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ANALYSIS OF HYPOCHLORITE PROCESS
FOR REMOVAL OF HYDROGEN SULFIDE
FROM GEOTHERMAL GASES

April 1980

Work Performed Under Contract No. AC05-79ER10092

MASTER

I. Sheinbaum Co., Inc.
Pasadena, California

U. S. DEPARTMENT OF ENERGY
Geothermal Energy

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FOR REMOVAL OF
HYDROGEN SULFIDE FROM GEOTHERMAL GASES

Prepared For
THE UNITED STATES DEPARTMENT OF ENERGY

by

I. SHEINBAUM CO., INC.
Pasadena, California

April, 1980

Contract No. DE-AC05-79ER10092

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SUMMARY

Most geothermal fluids contain noncondensable gases which may include some hydrogen sulfide. When the geothermal fluid is used for the generation of electric power, the noncondensable gases are normally discharged into the atmosphere. If the noncondensable gases contain hydrogen sulfide, it must be removed before the gases can be discharged.

Sodium hypochlorite reacts readily with hydrogen sulfide to convert the sulfide ion into free sulfur in a neutral or acid solution and to the sulfate ion in an alkaline solution. Sodium hypochlorite can be generated on site by processing geothermal brine in electrolytic cells. This report is an investigation to determine if this reaction could be economically used to remove hydrogen sulfide from geothermal noncondensable gases.

An economical system to remove hydrogen sulfide would be beneficial to the developing geothermal industry. The following five alternative processes were considered for comparison with the hypochlorite process:

1. Absorption in an ethanolamine solution
2. Absorption in a caustic solution
3. Absorption in an ammonia solution and oxidation to thiosulfate
4. Absorption in an alkaline solution containing an iron catalyst with subsequent oxidation to sulfur
5. Absorption in an alkaline solution which contains anthraquinone disulfuric acid and alkali vanadates. The solution is blown with air to oxidize the sulfide to sulfur.

The first three processes were rejected because of excessive operating costs or because the process could not achieve the high air quality standards imposed by the California Air Quality Control Board. The remaining two processes, the LO-CAT Process and the Stretford Process, were selected for comparison with the hypochlorite process.

Three geothermal reservoirs were considered for evaluation: Niland KGRA, Baca KGRA, and The Geysers KGRA. Because of the wide variation in the amount of hydrogen sulfide present at The Geysers, two different gas analyses were considered for treatment.

Plants were designed to process the effluent noncondensable gases from a 10 MW_e geothermal power plant. The effluent gas from each plant was to contain a maximum hydrogen sulfide concentration of 35 ppb.

Capital costs were estimated for each of the processes at each of the four sites selected. Operating costs were also calculated for each of the processes at each of the sites. The results of these studies are shown in Tables 1 and 2.

TABLE 1
ESTIMATED PLANT COSTS

	Case 1	Case 2	Case 3	Case 4
Location	Baca	Niland	Geysers-1	Geysers-2
Hypochlorite Process	\$ 283,400	\$ 131,800	\$ 340,100	\$ 634,300
LO-CAT Process	340,300	\$ 230,100	\$ 389,410	\$ 435,090
Stretford Process	1,198,500	1,013,000	1,005,000	1,115,000

TABLE 2
ESTIMATED PLANT OPERATING COSTS

Hypochlorite Process	\$ 335,190	\$ 271,390	\$ 354,060	\$ 467,740
LO-CAT Process	351,880	293,900	368,370	416,070
Stretford Process	537,380	484,900	490,550	527,690

The hypochlorite process plant involves the lowest-initial cost in all cases except Case 4, where the high content of hydrogen sulfide necessitated a large investment in relatively low capacity electrolytic cells. Lower plant costs could probably be achieved for this case if larger cells were available.

The operating costs of the three processes shown in Table 2 indicate that the hypochlorite process is the least expensive process in all cases except Case 4. Since operating costs are related to plant cost, it is probable that a reduction in the cost of the electrolytic cells would reduce the operating cost of the hypochlorite process in Case 4 to a point where it would be competitive with the LO-CAT Process.

Our conclusion is that the hypochlorite process is a feasible process for the removal of hydrogen sulfide from geothermal noncondensable gases. The low plant cost and low operating cost of the process make it an attractive and economical process for this application.

