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**AN EXPERIMENTAL STUDY OF ELECTRON BEAM INDUCED
REMOVAL OF H₂S FROM GEOTHERMAL FLUIDS**

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AN EXPERIMENTAL STUDY OF
ELECTRON BEAM INDUCED REMOVAL OF H₂S
FROM GEOTHERMAL FLUIDS

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ABSTRACT

Electric generating stations powered by geothermal steam release hydrogen sulfide fumes. This H_2S must be removed from the steam, upstream of the turbine, or from the non-condensable fraction of the steam, downstream of the turbine. Chemical approaches now in use lack the capability of upstream treatment, and chemical costs associated with the processes limit their attractiveness. The treatment of geothermal steam by electron beam irradiation is a potential alternative method of H_2S removal which can be applied upstream or downstream and has no chemical requirements.

The experimental work reported here examines the effectiveness of electron beam treatment of geothermal fluids. These fluids are produced by combining the constituents in a heated cell, which contains an electron beam transparent window. Irradiation of the contents and subsequent chemical analysis allows an evaluation of effectiveness. These results are used for a commercial feasibility assessment.

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1.0 SUMMARY

This report discusses the results obtained from the electron beam irradiation of sample mixtures of gases approximating geothermal fluids in composition. The purpose of these experiments was to assess the feasibility of removing hydrogen sulfide from geothermal steam and off gases by means of electron beam treatment. The electron beam irradiation of steam and other gases containing parts per million by volume (ppm) levels of H_2S was expected to produce ions, radicals and free atoms in the gaseous phase which would in turn react with the H_2S .

In August, 1981, the Geothermal Energy Division of the U.S. DOE contracted with Cottrell Environmental Sciences to conduct a laboratory study of this technique. The experiments were conducted at the Ion Physics Company, where the electron beam devices were located.

The testing consisted of irradiating gas mixtures contained in liter sized containers with electron beams. The gas mixtures were composed of 100 to 10,000 ppm H_2S in steam and in CO_2 , representative of geothermal fluid upstream of a turbine and downstream of

a condenser, respectively. Additional tests were made with ppm levels of H_2S in air. The gas irradiation cells were stainless steel pressure vessels equipped with titanium foil electron beam windows. Parameters varied were radiation dose, H_2S concentration, gas pressure and temperature.

The H_2S removal depended primarily upon the absorbed radiation dose, and this relationship was linear. It was found that the yield of H_2S removed in air per unit of absorbed radiation was substantially lower than that achieved by another study, but the yield could be predicted by a proposed reaction scheme. The yield of H_2S removal in steam was less than half the yield achieved when air or CO_2 were used as dilution gases. The reason for this appears to be a temperature enhanced back reaction.

Because of low yield, the energy required for H_2S removal from geothermal steam would be too large to allow commercial application at an electric generating station. The higher yields associated with the removal of H_2S from a CO_2 background would permit the commercial application of this method for the removal of H_2S from the non condensible gases following a surface condenser.

2.0 CONCLUSIONS

2.1 Electron beam irradiation will destroy ppm levels of H_2S contained in gases such as steam, CO_2 and air.

2.2 The amount of H_2S destroyed is proportional to absorbed radiation dosage and independent of H_2S concentration.

2.3 The yield of H_2S destroyed versus absorbed dosage is 1 molecule/100 eV in steam, 3.5 molecules/100 eV in CO_2 , and 5.0 molecules/100 eV in air.

2.4 The low yield of H_2S destruction in steam precludes the commercial application of this technique for H_2S removal upstream of a steam turbine.

2.5 The yield of H_2S destruction in CO_2 indicates commercial feasibility for removal of H_2S from the noncondensable fraction of geothermal stream, downstream of a turbine.

3.0 INTRODUCTION

Geothermal steam is nearly universally contaminated with ppm levels of hydrogen sulfide. In recent years strict emission controls have been set in the California area to limit emissions of H_2S . Several processes have been evaluated and in fact are operating at The Geysers plant of Pacific Gas and Electric. Most of these process approaches are restricted to treating the geothermal steam at conditions downstream of the turbine. Further, chemical additives are generally required for the conversion of H_2S , and sometimes for the regeneration of the sulfur containing product.

An H_2S conversion technique based on the use of electron beam treatment offers a potentially attractive alternative to conventional chemical processing schemes.

