES FOR A 50 MWe PLANT COST PER KILOWATT-HOUR IN PARENTHESIS

PROCESS	RESOURCE TEMPERATURE °C		
	170	210	270
Chemical Precipitation			
● Sedimentation	\$ 280,000	\$ 200,000	\$ 155,000
● Lime Addition	\$ 560,000	\$ 338,000	\$ 332,000
● Alum Addition	\$1,121,000	\$ 656,000	\$ 452,000
● Filtration	\$ 761,000	\$ 497,000	\$ 357,000
Total	\$2,722,000 (0.778¢)	\$1,691,000 (0.483¢)	\$1,156,000 (0.336¢)
Evaporation Ponds	\$8,000,000 (2.286¢)	\$4,000,000 (1.143¢)	\$2,400,000 (0.686¢)
Injection	\$2,645,000 (0.756¢)	\$1,320,000 (0.377¢)	\$ 790,000 (0.226¢)

3.5 Evaluation of Wastewater Treatment Systems

Based on the cost and performance information on wastewater treatment systems, it becomes apparent that injection is the least expensive disposal option. Chemical precipitation, excluding the cost of sludge treatment and disposal, is generally less expensive than evaporation ponds. A major cost item for evaporation ponds is the cost of land, which will vary considerably throughout the nation.

4.0 SOLID WASTE DISPOSAL

4.1 Waste Characterization

The major sources of solid wastes generated in geothermal operations include:

- Drilling fluid ("mud") and drill cuttings
- Scale from cleanout of wells and plant
- Sludge from H₂S abatement
- Sludge from spent brine treatment
- Sludge from cooling tower blowdown.

The amount of solids generated from these sources are difficult to quantify as they all depend on site-specific conditions, particularly H₂S concentration and the salinity of the brine. However, using a typical 50 MWe plant as described in the previous section, some semi-quantitative estimates on the annual amount of solid waste produced can be made.

The chemical characteristics of geothermal solid wastes are difficult to anticipate in a generic manner. The types of wastes produced are summarized below.

- Drilling Wastes mainly include drilling mud. Chemicals are often added to the drilling fluid to improve the fluidity of the mud and they typically contain lime, lignite, and other organic polymers. Drill cuttings (rock) are also produced as a result of the drilling operation.
- Scales are produced as a result of temperature decreases and/or when geothermal fluids are partially oxidized. The most common types of scales are silica, carbonate, and sulfide.
- Sludge from H₂S abatement contains elemental sulfur or sulfur-containing compounds, depending on the type of H₂S abatement system used.
- Residues from spent brine treatment will be highly dependent upon the suspended and dissolved solids present in the brine. Most likely, the sludge removed will contain silica, carbonates, and sulfides, as the solubility of these substances are

most sensitive to temperature changes and air oxidation. Some heavy metal compounds are also expected to be present.

- Sludge from cooling tower systems will contain chemicals similar to the sludge from spent fluid treatment. In addition, corrosion products, particularly copper ions, are most likely to be present.

Exhibit 4.1 summarizes the sources and characteristics of the solid wastes that might be expected from a typical 50 MWe plant. This information provides a basis for estimating the cost of solid waste treatment and disposal.

4.2 Selection of Treatment and Disposal Options

For geothermal operations, drilling-mud wastes are generally stored on site and recirculated as new wells are needed. Typically, 14 production wells are required to sustain an average power output of 50 MWe. In addition, since production wells occasionally fail for a variety of reasons, new wells have to be drilled to maintain the designed level of power output.

Scale cleanout of wells and plant requires complete or partial plant shutdown. The amount of scale produced is difficult to quantify. In addition, scale inhibitors can be added to geothermal fluids to minimize scale formation in the plant.

Exhibit 4.2 is an estimate of the H₂S abatement sludge generated from the four different processes described in Section 2. The Stretford process produces high-quality sulfur which can be marketed as a useful by-product. Other sludges, however, contain a significant amount of impurities and water. The high moisture content of these sludges adds cost to the transportation and ultimate disposal.

EXHIBIT 4.1

ESTIMATED SOLID WASTE CHARACTERISTICS
FOR "TYPICAL" 50 MWE GEOTHERMAL POWER PLANT

SOURCE	SIGNIFICANT CONSTITUENTS AND CHARACTERISTICS		QUANTITY FOR "TYPICAL" 50 MWe PLANT PER YEAR
DRILLING	<ul style="list-style-type: none"> • Drilling mud • Cuttings • Other 	<ul style="list-style-type: none"> • May be hazardous 	800 Tonnes
SCALE	<ul style="list-style-type: none"> • SiO₂ • Carbonates • Sulfides • Numerous others 	<ul style="list-style-type: none"> • Could be hazardous at some sites (e.g., presence of Pb) 	1,400 Tonnes
H ₂ S ABATEMENT	<ul style="list-style-type: none"> • Elemental S or S-containing compounds 	<ul style="list-style-type: none"> • May be non-hazardous and useful by-product 	800 Tonnes
SPENT BRINE TREATMENT	<ul style="list-style-type: none"> • Complex and site-specific 	<ul style="list-style-type: none"> • May be hazardous (e.g., presence of heavy metals) 	200,000 tonnes*
COOLING SYSTEM	<ul style="list-style-type: none"> • Treatment residue • Blowdown • Cooling tower sludge 	<ul style="list-style-type: none"> • May be hazardous due to metal erosion products 	Included in spent brine treatment

*Assumes the removal of heavy metals, calcium and silicons. Sodium and potassium ions remain in solution.