INTRODUCTION

Most geothermal fluids contain noncondensable gases which may include some hydrogen sulfide. The amount of hydrogen sulfide present is a characteristic property of each geothermal reservoir. Where the geothermal reservoir is liquid dominated, the hydrogen sulfide is dissolved in the liquid and is vaporized with the steam when the pressure on the system is reduced. When hydrogen sulfide is present in the steam, pollution controls must be provided to prevent discharge of this toxic gas into the atmosphere.

Increasing amounts of geothermal steam are being used to generate electrical power. At The Geysers, 15 geothermal power generating units have been built. In the Imperial Valley, five different geothermal power generation units are in planning or under construction. Each new geothermal power plant must determine the quantity of hydrogen sulfide that is present in the geothermal steam and make provision for preventing its release into the atmosphere.

Most geothermal power plants generate electric power by expanding steam through a turbine which drives an electric generator. To maximize the power extracted from the steam, the steam is condensed under vacuum. Any noncondensable gases present in the steam will collect in the condenser. These gases are normally compressed to atmospheric pressure and discharged into the atmosphere. If hydrogen sulfide is present in the steam, a part of it will dissolve in the steam condensate and part will remain with the noncondensable gases.

The discharge of gases containing more than 35 ppb of hydrogen sulfide into the atmosphere is prohibited by the State of California. Therefore, noncondensable gases containing hydrogen sulfide must be treated to remove this pollutant. Many of the conventional processes for removing hydrogen sulfide from gaseous streams cannot achieve the degree of purity required by the State of California. This report investigates the feasibility of using a solution of sodium

hypochlorite to remove hydrogen sulfide from geothermal gases and compares the process with two alternative processes for removing hydrogen sulfide.

Various methods of removing hydrogen sulfide have been tried. At The Geysers, about two-thirds of the hydrogen sulfide present in the steam is dissolved in the steam condensate which is used for makeup to the cooling tower. Some of this hydrogen sulfide is stripped from the cooling water in the tower and released into the atmosphere. A test program initiated by Pacific Gas and Electric Company investigated the following methods of treating the cooling water (9):

1. Direct injection of sulfur dioxide and air into the cooling water to oxidize the H_2S to sulfur by the reaction:

2. Simultaneous injection of sulfur dioxide and air into the cooling water to promote oxidation;
3. Addition of a metal catalyst, iron, to the cooling water to promote direct oxidation of the H_2S to sulfur by the oxygen dissolved in the cooling water in accordance with the following reaction:

4. Addition of Cataban, a chelated iron compound to catalyze the oxidation of H_2S .

Of these four procedures, the addition of an iron catalyst to the water was selected as the best method of treating the cooling water. However, the treatment caused rapid corrosion of plant facilities.

To remove H_2S from the noncondensable gases, PG&E investigated the following processes:

- 1) Burning the H_2S in the noncondensable gases to SO_2 and absorbing the SO_2 that is formed in the cooling water.
- 2) Scrubbing the noncondensable gases with a water solution containing a metal catalyst to promote the conversion of H_2S to sulfur.

The first process would be too expensive to operate and the second process did not achieve complete removal of hydrogen sulfide.

As a result, both procedures were dropped from further consideration. Recently, PG&E has elected to install three gas treating units which employ the Stretford Process to remove hydrogen sulfide from the noncondensable gases.

The Stretford Process facilities for the removal of hydrogen sulfide are complex and costly. However, the process is effective and achieves essentially complete removal of hydrogen sulfide. Complete removal of hydrogen sulfide can also be achieved by scrubbing the gases with a solution containing sodium hypochlorite. This study has been conducted to determine if sodium hypochlorite scrubbing would be a viable alternative for removing hydrogen sulfide from geothermal noncondensable gases.

THE HYPOCHLORITE PROCESS

Figure 1 is a process flow diagram which shows how the hypochlorite process can be used to remove hydrogen sulfide from the noncondensable gases. A solution of sodium chloride in water is electrolyzed to produce a dilute solution of sodium hypochlorite. The chemical reactions which occur are as follows:(10)

At the anode

At the cathode, two reactions are possible:

When the cathode fluid mixes with the anode fluid, the following reactions take place:

The following equation may be written to describe the net reaction:

The solution does not need to be alkaline for the reaction to occur and the formation of sodium hypochlorite does not change the pH of the solution. The NaClO that is produced in this manner is used as it is produced so that no degradation of the hypochlorite will occur in storage. The freshly formed hypochlorite solution flows from the cell into a low pressure bubble tray type contactor where the geothermal noncondensable gases are intimately contacted with the solution. The hypochlorite reacts rapidly with the hydrogen sulfide.