The notion of using high velocity electrons from man-made accelerators to initiate chemical destruction of H_2S in geothermal steam is based on work reported by Wiesbock and Proksch¹. The authors used 500 keV electrons, to destroy H_2S in undried air at initial H_2S concentrations of 0.1 to 0.6% by volume. Reaction products were not studied extensively but H_2O , SO_2 , SO_3 and

elemental sulfur were identified. The yield of H_2S destruction was determined to be 22 molecules per 100 eV of absorbed energy which is encouraging, since it indicates that only modest amounts of power need be consumed in the H_2S conversion process.

Several aspects of electron treatment are appealing from an applications standpoint. Advantages of electron utilization in an H_2S removal process for geothermal steam upstream of the turbine are listed below:

- o No chemical additives
- o Equipment similar to that which would be required for geothermal applications exists and has proven industrial reliability.
- o Electron beam machines have about an 80% conversion efficiency of input power to beam power.
- o Hands-off operation.
- o Instant start-up and shut-down.
- o Output can be regulated and slaved to some flow stream parameter.
- o E-Beam treatment for H_2S conversion can be readily backfitted in exiting plants.

Pursuant to the objective of evaluating the electron beam as a method for H_2S conversion, an experimental system was designed in which small quantities of steam with geothermal properties were manufactured in the laboratory. The steam, contained in small stainless steel vessels, was irradiated by electron beam and subsequently subjected to chemical analysis in order to determine percent H_2S conversion and reaction products. Steam constituents were varied as well as electron beam energy input so that the effects of these parameters on H_2S conversion could be determined.

The data resulting from these tests serves as a basis for the determination of commercial feasibility of the technique. Of particular importance is the G-value, or yield, which for economic projections is inversely proportional to the amount of electrical energy required for H_2S removal. A high G-value, such as that obtained by Wiesbock and Proksch for H_2S -air mixtures, would yield encouraging economic forecasts.

In addition to the removal of H_2S from geothermal steam upstream of the turbine, an E-Beam can remove H_2S from the non-condensable gases downstream of the turbine. This gas is primarily an H_2S - CO_2 mixture. Controlling H_2S downstream of the turbine is the conventional method, and absorption of H_2S by a

caustic is the most often used technique. The advantages of electron beam utilization on this application are the same as those already listed for the upstream application.

The evaluation of H_2S removal from CO_2 was done by the same methods as used for H_2S -steam mixtures, i.e., the mixtures were irradiated while contained in a small, stainless steel vessel. Also, as for the H_2S -steam mixtures, economic feasibility is determined by the G-value.

4.0 APPARATUS

4.1 Reaction Cells

Experimental chamber #1 is a cylinder, 15 cm in diameter and 14 cm long. A schematic of this chamber and its positioning relative to the FX-35 E-Beam machine is shown in Figure 4.1-1. Construction is all of 316 stainless steel, except for a titanium foil window at one end. In order for the 2 mil titanium window to withstand the steam pressures, it is backed up with a 90% open steel grid. Six 0.8 cm diameter steel tubes around the periphery of the cylindrical body provide access to the interior for filling and removing samples and/or pressure and temperature instrumentation. Resistance heaters, wrapped around the outside of the cylinder provide the heat needed to generate steam within the cylinder. Figure 4.1-2 is a photograph of the chamber, mounted on the FX-35, with the back wall removed. The interior of the chamber and the titanium window at the back can be seen. The pressure gauge can be seen as well as a thermocouple extending downward to approximately the middle of the chamber. Figure 4.1-3 shows the cell fully assembled.

FIGURE 4.1-1
2.6 LITER REACTION CELL

FIGURE 4.1-2

2.6 LITER CELL WITH BACK PLATE REMOVED

FIGURE 4.1-3
FULLY ASSEMBLED 2.6 LITER CELL

Filling the chamber with gas mixtures consists of first filling small, intermediate sample bottles with given amounts of each gas constituent. These intermediate 10 and 25 ml steel bottles are filled by using the gas mixing manifold shown in Figure 4.1-4 and 4.1-5. The sample bottles to be filled are connected to the manifold by means of gas-tight, quick disconnect fittings. The system, including the sample bottles, is evacuated. The gas of interest, usually H_2S , is then introduced into the manifold and sample bottles and allowed to equilibrate at a pressure which fills the bottles with the desired amount of the gas. The bottle valves are then closed and the bottles disconnected from the manifold.