EXHIBIT 4.2

MAJOR CHEMICAL CONSTITUENTS AND QUANTITIES OF
SLUDGE (DRY-WEIGHT) PRODUCED FROM H₂S ABATEMENT PROCESSES

PROCESSES	MAJOR CHEMICAL CONSTITUENTS	QUANTITY TONS/YEAR
Iron Catalyst	<ul style="list-style-type: none"> • Sulfur 	790
Stretford	<ul style="list-style-type: none"> • Sulfur (High Quality) 	880
EIC	<ul style="list-style-type: none"> • (NH₄)₂ SO₄ 	1,700
Dow Oxygenation	<ul style="list-style-type: none"> • CaSO₄ • Sulfur 	34,000

Cooling tower blowdown is generally combined with spent fluids for treatment and/or disposal. The amount of sludge generated from the wastewater treatment systems is shown in Exhibit 4.3. Chemical treatment produces a significant amount of sludge needed for disposal. The amount of sludge typically generated contains only 2-5% solid. Thus, sludge processing, including thickening and dewatering, is required before disposal. Unit processes applicable for the disposal of geothermal sludge are briefly described in Appendix C.

There are several methods of sludge disposal. They include land spreading, lagooning, landfilling, and ocean dumping. Landfilling, either on-site or off-site, is the only viable option for the disposal of geothermal sludge. The potential high metals content of the sludge would not be acceptable for land spreading or ocean dumping. Lagooning tends to create an aesthetic problem and also requires large land areas.

For the purpose of cost comparisons, the treatment options for sludges include mechanical thickening and filtration. The method of disposal is off-site disposal to a landfill site approximately 50 miles away from the power plant. It is further assumed that geothermal solid wastes are not considered as hazardous and would not, therefore, require the use of secured landfills.

4.3 Cost Estimates

For the iron catalyst, Stretford, and EIC processes, the cost associated with sludge treatment is included in the overall H₂S abatement process. In the Dow oxygenation process, the sludge produced remains in solution and is piped through the energy conversion unit

EXHIBIT 4.3

MAJOR CHEMICAL CONSTITUENTS AND QUANTITIES OF SLUDGE (DRY-WEIGHT) PRODUCED FROM WASTEWATER TREATMENT SYSTEMS

TREATMENT SYSTEMS	MAJOR CHEMICAL CONSTITUENTS	QUANTITY TONS/YEAR
Chemical Treatment	<ul style="list-style-type: none"> • Metal Hydroxides • Calcium Carbonates • Calcium Silicates • 95-98% Water 	1,300
Evaporation Pond	-	None *
Injection	-	None **

* Except for periodic cleaning of pond.

** Unless pre-treatment is required.

of the plant. The sludges become added suspended solids that will eventually precipitate out from the spent fluids. Thus the cost of sludge treatment has already been accounted for.

For wastewater treatment systems, the cost of sludge treatment and processing is highly dependent upon the treatment process. Estimates have been made that sludge treatment can cost an additional 30% to 50% of the waste treatment cost.

Exhibit 4.4 is a flow diagram of the treatment, transportation, and disposal options for sludges generated from H₂S abatement and wastewater treatment processes. The annual amounts of sludge generated are also provided. For the Stretford process, high-quality elemental sulfur is produced at the rate of about 3 tons per day. Sulfur is a marketable commodity and would not require treatment and disposal.

Cost estimates of treatment and disposal of sludges are provided in Exhibit 4.5. These estimates are based on the following assumptions:

- Sludge treatment for a chemical precipitation system is an additional 40% of the cost of wastewater treatment.
- Sludges contain about 20% to 30% solids and are hauled by a 15 cubic yard (11.5 m³) 3-axle dump truck to a disposal site 50 miles away.
- Cost for the transport of H₂S abatement sludge is about \$34 per wet ton, including loading and unloading.
- Cost for the transport of wastewater treatment sludge is about \$16 per wet ton. Cost saving is primarily due to mechanized loading facilities.
- Sludges are disposed of in a wide-trench disposal site. The landfill cost is \$15 for air abatement sludge and \$4.50 for wastewater sludge. The lower unit cost for wastewater sludge is due to the large volumes of sludge produced by the wastewater treatment processes.