Two reactions can occur. If the solution is alkaline and if an excess of hypochlorite is available, it can oxidize the hydrogen sulfide to H_2SO_4 by the reaction:

SCRUBBING COLUMN
30" Ø X 18' T-T

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HYPOCHLORITE PROCESS FLOW DIAGRAM DEPARTMENT OF ENERGY	
FIGURE 1	
SHEET NO.	OF

However, if the solution is neutral or acidic and if only a limited amount of hypochlorite is available, the hydrogen sulfide is oxidized to sulfur and water as shown in the following equation:

By controlling the pH of the solution and the concentration of oxidizer, the second reaction will predominate and most of the hydrogen sulfide can be converted to free sulfur (7).

The sodium chloride brine used to produce the sodium hypochlorite can be obtained by mixing salt and water. In some areas, the geothermal brine will have a high concentration of sodium chloride, and it may be possible to use this material to generate the hypochlorite.

The sodium chloride stream can be recycled through the electrolytic cell or it can be discarded with the cold geothermal brine.

The sulfur that is produced in this process would be filtered from the solution. If any market for the material can be found, the cost of handling will probably offset any profit realized from its sale.

The hydrogen that is produced is normally vented to the atmosphere. However, in a plant treating large quantities of hydrogen sulfide, the amount of hydrogen produced might justify collecting and purifying it. In a power plant, it could be used as a makeup gas for the generator cooling system.

SELECTION OF GEOTHERMAL RESERVOIRS

Four geothermal fluids having varying amounts of hydrogen sulfide were selected for comparison of the hypochlorite process.

A review was made of available information on noncondensable gases present in geothermal steam. Gas analyses were obtained for the KGRA's at Baca, NM; Niland, CA; Heber, CA; The Geysers, CA; Beowawe, ID and Raft River, ID. The Heber site was rejected because there was only a trace of noncondensable gas present in the steam. Raft River was rejected because there was no hydrogen sulfide present. The Beowawe Reservoir and the Niland Reservoir produced about the same quantities of H_2S . The Beowawe case was not considered further because the low temperature of the steam made this KGRA unlikely to be used for power generation.

Noncondensable gases from the three remaining KGRAs, Baca, Niland and The Geysers, were used in the comparison. These reservoirs have a wide variation in amounts of noncondensable gas and hydrogen sulfide present. The Niland Reservoir has a minimum amount of hydrogen sulfide present in a relatively large quantity of noncondensable gas. The Baca Reservoir has an intermediate quantity of hydrogen sulfide present in the same quantity of noncondensable gas. The hydrogen sulfide present in The Geysers steam varies from 2% to 8% by weight of the noncondensable gases present. The amount of noncondensable gas at The Geysers is significantly less than at the other two reservoirs. Two cases were selected for analysis from this reservoir: the first case considered an average gas containing 2.3 weight percent hydrogen sulfide and the second case contained 5 weight percent hydrogen sulfide. The four cases studied are representative of most commercial geothermal resources. Table 3 shows the concentrations and compositions of the noncondensable gases, the quantity of gas that must be processed and the amount of hydrogen sulfide to be removed at each of the three sites.

The reservoirs at Baca and Niland are liquid dominated reservoirs, whereas at The Geysers, the reservoir is vapor dominated. Figure 2

TABLE 3

CASE STUDIESNONCONDENSIBLE GASES FROM A 10MW POWER PLANT

Geothermal Reservoir	Case 1 <u>Baca(5)</u>	Case 2 <u>Niland(2)</u>	Case 3 <u>Geysers(1)</u>	Case 4 <u>Geysers (1)</u>
<u>NC Gas in Steam Wgt. %</u>	3.0	2.3	1.0	1.0
<u>Gas Composition, Wgt. %</u>				
CO ₂	99.07	99.55	83.9	81.2
H ₂ S	.72	.064	2.3	5.0
N ₂	.20	.057	2.6	2.6
H ₂	.01	.027	0.9	0.9
NH ₃	-----	-----	4.6	4.6
CH ₄	-----	.298	5.7	5.7
NC Gas Rate #/Hr.	5750	5610	1900	1900
Hydrogen Sulfide #/Hr.	41	4	44	95

is a process flow diagram showing a 10MW hydrothermal power plant designed to convert geothermal energy into electrical power. The plant is typical of a plant that would be built at either Baca or Niland. Material balances for both sites are shown on this diagram. Figure 3 is a process flow diagram and material balance for a 10MW power-generating facility at The Geysers.