Another procedure is used when the bottles must be filled with the amount of water necessary to produce the steam conditions needed within the chamber. In this case the bottles are first filled with nitrogen at one atmosphere. Water is then forced in at a pressure such that the mixture of liquid water and compressed nitrogen yields the required amount of water. As a check the sample bottle is weighed before and after filling.

FIGURE 4.1-4
GAS MIXING MANIFOLD

FIGURE 4.1-5
GAS MIXING MANIFOLD IN LAB

The gas and water filled sample bottles are attached to the evacuated reaction chamber by means of quick disconnects. The gas sample bottle valve is opened, followed by water. If the chamber was pre-heated, the water quickly flashes to steam. The chamber is thus charged with a gas mixture and can be irradiated.

Experimental chamber #2 is a cylinder, 7 cm in diameter and 13 cm long. Construction is of 316 stainless steel, except for a titanium foil window mounted along one side and UV glass windows at each end, as can be seen in Figure 4.1-6 and 4.1-7. Four 0.8 cm steel tubes provide access to the interior of the cylinder for filling and removing samples and for pressure and temperature instrumentation. Resistance heaters, wrapped around the outside of the cell, provide the heat needed to generate steam. Figure 4.1-8 shows this cell in place under the Resotron scanner.

Two methods were used to fill this cell with gases. One method utilized intermediate sample bottles, similar to the filling technique described for Chamber #1. A second method was utilized, whereby the gases and/or liquids were introduced into the cell via a syringe and septum.

FIGURE 4.1-6
0.21 LITER REACTION CELL

FIGURE 4.1-7

ASSEMBLED 0.21 LITER CELL

FIGURE 4.1-8

0.21 LITER CELL UNDER SCANNER

4.2 Electron Beam Generators

Two electron beam devices were utilized for the test program - An Ion Physics Model FX-35, producing pulsed current, and a Resotron continuous current machine. Descriptions of these devices are as follows:

FX-35

FX-35 consists of a coaxial gas capacitor attached to the high voltage terminal of a Van de Graaff generator. The coaxial capacitor is charged to the desired voltage and then discharged into a field emission tube by a triggered spark gap switch. The voltage and current in the resulting electron beam are determined from the impedance relation between the terminal and the field emission tube. Since the system is essentially a transmission line, the pulse width is twice the transit time of a wave on the line. Therefore, a 10-ft long terminal (characteristically terminated) produces a pulse width of approximately 20 ns. The electron beam voltage varies linearly with charging voltage while the total energy stored by the system varies as the square of the charging voltage. Mean accelerating voltages from 400 keV to 2.5 MeV can be obtained. With a matched load, the current is 55 kA.

The field-emitted electron beam is transmitted through a thin foil window into a drift region where it is utilized. Geometry of the beam is controlled by pressure in the drift tube. The system is shown in Figure 4.2-1.

Because of the simplicity of the FX-35 charging and switching scheme, shot-to-shot variability in initial conditions is essentially eliminated and reproducibility on the order of 5 percent can be expected for most beam mode experiments.

Resotron

The basic system is composed of a high voltage transformer and accelerator tube. By referring to Figure 4.2.-2, the principal components that make up this combination can be seen. The outer shell is the tank. Protruding from the bottom is the tube with its flared extension and the beam window at the bottom. The transformer is made up of a primary and secondary winding. The primary, which is located at the bottom of the tank, sets up the flux which links the secondary of the transformer and thus induces the voltage in the secondary which is used for electron acceleration. The location of the secondary coils which make up the secondary winding of the transformer can be seen in the Figure.

FIGURE 4.2-1
FX-35 SCHEMATIC

FIGURE 4.2-2
RESOTRON SCHEMATIC

The filament of the tube is located at the top of the secondary winding which is the high voltage end of the transformer. The filament is excited by means of additional turns of wire at the top of the stack which also intercept the flux set up by the primary. A variable reactor is connected in series with the filament. This controls the amount of current flowing through the filament and therefore controls the number of electrons which flow in the tube. The accelerating voltage is applied to the tube from the transformer by means of contacts, which protrude from the coils and make contact with the rings which are mounted on the tube. The contacts and rings are uniformly spaced from the bottom of the secondary coil stack to the top at approximately 80 kV between each set of rings.

The entire transformer is filled with sulfur hexafluoride. The high voltage end of the transformer is covered by a brass dome which serves as the high voltage surface and is shaped in such a manner as to minimize the voltage gradient and to avoid voltage breakdowns in this area. In order to get as narrow a beam of electrons as possible at the window of the tube, a focusing coil is mounted outside the tank just below the lower surface. This is also necessary in order to scan the beam accurately.