EXHIBIT 4.4

FLOW DIAGRAM OF SLUDGE TREATMENT, TRANSPORT AND DISPOSAL (NUMBERS IN PARENTHESIS) ARE THE TONS OF WET SLUDGE PRODUCED PER YEAR)

EXHIBIT 4.5

SUMMARY OF SLUDGE TREATMENT, TRANSPORTATION AND
DISPOSAL COSTS FOR THE H₂S ABATEMENT AND
WASTEWATER TREATMENT OPTIONS

PROCESSES	TREATMENT	TRANSPORTATION	DISPOSAL	TOTAL
Air Abatement				
• Iron Catalyst	-	\$108,000 (0.031¢)	\$47,000 (0.013¢)	\$155,000 (0.044¢)
• Stretford	-	-	-	-
• EIC	-	\$190,000 (0.054¢)	\$88,400 (0.025¢)	\$278,400 (0.079¢)
• Dow Oxygenation	-	-	-	-
Wastewater Treatment				
• Chemical Precipitation	\$1,100,000 (0.314¢)	\$ 4,000,000 (1.143¢)	\$1,420,000 (0.406¢)	\$ 6,520,000 (1.863¢)
• Evaporation	-	-	-	-
• Injection	-	-	-	-
• Injection w/ Pretreatment	\$335,000 (0.096¢)	\$ 1,710,000 (0.489¢)	\$ 475,000 (0.136¢)	\$ 2,520,000 (0.721¢)

As evident from Exhibit 4.5, the cost of H₂S sludge treatment and disposal is substantially less than that of the transportation and disposal cost for wastewater treatment sludge. Further, transportation of sludge is a very significant cost item, to the extent that on-site disposal warrants serious consideration.

4.4 Sensitivity Analysis

In an effort to identify which parameter(s) would affect the cost of sludge treatment and disposal, a sensitivity analysis was performed by changing the following operational parameters:

- H₂S concentration
- Dissolved solids content in brine
- Resource temperature
- Energy conversion system
- Size of power plant.

4.4.1 H₂S Concentration

The amount of sludge produced from the various H₂S abatement systems is proportional to the H₂S concentration in the gas phase. Within the range of H₂S concentrations under consideration, the relationship is essentially linear. The cost of sludge process and treatment for the iron catalyst, Stretford, and EIC processes were included in the cost of each abatement system. The Dow oxygenation process is an up-stream treatment of geothermal fluid. The sludge produced is not processed and remains in the geothermal fluid until removal in the wastewater treatment process. Exhibit 4.6 summarizes the cost of sludge disposal at different H₂S concentrations.

EXHIBIT 4.6

SUMMARY OF ANNUALIZED COST ESTIMATES FOR THE
DISPOSAL OF H₂S ABATEMENT SLUDGE (1977 DOLLARS)
COST PER KILOWATT-HOUR IN PARENTHESIS

PROCESS	H ₂ S CONCENTRATION			
	40 ppm	220 ppm	800 ppm	1600 ppm
Iron Catalyst	\$28,000 (0.008¢)	\$155,000 (0.044¢)	\$390,000 (0.111¢)	\$740,000 (0.211¢)
Stretford	-	-	-	-
EIC	\$60,000 (0.017¢)	\$278,400 (0.080¢)	\$743,000 (0.212¢)	\$1,350,000 (0.386¢)
Dow Oxygenation	-	-	-	-

4.4.2 Total Solids Contents

The amount of wastewater sludge produced is related to the amount of suspended and dissolved solids present in the geothermal fluid. Three concentration levels of total dissolved solids have been selected for cost comparison. The results are presented in Exhibit 4.7. The transportation and treatment costs are based on the sludge being dewatered to a solids content of about 20% to 30%.

4.4.3 Resource Temperature

The resource temperature affects the total amount of fluid required to produce the same power output. When other conditions remain unchanged, a high resource temperature would produce less sludge, with the consequence that the cost of sludge treatment and disposal would be less. Exhibit 4.8 summarizes sludge disposal cost estimates at three different resource temperatures.

4.4.4 Energy Conversion System

The choice of energy conversion systems, e.g., flashed steam vs. binary, would affect the amount of H_2S sludge and, consequently, the cost of disposal. Wastewater sludges are less sensitive to the type of energy conversion system employed. The cost of sludge disposal is seldom a consideration in the selection of energy conversion systems.

4.4.5 Size of Power Plant

Economies of scale will bring down the cost of sludge treatment, handling, and disposal. However, other overriding factors will determine the size of power plants.