ALTERNATIVE METHODS OF REMOVING HYDROGEN SULFIDE

The following alternative processes were considered for comparison with the hypochlorite process:

- 1) Absorption of hydrogen sulfide in a water solution of mono- or diethanolamine
- 2) Absorption of hydrogen sulfide in a caustic solution
- 3) Partial oxidation of the hydrogen sulfide and reaction with ammonia to form ammonium sulfite and bisulfite which is oxidized to ammonium thiosulfate
- 4) Absorption of hydrogen sulfide in an alkaline water solution containing an iron catalyst which promotes the oxidation of the H_2S to sulfur. This process is a proprietary process called the LO-CAT Process.
- 5) Absorption of hydrogen sulfide in an alkaline solution which contains the sodium salts of anthraquinone disulfonic acid and alkali vanadates. The sulfide is oxidized by the vanadium oxide to form free sulfur. The solution is blown with air to oxidize the vanadium. This process is a proprietary process called the Stretford Process.

ETHANOLAMINE ABSORPTION

Carbon dioxide is normally the predominant noncondensable gas present in geothermal fluids. This gas reacts with water to form carbonic acid, which is absorbed by the ethanolamines. In order to achieve complete removal of the hydrogen sulfide, the acid gas absorption systems must be designed with enough capacity to absorb

V-1
KNOCK OUT DRUM

T-1
TURBINE

G-1
GENERATOR

E-1
SURFACE CONDENSER

CT-1
COOLING TOWER

	1	2	3	4	5			
FLUID	STEAM	CONDENSATE	NC GAS	VENT GAS	SULFUR			
FLOW, LB./HR.	190,000	189,400	2,500	1,950	95			
STEAM, LB./HR.	188,100	-	600	50	-			
NC GAS, LB./HR.	1,900		1,900	1,900	-			
TEMP °F	320	100	100	110	110			
PRESS, PSIA	113	1.99	15.7	14.7	-

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10 MW. POWER PLANT GEYSERS, CA. DEPARTMENT OF ENERGY	
FIGURE 3	
SHE. NO.	OF SHE.

both gases. This increases both the capital cost and the operating cost of the system. The amine absorption fluid must be regenerated and the H_2S which is released must be converted to sulfur using the Claus process, or reacted with an alkali such as sodium hydroxide. Either procedure adds to both plant and operating cost. Further, the amine absorption system cannot absorb enough H_2S to meet California Air Purity requirements. For these reasons, amine absorption was not considered further.

CAUSTIC ABSORPTION

Absorption of the acid gases by caustic results in the formation of the alkali sulfide, bisulfide and carbonate. If sodium hydroxide is used as the reactant, the cost of the chemical reagent would be excessive. If calcium hydroxide is used to react with the acid gases, the products of the reaction would be insoluble calcium carbonate together with soluble sulfides and acid sulfides. These sulfides cannot be safely discharged into any waterway, since if the stream were acidified, hydrogen sulfide would be released and would present a toxic hazard. If oxidation of the sulfides occurs, the product would be insoluble calcium sulfate.

The problems created by the products of the reaction between the caustic and the hydrogen sulfide and carbon dioxide make this method of treating noncondensable gases undesirable.

THE AMMONIUM THIOSULFATE PROCESS (ATS)

Figure 4 is a process flow diagram of the ATS Process which has been used effectively to control air pollution from Claus sulfur plants. The noncondensable gas containing H_2S is partially oxidized to SO_2 in a burner and excess heat is recovered in a waste heat boiler. The sulfur compounds out of the boiler are absorbed in a dilute aqueous solution of ammonia. Anhydrous ammonia is added to maintain the strength of the ammonia solution. The ATS process converts the absorbed sulfites and bisulfites into ammonium thiosulfate, which is sold as a commercial fertilizer. Tail gases from this plant

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ATS UNIT
PROCESS FLOW DIAGRAM
DEPARTMENT OF ENERGY

FIGURE 4

must be incinerated to convert the residual H_2S to SO_2 . This process was not investigated in detail because a preliminary cost comparison with alternative processes indicated that this process would not be competitive.