Figure 4.2-3 shows the principle of operation of the resonant transformer. The view on the left shows a simplified physical layout which includes only the transformer, tube, and tank. The center view shows the electrical equivalent circuit and is drawn as a distributed parameter circuit where the inductance is made up of all the secondary coils which are stacked one upon the other. The surfaces of the tank and the secondary coil make up the incremental capacitances shown at left and right of the inductance. The single capacitor on top is equivalent capacity made up of the dome and the adjacent tank surface. In order to simplify analysis, the components have been lumped as illustrated in the equivalent circuit on the right. It resolves to a simple parallel LC circuit where the high voltage appears at the top of the stack. This high voltage is the voltage that appears at the cathode and filament end of the tube.

Thus the resonant transformer achieves resonance from the fact that secondary inductance in combination with the inherent capacities between the secondary and the tank, as well as the dome of the tank, becomes a resonance circuit and can be well approximated by the circuit shown on the right. This is the standard LC circuit, and its resonance or principal of resonance is well known.

FIGURE 4.2-3

RESONANT TRANSFORMER PRINCIPLES

SIMPLIFIED
PHYSICAL LAYOUT

EQUIVALENT ELECTRICAL
DISTRIBUTED PARAMETER
CIRCUIT

APPROXIMATE ELECTRICAL
EQUIVALENT CIRCUIT

Typical operational parameters used during the test program are shown below:

	FX-35	Resotron
Voltage	.8 Megavolt	2.0 Megavolt
Current	50,000 Amp	1.0 Milliamp
Dosage	1 Mrad/Pulse	4 Mrad/Minute

5.0 ANALYTICAL METHODS

5.1 Chemical Analysis

The contents of the reaction cell were forced out of the cell and through the gas washing bottle by means of a nitrogen purge. The gas sampling train consisted of one gas washing bottle containing 100 ml of SAOB(II). This purging of the reaction cell would continue for 15 minutes. The H_2S present in the gas would be absorbed by the SAOB(II), forming sodium sulfide. The occasional use of a second gas washing bottle in series showed that all H_2S was absorbed in the first bottle, since none was carried over into the second bottle.

Following the nitrogen purge, the contents of the gas washing bottle were transferred to a 150 ml beaker. The beaker was placed on a magnetic stirring plate and the contents slowly stirred. The sulfide ion was measured by a pre-calibrated sulfide ion electrode and a 901 Orion Ion Analyzer. The analysis was completed within 10 minutes following the collection of the sample.

A typical calculation is as follows:

Orion Meter Reading: 80.4 ppm

Volume of absorbing solution 100 ml

$$C_S \text{ (mg of } S^-) = (80.4/1000) \times 100 = 8.04 \text{ mg}$$

$$C_{H_2S} \text{ (mg of } H_2S) = 8.04 (34/32) = 8.54 \text{ mg}$$

A more complete description of the procedures and reagents used are given in Appendix A.3.

5.2 UV Absorption

An ultra-violet photometer was used briefly in an attempt to obtain real-time measurements of H_2S concentration during irradiation. An Anacon Model 207 Process UV Analyzer and a reaction cell with UV transparent windows (Cell #2) was used for this purpose. The Model 207 UV Analyzer utilizes a dual path, dual frequency operating principle in order to compensate for drift of source intensity and sample cell contamination. The arrangement and principle of operation is shown in Figure 5.2-1. H_2S is measured by UV absorption at the 214 nm wave length. Interference from O_3 , produced during the irradiation is compensated for by

FIGURE 5.2-1

UV ANALYZER OPTICAL ARRANGEMENT

THE DUAL PATH-DUAL FREQUENCY
OPERATING PRINCIPLE

SAMPLE PATH

Light from the source is split into two identical parallel beams by means of a pair of prisms and lenses. Only one beam passes through the sample cell where it is modified by UV/Visible absorption of the sample. The sample beam is optically split and focused onto two detectors. One detector is sensitized to the 'measure frequency' and the other to the 'reference frequency' by suitable filters.

COMPENSATION PATH

The compensation beam is split and focused onto another pair of detectors which are sensitized to the same frequencies as those in the sample beam.