EXHIBIT 4.7

SUMMARY OF ANNUALIZED COST ESTIMATES (1977 DOLLARS) FOR SLUDGE
DISPOSAL AT DIFFERENT RESOURCE TEMPERATURES
COST PER KILOWATT-HOUR IN PARENTHESIS

WASTEWATER TREATMENT	LOW SALINITY (TS=2,000 ppm)	MEDIUM SALINITY (TS=10,000 ppm)	HIGH SALINITY (TS=100,000 ppm)
Chemical Precipitation	\$2,245,000 (0.641¢)	\$6,520,000 (1,863¢)	\$11,180,000 (3.194¢)
Evaporation Pond	-	-	-
Injection	-	-	-
Injection w/ Pretreatment	\$ 790,000 (0.226¢)	\$2,520,000 (0.720¢)	\$ 4,135,000 (1.181¢)

EXHIBIT 4.8

SUMMARY OF ANNUALIZED COST ESTIMATES (1977 DOLLARS) FOR SLUDGE
DISPOSAL AT DIFFERENT RESOURCE TEMPERATURES
COST PER KILOWATT-HOUR IN PARENTHESIS

PROCESSES	170°	210°	270°
Air Abatement			
● Iron Catlayst	\$ 155,000 (0.0443¢)	\$ 138,000 (0.039¢)	\$ 109,000 (0.031¢)
● Stretford	-	-	-
● EIC	\$ 278,400 (0.080¢)	\$ 248,000 (0.071¢)	\$ 200,000 (0.057¢)
● Dow Oxygenation	-	-	-
Wastewater Treatment			
● Chemical Precipitation	\$6,520,000 (1,863¢)	\$3,620,000 (1.034¢)	\$2,050,000 (0.586¢)
● Evaporation	-	-	-
● Injection	-	-	-
● Injection w/ Pretreatment	\$2,520,000 (0.620¢)	\$1,560,000 (0.446¢)	\$ 930,000 (0.266¢)

4.5 Evaluation of Solid Wastes Disposal Options

Despite the high cost of sludge disposal, landfilling is probably the least expensive sludge disposal option. Additional savings can be achieved if the sludge is disposed of on-site. However, the geothermal operators will have to deal with additional problems associated with landfill operations in this case.

5.0 COST COMPARISON OF ENVIRONMENTAL CONTROL SYSTEMS

As indicated in Section 4.0, a major portion of geothermal solid wastes is derived from the air abatement system and wastewater treatment system. It is, therefore, more meaningful to incorporate sludge treatment and disposal costs into the cost of air abatement and wastewater treatment systems. In other words, the total cost of each process would include:

- Air abatement or wastewater treatment costs
- Sludge treatment cost
- Sludge handling and transportation cost
- Final disposal cost.

The analyses performed in Sections 2 through 4 revealed that the cost of environmental controls are most sensitive to the following three parameters (all of which are inherent characteristics of geothermal fluids):

- Temperature of resource
- Total solids concentration
- H₂S concentration.

The temperature and dissolved solids content of geothermal fluids vary extensively from site to site. It is, therefore, difficult to establish "typical" fluid characteristics. Generally, high-temperature resources tend to have a higher dissolved solids content, primarily due to the fact that the solubilities of most solid materials increases with temperature. The correlation between dissolved solids and temperature is, however, rather weak, as illustrated in Exhibit 5.1.

EXHIBIT 5.1
CORRELATION OF FLUID TEMPERATURE
AND TOTAL DISSOLVED SOLIDS

Three scenarios have been identified to permit cost analysis and comparison. These are:

- o "Best Case" scenario, characterized by
 - high temperature
 - low salinity
 - extremely low H₂S concentration.
- o "Most Probable Case" scenario, characterized by
 - medium temperature
 - medium salinity
 - relatively low H₂S concentration.
- o "Worse Case" scenario, characterized by
 - low temperature
 - high salinity
 - medium to high H₂S concentration.

Cost summaries of these three scenarios are presented in Exhibits 5.2 through 5.4. The following observations can be made about these three cases:

"Base Case" 50 MWe Plant (Exhibit 5.2)

No H₂S abatement systems are required because of the extremely low H₂S concentration.

At a cost of 0.226¢ per kilowatt-hour, injection is the least costly method of disposal. If pretreatment is required (which is unlikely because of the low solids content), the cost will increase to 0.579 per KWh, still less than evaporation ponds and chemical precipitation. If on-site disposal is used, some money can be saved in the sludge handling and transportation categories. This would make the cost of chemical precipitation system less than that of an

EXHIBIT 5.2
COST SUMMARY FOR A "BEST CASE"
50 MWe PLANT (1977 DOLLARS)
COST PER KILOWATT-HOUR IN PARENTHESIS

PROCESSES	AIR ABATEMENT/ WASTEWATER TREATMENT	SLUDGE			TOTAL COST
		TREATMENT	HANDLING & TRANSPORTATION	DISPOSAL	
Iron Catalyst					
Stretford					
EIC					
Dow Oxygenation					
		None Required			
Chemical Precipitation	\$1,156,000 (0.330¢)	\$460,000 (0.131¢)	\$875,000 (0.250¢)	\$270,000 (0.077¢)	\$2,761,000 (0.788¢)
Evaporation Ponds	\$2,400,000 (0.686¢)	-	-	-	\$2,400,000 (0.686¢)
Injection	\$ 790,000 (0.226¢)	-	-	-	\$ 790,000 (0.226¢)
Injection w/ Pretreatment	\$1,277,000 (0.365¢)	\$195,000 (0.056¢)	\$400,000 (0.114¢)	\$155,000 (0.044¢)	\$2,027,000 (0.579¢)