THE LO-CAT PROCESS

Figure 5 is a process flow diagram of another process which can be used to absorb hydrogen sulfide in the presence of carbon dioxide. The process is licensed by Air Resources, Inc. under the name of LO-CAT. This process absorbs the hydrogen sulfide in an alkaline solution containing an organometallic iron compound. The sulfide is oxidized to sulfur by blowing air through the solution and is removed by settling or filtration. The used absorption solution and the products are non-toxic and can be used as a soil supplement.

This process reduces the level of hydrogen sulfide in the effluent gases to levels of about 5 ppm. Final removal of hydrogen sulfide can be accomplished by increasing the circulation of solution and the size of the absorber, or by adding a small potassium permanganate scrubber to remove the residual H_2S . In this study, potassium permanganate scrubbers were used in all cases because they required the lowest capital and operating cost.

THE STRETFORD PROCESS

Figure 6 is a process flow diagram of the Stretford Process. This process has been successfully used for the absorption of hydrogen sulfide from refinery gases, synthesis gas, natural gas and is presently being used to remove hydrogen sulfide from geothermal noncondensable gases at The Geysers. Hydrogen sulfide is absorbed in an alkaline solution which contains the sodium salts of anthraquinone disulfonic acid and alkali vanadates. The equations for the process are:

The solution is blown with air to oxidize the vanadium to the penta-

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LO CAT PROCESS FLOW DIAGRAM DEPARTMENT OF ENERGY		
		SHEINBAUM FIGURE 5
DRY NO	OF	SHOTS

ABSORBER
42" ϕ x 70' T-T

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STRETTFORD PROCESS
FLOW DIAGRAM
DEPARTMENT OF ENERGY

FIGURE 6

valent state. The process achieves essentially complete removal of hydrogen sulfide from the gas, even in the presence of carbon dioxide.

The sulfur is aerated during the blowing process and is removed from the vessel as a froth. The froth is pumped to a melter where the sulfur is liquified and separated from the water phase. The sulfur product is stored and shipped from the plant as a liquid.

The LO-CAT Process and the Stretford Process were selected for comparison with the hypochlorite process because they are reliable processes capable of reducing the hydrogen sulfide in the effluent gases to the requisite level. They can be operated without using excessive amounts of absorbent and without producing excessive amounts of waste products.

DESIGN BASIS

This study is based on a 10MW geothermal power plant. This size plant is capable of supplying a small town with power and might be installed in a remote area which was located relatively close to a suitable geothermal reservoir. Geothermal power plants are limited in size because of the extensive surface piping that is required to collect the geothermal fluid from the wells and to redistribute the spent fluid to the reinjection wells. To avoid excessive heat losses from the collecting pipelines, geothermal power plants must be significantly smaller than conventional coal or oil fired power plants.

An economical process for the treatment of noncondensable gases to remove hydrogen sulfide should have the following characteristics:

1. Minimum plant cost
2. Low operating cost
3. The quantities of chemicals required to treat the gases should be low
4. The waste materials produced by the process should be non-polluting and the quantity of waste material should be low

To compare these three processes, we have assumed that the non-condensable gases shown in Table 1 are available at the plant limit at a pressure of 1 PSIG and a temperature of 120°F. Each process must reduce the H_2S in the effluent gas to a level of 35 ppb.

The electric power generating facility is assumed to be the same in each case and consequently, it will have no effect on the comparison of the three processes. As a basis for comparison of utility costs, the cost of electric power is assumed to be 20 mils/kWh.

Geothermal steam will be used for heating of process fluids. Based on Reference (6), steam can be obtained from a liquid dominated reservoir at a cost of 50¢/1,000 lbs. The cost of steam from a vapor dominated reservoir would be slightly less.

The quantity of sulfur produced in these plants is small and

consequently no credit has been taken for the sulfur that is recovered. An operating factor of 80% was used to calculate the utilities and chemical consumption of the individual plants.

ECONOMIC COMPARISON

To compare the three processes at the three sites, it is necessary to complete the following steps:

1. Prepare estimates of the sulfur treating plant costs at each of the three sites for each process
2. Prepare operating and maintenance costs for each process at each site. Included in these costs will be the direct processing costs, fixed charges, administrative expenses, plant overhead costs and financing costs.

PLANT COSTS

The plant costs used in this report are based on estimated costs from the companies which sell or license the different processes. Where actual plant costs were available, these values were factored to a 10MW capacity based on the 0.6 power of the actual plant capacity.