DUAL FREQUENCY

The four detectors generate electrical signals M_s , R_s , M_c , R_c respectively, each of which is proportional to the energy focused on the detector. In accordance with Beer's Law, the sample concentration is proportional to the logarithmic ratio of the detector signals. Examination of the equation confirms that neither sample cell contamination nor variations in source intensity will affect the value of "C."

PRINCIPAL

$$C = \log_{10} \frac{R_s \times M_c}{M_s \times R_c}$$

C = Concentration

M_s = Measure Signal Sample Path

R_s = Reference Signal Sample Path

M_c = Measure Signal Compensation Path

R_c = Reference Signal Compensation Path

the addition of a second cell, containing no H_2S , in the path of the compensation beam. Both cells are then identically irradiated. The reference wave length of 334 nm was chosen such that it would not be affected by H_2S or O_3 absorption.

6.0 TEST PROGRAM

The overall objective of the program was to determine the technical and economic feasibility of electron beam treatment as an integral part of a process for removing H_2S from geothermal steam. Economic feasibility depends upon a relatively high G-value, which is inversely proportional to the electron beam energy needed per unit of H_2S destruction. A test matrix involving variations in temperature, pressure, H_2S concentration, NH_3/H_2S concentration and radiation dose was planned in order to characterize the electron beam process. The G-values obtained in early testing were considerably lower than anticipated, however, and this result gave rise to an investigative effort to improve the yield. The original test matrix was thus abandoned in hopes of discovering a method by which the yield of destroyed H_2S could be improved.

The original expectation that the G-value for H_2S destruction would be at least greater than 10 came from the publication by Wiesbock and Proksch,¹ in which they indicate a G-value of 22 when an H_2S -air mixture is electron beam irradiated. Because of this expectation, initial efforts were directed toward repeating the Wiesbock and Proksch results, and many tests were carried out using H_2S -air mixtures. In order to present an overview of the

testing that took place, the following chronological description is offered. Each grouping of tests is prefaced by the dates, the E-beam device and reaction cell used. A complete summary of recorded data is given in Appendix A.4.

2/2 - 3/12/82, FX-35, 2.6 liter cell

Initial trials with 300 ppm H_2S in steam. It was found that up to 40% of the H_2S is lost in the system, even without E-Beam irradiation. When adjusting the initial concentration of H_2S downward to account for this loss, the efficiency of E-beam conversion of H_2S is dissappointingly low, with yields of $G = 1-2$ molecules/100 ev.

3/13 - 3/18/82, FX-35, 2.6 liter cell

Trials with 2300 ppm H_2S in STP air were carried out, in an attempt to duplicate the Proksch data. It was found that a 20% H_2S loss to the system occurs when air is used as compared with the 40% loss when steam is used. G-values for H_2S removal in air were approximately 3.5, still considerably lower than anticipated.

3/18 - 3/26/82, FX-35, 2.6 liter cell

Trials with various concentrations of H_2S in steam from 300 to 1000 ppm. Radiation dosage from 0 to 12 Mrad, in order to determine how G-value is effected by concentration and radiation dose. It was found that $G = 1-2$ and was relatively independent of these parameters.

4/5 - 4/8/82, Resotron, 2.6 liter cell

300-600 ppm H_2S in steam was irradiated, using a continuous beam of 2 Mev electrons. Resulting yields were somewhat lower than prior pulse irradiation of steam.

4/16 - 4/29/82, Resotron, 2.6 liter cell

2000 ppm H_2S in STP air was irradiated. An average G-value of 4.0 was obtained, which was close to the $G = 3.5$ which resulted with pulsed beam.

4/30 - 6/3/82, Resotron, 2.6 liter cell

300-2000 ppm of H_2S in mixtures of background gases such as H_2O , CO_2 , N_2 , NH_3 , and C_4H_{10} were irradiated. These background gases were used in roughly the proportions that they are found in geothermal steam. G-values obtained did not differ significantly from the values obtained when simple H_2S , H_2O mixtures are irradiated.

During this time H_2S in STP air was irradiated while the chamber was packed with pure glass wool. This was done in order to evaluate the importance of gas-surface interactions. Because the yield was similar to that obtained with no glass wool, it was determined that surface area does not affect the yield.

7/7-7/15/82, Resotron, 2.6 liter cell

4-8% H_2S in STP CO_2 was irradiated in order to evaluate the effect of electron beam irradiation of the non-condensable gases downstream of a turbine. The yields which resulted were very similar to those obtained with .1% H_2S in air, $G = 3.5$.