EXHIBIT 5.3
 COST SUMMARY FOR A "MOST PROBABLE CASE"
 50 MWe PLANT (1977 DOLLARS)
 COST PER KILOWATT-HOUR IN PARENTHESIS

PROCESSES	AIR ABATEMENT/ WASTEWATER TREATMENT	SLUDGE			TOTAL COST
		TREATMENT	HANDLING & TRANSPORTATION	DISPOSAL	
Iron Catalyst	\$ 242,600 (0.069¢)	-	\$ 20,000 (0.006¢)	\$ 8,800 (0.003¢)	\$ 271,400 (0.078¢)
Stretford	\$ 300,000* (0.086¢)	-	-	-	\$ 300,000 (0.086¢)
EIC	\$ 400,000* (0.114¢)	-	\$ 35,000 (0.010¢)	\$ 16,000 (0.005¢)	\$ 451,000 (0.129¢)
Dow Oxygenation	\$ 986,000 (0.281¢)	-	-	-	\$ 986,000 (0.281¢)
Chemical Precipitation	\$1,691,000 (0.483¢)	\$680,000 (0.194¢)	\$2,300,000 (0.657¢)	\$640,000 (0.183¢)	\$5,311,000 (1.517¢)
Evaporation Ponds	\$4,000,000 (1.143¢)	-	-	-	\$4,000,000 (1.143¢)
Injection	\$1,320,000 (0.377¢)	-	-	-	\$1,320,000 (0.377¢)
Injection w/ Pretreatment	\$1,858,000 (0.531¢)	\$210,000 (0.060¢)	\$1,030,000 (0.294¢)	\$320,000 (0.091¢)	\$3,418,000 (0.976¢)
*This number is extrapolated.					

EXHIBIT 5.4
 COST SUMMARY FOR A "WORST CASE"
 50 MWe PLANT (1977 DOLLARS)
 COST PER KILOWATT-HOUR IN PARENTHESIS

PROCESSES	AIR ABATEMENT/ WASTEWATER TREATMENT	SLUDGE			TOTAL COST
		TREATMENT	HANDLING & TRANSPORTATION	DISPOSAL	
Iron Catalyst	\$ 293,000 (0.084¢)	-	\$ 108,000 (0.0314¢)	\$ 47,000 (0.013¢)	\$ 448,000 (0.128¢)
Stretford	\$ 401,000 (0.115¢)	-	-	-	\$ 401,000 (0.115 ¢)
EIC	\$ 512,000 (0.146¢)	-	\$ 190,000 (0.054¢)	\$ 88,400 (0.026¢)	\$ 790,400 (0.225¢)
Dow Oxygenation	\$2,950,000 (0.843¢)	-	-	-	\$ 2,950,000 (0.843¢)
Chemical Precipitation	\$4,820,000 (1.377¢)	\$1,930,000 (0.551¢)	\$7,450,000 (2.129¢)	\$2,630,000 (0.751¢)	\$16,830,000 (4.808¢)
Evaporation Ponds	\$8,000,000 (2.286¢)	-	-	-	\$ 8,000,000 (2.286¢)
Injection	\$2,600,000 (0.743¢)	-	-	-	\$ 2,600,000 (0.743¢)
Injection w/ Pretreatment	\$3,485,000 (0.995¢)	\$ 354,000 (0.101¢)	\$3,000,000 (0.857¢)	\$ 800,000 (0.229¢)	\$ 7,639,000 (2.183¢)

Injection	0.226¢
Injection with pretreatment	0.579¢
Evaporation	0.686¢
Chemical precipitation	0.788¢

"Most Probable Case" 50 MWe Plant (Exhibit 5.3)

The iron catalyst process, at a cost of 0.078¢ per KWh, is the least costly method of air abatement.

For wastewater treatment systems, injection, even if pre-treatment is required, is the least costly method of disposal. Again, if sludge from chemical precipitation is disposed of on-site, it would be less costly than evaporation ponds. The cost per KWh for these systems are:

Injection	0.377¢
Injection with pretreatment	0.976¢
Evaporation	1.143¢
Chemical precipitation	1.157¢

"Worst Case" 50 MWe Plant (Exhibit 5.4)

For air abatement systems, both the iron catalyst and Stretford processes are relatively inexpensive for the control of H₂S systems.