Plant costs for the LO-CAT Process were obtained from the licensor and corrected for additional equipment needed to meet the process requirements. The costs of the electrolytic cells required to produce sodium hypochlorite were obtained from manufacturers of the hypochlorite units. The costs of added equipment required for the hypochlorite process were obtained by telephone estimates of equipment costs. Plant costs for the Stretford Process were not obtainable from process licensors, but were obtained by factoring actual plant costs at The Geysers. The plant costs for the three processes are tabulated in Table 4.

TABLE 4

SUMMARY OF PLANT COSTS

<u>Process</u>	<u>Case 1</u>	<u>Case 2</u>	<u>Case 3</u>	<u>Case 4</u>
Hypochlorite	\$ 283,400	\$ 131,800	\$ 340,100	\$ 634,300
LO-CAT	340,300	230,100	389,410	435,090
Stretford	1,198,500	1,013,000	1,115,000	1,005,000

PLANT OPERATING COSTS

The operating costs used in this report were calculated as discussed in the following paragraphs:

Direct Operating Costs:

1. Manpower

It was assumed that each hydrogen sulfide removal plant would require one operator per shift to operate the plant. On this basis, the labor costs for all the plants are identical. The estimated manpower costs include supervisory labor necessary to operate each plant. The costs represent operating personnel only and do not include maintenance labor and overhead personnel.

2. Maintenance

The average annual cost of labor, materials and supervision for maintenance is estimated to be 4% of the initial capital investment. This is an amount sufficient to keep the plant in good operating condition. Actual costs may be slightly lower during the first years of operation when equipment is new.

3. Chemicals

The costs allotted under this heading include chemical and catalysts required for plant operation. Costs are based on 1980 listed prices for industrial grade chemicals.

No chemical costs are shown for the hypochlorite plants at Baca and Niland since these plants would utilize the geothermal brine as a raw material from which the hypochlorite solution would be made. At The Geysers, the brine solution would be recirculated and only a minimum amount of makeup would be required. Used solution would be reinjected in the reservoir with the geothermal brine.

The sulfur produced at these plants is a crude product that has relatively little value. No credit was taken for the sulfur product. No credit has been taken for the hydrogen that is produced in the hypochlorite process.

4. Utilities

The major utility cost in these plants is the cost of electric power which is being generated at the site. Power that is used with-

in a power generation plant should not be subject to a transmission charge and should not be expected to make a profit for the utility. It should be available at a cost that is less than the cost of commercial power. A cost of 20 mils/kWh was used for the power consumed in the plants.

Geothermal steam can be produced at a cost of \$0.50/1,000 lbs. (6). This figure was used for the steam consumed by the Stretford plant.

Fixed Charges:

1. Capital Costs

To establish a capital cost for each of these plants, it was assumed that the funds to build the plant were borrowed at 10% interest.

2. Depreciation

Depreciation is calculated, based on a 15-year life, using straight line book depreciation.

3. Local Taxes and Insurance

The annual cost of local property taxes and insurance is taken to be 2.5% of the initial capital investment.

4. General and Administrative

These costs include such items as sales, research and development, governmental relations, legal, accounting and other services in the home office allocated to this activity. The annual cost is estimated to be 1% of initial capital investment.

5. Overhead

This is the plant burden cost and is estimated to be 100% of the operating manpower. It includes all costs associated with the operation of the plant and not otherwise accounted for.

The cost of land was assumed to be the same for each plant, and therefore was not included in the estimated cost. Royalty costs are included in the individual plant costs.

Operating costs for the three different processes are shown in Tables 5, 6, and 7.

TABLE 5

HYPOCHLORITE PROCESS
ANNUAL OPERATING COSTS

<u>Direct Costs</u>	<u>Case 1</u>	<u>Case 2</u>	<u>Case 3</u>	<u>Case 4</u>
Labor	\$118,260	\$118,260	\$118,260	\$118,260
Maintenance @ 4%	11,330	5,270	13,600	25,370
Chemicals	-----	-----	3,920	7,830
Utilities	30,200	3,020	32,240	70,100
 <u>Fixed Charges</u>				
Capital (10%)	28,340	13,180	34,010	63,430
Depreciation	18,890	8,790	22,670	42,290
Taxes and Ins. (2.5%)	7,080	3,290	8,500	15,860
G & A (1%)	2,830	1,320	3,400	6,340
Overhead	<u>118,260</u>	<u>118,260</u>	<u>118,260</u>	<u>118,260</u>
 ANNUAL OPERATING COST TOTAL	 \$335,190	 \$271,390	 \$354,860	 \$467,740