Also during this time, the H_2S , CO_2 mixture was rapidly stirred during irradiation in order to evaluate the importance of gas mixing. It was found that the yield was not affected by mixing the gas during irradiation.

11/22 - 12/10/82, Resotron, 0.21 liter cell

The smaller, 0.21 l cell was used in these tests. This cell was cylindrical with a quartz window at each end which allowed a UV beam to pass through the cell. UV absorption at the H_2S wave length was monitored during irradiation in order to determine real time H_2S concentration. Tests were conducted with 300-3000 ppm H_2S in STP air. The UV absorption technique did not yield reliable concentrations due to interference from SO_2 and other sulfur compounds. The overall yield of destroyed H_2S ; however, was high and averaged $G = 7$.

5/3 - 6/15/83, Resotron, 0.21 liter cell

Because of the observed difference in yields between the 2.6 l and the 0.21 l chambers, additional tests using the 0.21 l cell were made with various H_2S -gas mixtures. The gases were air, CO_2 , N_2 , and H_2O . The G-values obtained verified earlier values from the 2.6 l chamber and were $G = 5$ for air, N_2 and CO_2 and $G = 1$ for steam.

6/16 - 6/23/83, Resotron, 2.6 liter cell

300-2000 ppm of H_2S in steam and in nitrogen at various pressures and temperatures was irradiated in order to determine the effect of pressure and temperature on the yield. Also during this time the condensate containing the reaction products was saved for later analytical testing.

7.0 DISCUSSION

The vast majority of all tests were done using air, steam or CO_2 as the background gas. We will therefore concentrate on these tests in the following discussion. Testing was conducted at various times over the period of more than one year. The two electron beam generators were used with two reaction cells. Principal variables were radiation dosage and initial H_2S concentration. In the following discussion, data collected using the different cells and E-beam generators will be presented in the same figures, but identified by distinct symbols. Hence, any effect on the results caused by the cell type or E-beam should be detectable.

Figure 7.0-1 shows the G-value for various concentrations of H_2S in 20°C , 1 atm air as a function of applied dose. The data is very scattered and reflects the difficulty experienced throughout the program in achieving repeatability on a daily basis. A best fit line indicates a yield of $G = 5$, with no dependence on dose. If this same data is plotted as a function of initial H_2S concentration, then Figure 7.0-2 results. Here too, a best fit line indicates a yield of $G = 5$ with no dependence on

FIGURE 7.0-1

 H_2S CONVERSION IN AIR

FIGURE 7.0-2
H₂S CONVERSION IN AIR

63

initial concentration. When final H_2S concentration is plotted as a function of applied dosage, the data becomes more meaningful. It can be seen in Figure 7.0-3 that, except for very low concentrations, H_2S concentration decreases linearly with applied dosage.

The results of electron beam irradiation of various concentrations of H_2S in steam are shown in Figure 7.0-4, 7.0-5, and 7.0-6. Steam conditions were 10 atm and $190^\circ C$ for these runs. As for the case of H_2S in air, the yield is seen to be independent of applied dosage and of H_2S concentration. The yield, $G = 1$, however, is much lower than that of H_2S in air. From Figure 7.0-6 it can be seen that, as for H_2S in air, the H_2S concentration decreases linearly with dosage.

The concentration of H_2S used in H_2S-CO_2 mixtures was much higher than the concentrations used in steam, such that a mixture with concentrations approximating that found in the non-condensable gas following the steam turbine would be evaluated. In this case H_2S concentrations from .2% to 8% were irradiated and the results are shown in Figure 7.0-7, 7.0-8 and 7.0-9. Although H_2S concentrations and applied dosage differed considerably, the yield, $G = 3.5$, was similar to the H_2S -air mixture.

FIGURE 7.0-3
H₂S CONVERSION IN AIR

FIGURE 7.0-4

H₂S CONVERSION IN STEAM

FIGURE 7.0-5

H₂S CONVERSION IN STEAM

FIGURE 7.0-6

H₂S CONVERSION IN STEAM

FIGURE 7.0-7
H₂S CONVERSION IN CO₂

FIGURE 7.0-8

H₂S CONVERSION IN CO₂

FIGURE 7.0-9

H₂S CONVERSION IN CO₂

The tests with $\text{H}_2\text{S}-\text{N}_2$ mixtures were too few to reasonably put in graphical form, but the individual tests were very similar to the H_2S air mixtures in conditions and results.