For wastewater treatment systems, injection and injection with pre-treatment are the least costly methods for spent fluid disposal. The cost per KWh for these systems are:

Injection	0.743¢
Injection with pretreatment	2.186¢
Evaporation ponds	2.286¢
Chemical precipitation	4.808¢

Exhibit 5.5 depicts the total cost of air abatement and wastewater treatment for these three scenarios. The high cost of chemical precipitation is mainly due to the high cost of sludge handling and

EXHIBIT 5.5

COST SUMMARY FOR THE H₂S ABATEMENT AND WASTEWATER
TREATMENT SYSTEMS FOR THE THREE DIFFERENT
HYPOTHETICAL 50 MWe PLANT (CENTS/KILOWATT-HOUR)

transportation. Injection eliminates the need for treatment, handling, and transportation. Consequently, it turns out to be the least expensive option for all these cases.

6.0 CONCLUSIONS AND RECOMMENDATIONS

Based on the results of the analyses performed for this document of different H_2S abatement and wastewater treatment systems, the following conclusions can be made.

- The cost for H_2S abatement is generally less than the cost of wastewater treatment systems.
- The iron catalyst and Stretford H_2S abatement systems have been fieldtested, while most other systems are still in laboratory or pilot-plant stages.
- Injection of spent brine is the least expensive method of treatment primarily because the need for sludge transport and disposal is eliminated.
- Even if pretreatment of spent fluid is required, injection with pretreatment is still less expensive than chemical precipitation and evaporation ponds.
- Advanced wastewater treatment systems, such as reverse osmosis and electrodialysis, are even more costly than chemical precipitation systems.
- Sludge treatment, handling, and transportation are the most costly items in the wastewater treatment process. For a typical 50 MWe plant with a resource temperature of about $220^{\circ}C$ and 10,000 ppm dissolved solids, sludge treatment and disposal cost exceeds 1.0¢ per KWh.
- If sludge is considered hazardous and requires disposal in a secured landfill, the sludge disposal cost will be significantly higher.
- The costs of environmental control systems are most sensitive to three operational parameters:
 - Resource temperature
 - Total solids concentration
 - H_2S concentration.
- Transportation and handling of sludge is a major cost item. Locating a disposal site closer to the power plant would reduce the cost of transportation, but not the cost of handling. On-site disposal, with automated facilities to pump the sludge to the disposal site, may be a feasible alternative. However, the geothermal operator must be prepared to deal with other problems associated with the operation of a landfill.

Since the highest cost items in the environmental control system are sludge processing, handling, transportation, and disposal, studies can be performed in this area to minimize the cost. Specifically, the following investigations are recommended.

- The solids content in most dewatered sludges is about 20 to 30 percent. Further removal of water would decrease the cost of transport and landfilling. Perform system analysis to determine the trade-off between wet sludge transportation and drying of sludge before transport.
- Study the feasibility and effect on overall cost of sludge disposal with other solid wastes.
- As an effort to offset sludge disposal cost, investigate the feasibility of recovering marketable materials from sludge.

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APPENDIX A

DESCRIPTION OF WASTEWATER TREATMENT
UNIT PROCESSES

IRON CATALYST PROCESS

Process Description

The iron catalyst system was developed by PG&E for the removal of H_2S from the cooling water/condensate stream. Ferrous sulfate is added to the circulating water upstream of the cooling tower. When the circulating water enters the cooling tower, the ferrous ion is oxidized by oxygen in the air to form ferric ion:

The ferric ion reacts with H_2S in the aqueous phase to form elemental sulfur:

The net reaction is:

To assume more complete oxidation of ferrous to ferric ion, the process has been modified to include the addition of hydrogen peroxide (H_2O_2) to the circulation water just before it enters the condenser.

Ferrous ion, in excess, can react with H_2S to form ferrous sulfide (FeS). Therefore ferrous sulfate must be carefully metered into the cooling water.

Status

This process is currently being used at The Geysers. The system efficiency is reported to be about 90%. This system does not control pre-plant emission or steam stacking.

STRETFORD PROCESS

Process Description

The Stretford process was originally designed for the removal of H_2S from synthetic fuel gas. In this process, the off-gas is scrubbed in a countercurrent flow with a sodium containing sodium carbonate, sodium metavanadate and anthraquinone disulfuric acid (ADA). The H_2S is dissolved in the carbonate solution, forming bisulfide ion (HS^-):

The bisulfide ion reacts with V^{+5} to form sulfur and V^{+4} ion:

The reduced vanadium is regenerated through a mechanism involving oxygen transfer by the ADA

Air passed through the solution in the oxidation tank oxidizes the ADA and simultaneously brings the elemental sulfur to the surface as a froth. The sulfur is then removed to a skim tank, separated, washed and processed to produce high quality sulfur.

Status

The first application of the Stretford process is on Unit 15 - at The Geysers for downstream H_2S removal. A system efficiency of 99% was reported.

EIC PROCESS

Process Description

The EIC process is developed by the EIC Corporation with cooperative funding from the U.S. Department of Energy. In this process, the raw geothermal steam is contacted in a scrubber with a recirculating solution of copper sulfate, forming copper sulfide (CuS):

Because of the inevitable formation of sulfuric acid, ammonia is added to the scrubbing solution, forming ammonium sulfate.