TABLE 6

LO-CAT PROCESSANNUAL OPERATING COSTS

<u>Direct Costs</u>	<u>Case 1</u>	<u>Case 2</u>	<u>Case 3</u>	<u>Case 4</u>
Labor	\$118,260	\$118,260	\$118,260	\$118,260
Maintenance @ 4%	13,610	9,200	15,580	17,400
Chemicals	29,500	3,300	32,450	26,000
Utilities	4,810	616	5,300	10,650
 <u>Fixed Charges</u>				
Capital (10%)	34,030	22,100	38,940	42,610
Depreciation	22,690	14,740	25,960	28,410
Taxes and Ins. (2.5%)	8,510	5,420	9,730	10,650
G & A	3,310	2,210	3,890	5,810
Overhead	<u>118,260</u>	<u>118,260</u>	<u>118,260</u>	<u>118,260</u>
 ANNUAL OPERATING COST TOTAL	 \$351,880	 \$293,900	 \$368,370	 \$416,070

TABLE 7

STRETFORD PROCESS
ANNUAL OPERATING COSTS

<u>Direct Costs</u>	<u>Case 1</u>	<u>Case 2</u>	<u>Case 3</u>	<u>Case 4</u>
Labor	\$118,260	\$118,260	\$118,260	\$118,260
Maintenance @ 4%	47,940	40,250	40,200	44,600
Chemicals	4,710	1,600	5,200	10,920
Utilities	6,520	2,030	5,960	10,800
 <u>Fixed Charges</u>				
Capital	119,850	101,300	100,500	111,500
Depreciation	79,900	67,530	67,000	74,330
Taxes and Ins. (2.5%)	29,960	25,300	25,120	27,870
G & A	11,980	10,100	10,050	11,150
Overhead	<u>118,260</u>	<u>118,260</u>	<u>118,260</u>	<u>118,260</u>
 ANNUAL OPERATING COST TOTAL	 \$537,380	 \$484,900	 \$490,250	 \$527,690

EVALUATION

1. Capital Cost of Facilities

The cost of each of the plants studied is influenced by (1) the quantity of hydrogen sulfide to be removed; (2) the volume of non-condensable gas to be processed, and (3) whether or not ammonia is present in the gas to be treated.

The hypochlorite process is primarily affected by the quantity of H_2S to be removed. The major capital cost of the plant is the electrolytic cell assembly, which must increase proportionately with the quantity of hydrogen sulfide to be reacted.

The presence of ammonia in the gas could also affect the plant cost, as the ammonia molecule is readily oxidized by sodium hypochlorite. However, at The Geysers, the major noncondensable gas is carbon dioxide, which will dissolve in the condensate and stabilize the ammonia in solution as the bicarbonate. As a result, very little ammonia will be present in the gas phase. The amount that is present should not have a significant effect on the hypochlorite requirements of the system.

The Stretford Process is primarily affected by the first two factors. Cases 1 and 2 have similar volumes of gas to be treated. Therefore, there is little saving in Case 2, although the quantity of hydrogen sulfide treated is much less. Case 3 has an intermediate quantity of hydrogen sulfide, but the quantity of gas is about half the quantity in Cases 1 and 2. In Case 4, the quantity of gas is the same as in Case 3, but the hydrogen sulfide content is much higher, resulting in a plant cost that is comparable to Case 1.

The LO-CAT Process is primarily affected by the quantity of sulfur to be removed and to a lesser extent by the quantity of gas being processed. The presence of ammonia should not affect the process.

The initial cost of the hypochlorite plant equipment is less than the cost of either the Stretford Process or the LO-CAT Process equipment in Cases 1, 2 and 3.

In Case 4, which has a relatively large quantity of hydrogen sulfide to process, the cost of the hypochlorite plant is slightly greater than the LO-CAT plant, but is significantly less than the Stretford plant cost. The high cost of the hypochlorite plant in this case is probably due to the fact that the electrolytic cells presently available have been developed for processes requiring limited amounts of hypochlorite. The plant design was based on the use of several small units. It is probably that larger cells could be developed that would reduce the cost for such a plant.

2. Operating Costs

The utility costs presented in the previous section are based on the electric power use tabulated in Table 8. The electric power consumption of the hypochlorite plant is higher than either the LO-CAT Process or the Stretford Process because of the power consumption of the cells used to generate the hypochlorite solution. The cost of power for the hypochlorite process is comparable to the cost of catalysts and chemicals required for the other two processes.