Late in 1982, tests utilizing ultra-violet extinction as a measurement technique were carried out in an effort to observe real-time changes in chemical composition. The UV photometer and reaction cell are described in Section 5.2. This information would help interpret the reaction kinetics and would indicate the occurrence of H_2S recombination subsequent to irradiation.

H_2S in air was measured by UV absorption at the 214 nm wavelength. Interference from O_3 produced during irradiation of H_2S -air mixtures was compensated with a second UV beam through a second cell containing only air. The difference in absorption then represents only that absorption contributed by the H_2S . A reference wavelength of 334 nm was also monitored. This wavelength would not be absorbed by H_2S or O_3 and serves to compensate for fluctuations in source intensity and UV window foulings.

An analysis of the initial unusual output of the photometer led to the discovery that SO_2 , produced during irradiation, absorbs principally at 217 nm and interferes with H_2S absorption at 214 nm. In addition, an undetermined sulfur compound was found to be

absorbing the 334 nm reference wavelength. The reference wavelength could be moved to a value not absorbed by any constituents by exchanging filters, but the 214 nm wavelength obviously could not be changed. As a result of this conclusion and of time restraints, it was decided not to continue attempts at UV absorption measurements.

A great deal of data scatter is evident from Figures 7.0-1 - 7.0-9. Data obtained during a single day of testing was in general much more self consistent than data taken on different days. This can be seen from Figures 7.0-3, 7.0-6 and 7.0-9, in which each set of data points was recorded during a single day of testing. The scatter in data from day to day probably results from the variation in H_2S lost to the system. As much as 20% of H_2S was unaccountably lost in the system when 20°C gases were used and as much as 40% was lost when steam was used. Blank runs, in which no irradiation was applied, were conducted at the beginning of each day in order to determine a base from which to calculate yields. A difference in this base from that of prior days would offset the yields by the ratio of the base runs. The reason for this H_2S loss is not known, but may result from a surface reaction with the cell walls, or adsorption by the walls. A small amount of iron present in the steam after irradiation tends to support this conclusion.

Another source of data scatter (in the direction of low G-values) are test runs in which less than 100 ppm of H_2S remains after irradiation. The reaction kinetics appear to shift from zeroth order (concentration independent) to first order (concentration dependent) at about the 100 ppm level. This can be observed in Figure 7.0-3, where the decrease in final H_2S concentrations with increasing absorbed dosage ceases to be a linear relationship below 100 ppm. G-values calculated from data in this regime tend to be considerably lower.

Lower than anticipated yields occurred in virtually all trials, regardless of the gas mixture, chamber configuration, or conditions of irradiation. The anticipated yield was $G = 22$, based upon the work of Wiesboch and Proksch¹. In a subsequent phone conversation with D. Helfritch, Dr. Proksch revised his yield value to $G = 15$ based upon more recent dosimetry. The yield of course depends on the chemical kinetics involved. In the simplest case, the H_2S reacts with an ion produced by the irradiation of the gas mixture. The reaction is an ion-molecule charge transfer, and the specificity of charge transfer to H_2S results because H_2S is the gas constituent with the lowest ionization potential. The H_2S^+ ions are destructively neutralized in subsequent reactions. For the case of H_2S in air, an anticipated reaction scheme is:

1. $\text{N}_2 \longrightarrow \text{N}_2^+ + \text{e}^-$
2. $\text{N}_2^+ + \text{H}_2\text{S} \longrightarrow \text{H}_2\text{S}^+ + \text{N}_2$
3. $\text{H}_2\text{S}^+ + \text{e}^- \longrightarrow \text{Products}$

The energy required for ion pair formation by electron collision in air is 35 eV per ion pair. If we assume that each ion pair thus produced reacts with an H_2S molecule as shown in 1, 2 and 3, then the yield would be $G = \# \text{H}_2\text{S} \text{ molecules affected} / 100 \text{ eV} = 2.86$.