The copper sulfide formed can be regenerated by roasting with air to form CuSO_4 :

Unfortunately, SO_2 might also be formed in this process by the following reaction:

Acid pressure leaching is another method of CuSO_4 regeneration. In this process, the copper sulfide in sulfuric acid is treated with oxygen on air under elevated pressure and temperature. Depending on the condition used, the sulfide can be oxidized to sulfate or elemental sulfur.

Status

Recent tests have shown that 95 to 98% removal of H_2S from the steam is feasible. Although reliable sources have indicated that the cost of EIC system turns out to be significantly higher than the original cost estimates.

DOW OXYGENATION

Process Description

In this process, gaseous oxygen is used for the removal of H₂S at the wellhead. The overall reaction is as follows:

Sulfides and free sulfur may also be formed by other reaction paths.

Oxygen can be injected either through a flow control valve into a packed column or through a series of in-line mixers.

This process is only applicable for the treatment of liquid. Its reaction time in the gas phase is too slow to be feasible for steam or two-phase fluids. In addition, corrosion is a major problem particularly when excess oxygen is injected.

Status

This system is still at the laboratory testing scale. Approximately 90% H₂S abatement can be achieved at a pH of 7 and a temperature of 170°C.

APPENDIX B

DESCRIPTION OF WASTEWATER TREATMENT
UNIT PROCESSES

CHEMICAL PRECIPITATION

Process Description

Chemical precipitation in wastewater treatment involves the addition of chemicals for the purpose of removing specific components contained in the wastewater. Many different substances can be used as precipitants. The most common ones include lime ($\text{Ca}(\text{OH})_2$), alum ($\text{Al}_2(\text{SO}_4)_3$) and ferrous sulfate (FeSO_4). An advantage of chemical precipitation is that such a process is more readily incorporated into an existing treatment facility. It involves the use of a chemical feed system directly to the flocculation tank, and perhaps ancillary monitoring equipment to monitor the chemical characteristic, of influent and effluent. Further, many other types of chemicals can be used to enhance solid formation.

Because of the low solubility of sulfide salts, sodium sulfide (Na_2S) and sodium bisulfide (NaHS) has been used to remove heavy metal ions in solution. Such systems have been tested by the electroplating industry and is also being studied at a pilot plant scale for the removal of heavy metal ions in geothermal fluids.

Status

Chemical precipitation is perhaps the most versatile unit process for the removal of heavy metals in geothermal fluids. It is possible to selectively precipitate one or a few chemicals from the fluid thereby improving the overall quality of the sludge.

SEDIMENTATION

Process Description

Sedimentation is the separation of suspended particles that are more dense than water by gravitational settling. Although the concept of sedimentation is rather simple, many design options are available to increase the efficiency of the operation. Sedimentation tanks are designed on the basis of surface loading rate expressed in gallons per day per square foot of horizontal area. The selection of loading rate depends on the types of suspension to be separated. The surface loading rate together with the depth of the sedimentation tank will determine the detention time of the fluid to be treated.

Most treatment plants now use mechanically cleaned sedimentation tanks of standard circular or rectangular design. A typical tank, as shown above, has a sloped bottom at about 1 inch per foot to form an inverted cone. The sludge is scraped to a relatively small hopper near the center of the tank. Sedimentation tanks can be used by themselves or in conjunction with other treatment processes, particularly chemical precipitation and flocculation.

Status

Spent geothermal fluids typically contain higher amounts of suspended solid relative to raw geothermal fluids mainly because of the decrease in temperature after they pass through the energy conversion system. Sedimentation is probably the most simple and least expensive pre-treatment process.

FLOCCULATION

Process Description

Flocculation is an essential part of any chemical or chemically aided precipitation system. It involves stirring or agitation to increase the opportunity for particle contact after the chemicals have been added. Increased particle contact will promote floc growth. However, if the agitation is too vigorous, the shear forces that are set up will break up the floc into smaller particles. Agitation should be carefully controlled so that the floc particles will be of suitable size and settle readily.

Two types of flocculation systems are available for wastewater treatment, namely mechanical agitation and aeration. Paddles for mechanical agitator usually have a peripheral speed of about 1.5 feet per second. Sometimes stationary slats or stator blades are installed in the flocculation tanks to break up the mass rotation of fluid and promote mixing. For air agitation systems, porous tubes or diffuser nozzles are used. The amount of air required is approximately 0.10 cubic feet per gallon for a 45-minute detention period. A typical tank design, as shown above, is similar aeration tanks used in many wastewater treatment systems.

STATUS

Flocculation is used to improve the settling of suspended solids. It can be used in association with chemical precipitation.

FILTRATION

Process Description

Filtration is generally used following the coagulation-sedimentation process and is designed to further remove the solid particles from the treated water. Filter beds are generally designed with consideration given to the characteristics of the fluid to be treated. The suspended solids concentration; particle size and distribution; and particle changes often determine the types of filter medium to be used.