The cost of producing sodium hypochlorite varies depending on the raw materials and on the cost of electric power. If salt costs 2¢/lb., water costs 0.03¢/gal. and power costs 20 mils, cost to produce enough hypochlorite to react with one pound of hydrogen sulfide would be \$0.25. However, if a geothermal brine is used to make the sodium hypochlorite solution, the cost would be reduced to \$0.11.

The operating cost of the hypochlorite unit is strongly affected by the cost of electric power. The assumed cost of 20 mils/kWh is lower than some sources indicate that geothermal power will cost. (6). However, operating data from The Geysers indicate power costs of 4.2 mils/kWh in 1976 and a predicted cost of 18.03 mils/kWh in 1980(8). Since the major operating costs are labor and capital oriented, the cost of power could increase considerably without affecting the relative operating costs of the three processes. If the cost of power were increased to 30 mils/kWh, plant operating costs would be increased to the values shown in Table 9.

TABLE 8

ELECTRIC POWER USE

	Case 1	Case 2	Case 3	Case 4
	<u>KW</u>	<u>KW</u>	<u>KW</u>	<u>KW</u>
<u>Hypochlorite Process</u>				
Electrolytic Cells	215	21	230	499
Circulating Pump	<u>.5</u>	<u>.5</u>	<u>.5</u>	<u>1</u>
	215.5	21.5	230.5	500
<u>LO-CAT Process</u>				
Circulating Pumps	27	3.5	30	61
Blower	<u>7.3</u>	<u>.8</u>	<u>7.8</u>	<u>15</u>
	34.3	4.3	37.8	76
<u>Stretford Process</u>				
Pumps	24	10	20	38
Blower	7.5	1.5	7.5	15
Agitators	<u>15</u>	<u>3</u>	<u>15</u>	<u>24</u>
	46.5	14.5	42.5	77

TABLE 9

ANNUAL OPERATING COSTS USING 30 mil POWER

<u>PROCESS</u>	<u>Case 1</u>	<u>Case 2</u>	<u>Case 3</u>	<u>Case 4</u>
Hypochlorite	\$350,290	\$272,900	\$370,980	\$502,790
LO-CAT	354,290	294,210	371,020	421,400
Stretford	540,640	485,915	490,550	533,090

The electric power required for the hypochlorite process was calculated based on the oxidation of hydrogen sulfide to sulfur. Considerably more power would be required if the hydrogen sulfide were oxidized to sulfate. By maintaining the pH of the solution in a neutral or acid condition, the primary product will be sulfur (7). However, laboratory tests should be performed to determine the optimum pH and hypochlorite concentration for maximum production of sulfur.

The total operating costs of the hypochlorite process are slightly less than the operating costs of the LO-CAT Process in Cases 1, 2 and 3, and greater in Case 4. Since operating costs are related to plant cost, it is probable that a reduction in the cost of the electrolytic cells would reduce the operating cost of the hypochlorite process in Case 4 to a point where it would become competitive with the LO-CAT Process.

The operating costs of the Stretford Process are 20% to 90% greater than the hypochlorite process in all cases.

Utility and chemical requirements for the LO-CAT and the hypochlorite processes were obtained from the vendors of the processes. Utilities for the Stretford Process were obtained from Pacific Gas & Electric Company and from references (3) and (4).

CONCLUSIONS AND RECOMMENDATIONS

The following conclusions have been reached as a result of this study:

1. The hypochlorite process is a feasible alternative to the Stretford Process for removing hydrogen sulfide from geothermal noncondensable gases.
2. The low plant cost and operating cost of the hypochlorite process make it an attractive and economical process for treating moderate quantities of hydrogen sulfide.
3. Where the concentration of H_2S is high, the plant cost and the operating cost of the hypochlorite process exceeds the plant and operating costs of the LO-CAT Process, but is significantly lower than the plant and operating costs of the Stretford Process.

This investigation has demonstrated that the oxidation of hydrogen sulfide by an electrolytic hypochlorite solution is feasible and economical when the product of this reaction is free sulfur. Further laboratory tests should be performed to determine the optimum pH and hypochlorite concentration for the conversion of the hydrogen sulfide to free sulfur. Following the laboratory test program, a pilot unit should be built and performance-tested, using geothermal fluids to form the hypochlorite solution and using this solution to remove hydrogen sulfide from the noncondensable gases.

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