In recent years, increasing emphasis has been placed on the use of multi medium filter beds. Common filter media includes anthracite, sand, garnet, activated carbon, and weighted spherical resin bed. Since filter performance is related directly to the characteristics of the liquid to be filtered, it is recommended that pilot plant studies be conducted to determine the optimum combination of filter materials.

STATUS

Filtration is a necessary step following chemical precipitation and sedimentation.

FLOTATION

Process Description

Flotation is a process used to separate solid or liquid particles from a liquid phase. Separation is brought about by introducing fine gas bubbles into the liquid phase. The bubbles attach to the particulate matter and the buoyant force of the combined particle and gas bubbles causes the particle to rise to the surface. Given particles with a higher density than water can be made to rise. Once the particles have floated to the surface, they can be collected by a skimming operation. The major advantage of flotation over sedimentation is that very small or light particles that settle slowly can be removed more completely and in a short time using the flotation method.

Sometimes chemicals are used to aid the flotation process. These chemicals function to create a surface or a structure that can easily absorb or entrap air bubbles. Aluminum and iron salts, and activated silica are the most common chemicals used.

STATUS

Flotation can be most effectively applied to fluid systems that contain solids having specific gravity slightly greater than unity. It will have limited application in the geothermal fluid system if precipitation of heavy metal ions is the main concern.

APPENDIX C

DESCRIPTION OF SLUDGE TREATMENT
UNIT PROCESSES

GRAVITY THICKENER

Process Description

In this process, sludge is fed continuously into the thickening tank. Conventional sludge-collecting mechanisms with deep trusses or vertical pickets are used to stir the sludge gently, thereby opening up channels for water to escape and promote densification. The thickened sludge that collects on the bottom of the tank is pumped to the dewatering equipment as required. The continuous supernatant flow that results is returned to the settling tank.

In operation, a sludge blanket is maintained on the bottom of the thickener to aid in concentrating the sludge. Typical surface loading rates are 400 to 900 gallons per day per square foot. Sludge removed from the thickener contains 8 - 10 percent solid and requires further dewatering prior to disposal.

Status

Gravity thickening is a process that has been used for along period of time. It has to be used in conjunction with other dewatering mechanisms.

CENTRIFUGATION

Process Description

The centrifugation process is widely used in industry for separating liquids of different density and for thickening slurries or for removing solids. Sludge is fed into a rotating bowl at a constant flow rate where it separates into a dense cake containing the solids and a dilute stream called centrate. The sludge cake, containing 75 to 80 percent moisture is discharged from the bowl by a screw feeder into a hopper or onto a conveyor belt. The centrate, containing fine, low density suspended solids is returned to the raw sludge thickener or primary clarifier.

The capital cost for a centrifuge installation is less than that of a vacuum filter of equal capacity. However, higher power costs generally off-set the advantage of the lower initial cost.

Status

This process is a demonstrated technology and will produce sludge cake with a solid content of 15 to 40 percent. However, solids content exceeding 25 percent is not economical, due to the high cost of power required.

DRYING BEDS

Process Description

Drying beds can be used to dewater digested sludge by placing the sludge on beds in an 8 to 12-inch layer and allowed to dry. The drying area is partitioned into individual beds about 20 ft. by 100 ft. or other convenience size so that one or two beds will be filled by a normal withdrawal of sludge from digestors. Open beds are used where adequate area is available in sufficiently isolated areas to avoid complaints caused by occasional odors. Covered beds with greenhouse type of enclosure are used where it is necessary to dewater sludge continuously throughout the year regardless of the weather.

Sludge dewaterers by drainage through the sludge mass and supporting sand and by evaporation. Most of the water leaves the sludge by drainage; thus the provision of an adequate underdrainage system is essential. Sludge can be removed from the drying bed after it has drained and dried sufficiently to be spadable. The moisture content is about 60 to 70 percent after 10 to 15 days under favorable conditions.

Status

Drying bed is an acceptable and established dewatering technology. The disadvantage is that a long drying period implies large land area requirements.

VACUUM FILTRATION

Process Description

Vacuum is probably the most widely used method of dewatering sludge by mechanical means. A uniformly dewatered sludge cake can be produced from raw or digested sludge at any time regardless of weather conditions.

Vacuum filters are generally made of cotton, wool, nylon, dacron and other synthetic material and are available in a variety of weaves having different porosities. The performance of a vacuum filter is measured in terms of the yield of solids on a dry weight basis expressed as pounds per square foot per hour. Moisture content of the sludge cake generally ranges from 70 to 80 percent. Filters can be operated to produce a cake of 60 to 70 percent moisture content.

Status

Vacuum filtration has been used for sludge dewatering in many domestic and industrial waste treatment plants. Generally a yield of 4 - 8 pounds per square foot of filter per hour is attainable.