In order to expect higher yields, reaction 2 and 3 must yield products which can in turn react with H_2S molecules. For example, the H_2S^+ ion of reaction 2 can react with another H_2S molecule:

4. $\text{H}_2\text{S}^+ + \text{H}_2\text{S} \longrightarrow \text{H}_3\text{S}^+ + \text{SH}$
5. $\text{H}_3\text{S}^+ + \text{e}^- \longrightarrow \text{H}_2 + \text{SH}$

In this way $G = 5.72$ could be justified. For the case of irradiation of pure $\text{H}_2\text{S}^{(2)}$, two H_2S molecules are decomposed for each ion pair, which supports reactions 4 and 5. By virtue of the low ionization potential of H_2S (10.5 eV as compared to 15.6 for N_2 , 13.8 for CO_2 , 12.6 for H_2O and 12.1 for O_2) it can

be expected that the initial ionic charge produced by the irradiation is mostly transferred to the H_2S by reactions 1-3, and this should occur regardless of the host gas used.

Based upon this reaction scheme, it appears that G values between 3 and 6 are most probable and a value of 15 is unexplainably high. The low G-value of 1.0, found for the irradiation of H_2S in steam can be accounted for when back reactions are considered. The work of E.E. Wourtsel reported in Reference (2), showed that the yield of the decomposition of H_2S by radon decreased significantly as the temperature was increased from $18^\circ C$ to $220^\circ C$. The reason for this was shown to be a reverse reaction (i.e. synthesis of H_2S), the rate of which increases with temperature. The steam temperature is thus a likely cause of the low yields observed for the radiolysis of H_2S -steam mixtures.

Various gas mixtures of constituents in proportions found in geothermal steam were irradiated in the course of the experiments. This was done primarily to assess the effect of secondary gases on the destruction of H_2S in steam. Mixtures used were steam- H_2S - NH_3 , steam- H_2S - NH_3 - CO_2 - C_4H_{10} , steam H_2S - CO_2 -

C_4H_{10} . None of these mixtures resulted in yields of destroyed H_2S which were significantly different than that for steam- H_2S alone.

Other efforts to increase yields included stirring the gas during irradiation and the addition of surface area inside the cell. The non-uniformity of absorbed radiation dosage within the cell and stagnant gas conditions were thought to suppress the achievable yield. A paddle wheel stirring mechanism was used during a series of H_2S - CO_2 irradiations and no difference in yield relative to similar non-stirred irradiations was recorded. Glass wool was packed inside the 2.6 liter cell during several irradiation runs of H_2S air mixtures. This was done in order to determine the effect of increased surface area on the yield, but, here too, no difference in yield was observed.

Reaction products were difficult to determine. Sulfur balances were never complete, with sometimes as much as 50% of sulfur unaccounted for at the end of a test. As an example, a steam- H_2S mixture contained in the 2.6 liter cell was irradiated with the Resotron device. The initial amount of H_2S in the mixture was

8.4 mg, and the absorbed dose was 25.5 Mrad. After irradiation the contents of the cell were bubbled through water and subsequently through SAOB solution by means of a nitrogen purge. This purge was continued for 15 minutes to assure that all gaseous sulfur products had been removed from the cell.

The water contained in the first impinger bottle became cloudy as a result of the gas bubbled through it. This cloudiness disappeared after a few days. Analysis of the water revealed that H_2S and SO_3 could not be detected, but 1.17 mg of H_2SO_4 was present, and the pH of the solution was 2.9.

The SAOB II solution in the second impinger bottle contained 3.32 mg of H_2S and had a total sulfur content of 3.58 mg.

A blank, non irradiation run, performed prior to the subject test, indicated that 2.78 mg of H_2S is lost by surface absorption on the walls of the cell, as determined by the presence of iron in the steam condensate. The sulfur balance is therefore:

Initial Sulfur

Final Sulfur

$$(8.4) (32/34) = 7.9 \text{ mg}$$

$$\text{in water } (1.17) (32/98) = .38 \text{ mg}$$

in SAOB

$$3.58 \text{ mg}$$

wall absorption

$$(2.78) (32/34) = 2.62 \text{ mg}$$

$$7.9 \text{ mg}$$

$$6.58 \text{ mg}$$

One reaction product was sulfate as evidenced by the H_2SO_4 in the water. Another reaction product is an undetermined sulfur compound making up the difference between the total sulfur contained in the SAOB II and the H_2S . When the initial H_2S is considered to be the amount placed in the cell minus that absorbed by the walls, $(8.4 \text{ mg} - 2.78 \text{ mg}) = 5.62 \text{ mg}$, then the E-beam removal efficiency for this test was

$$(5.62 - 3.32)/5.62 \times 100 = 41\%$$

8.0 COMMERCIAL FEASIBILITY

The average yield for the irradiation of H_2S -steam mixtures is $G = 1$ (molecules of $\text{H}_2\text{S}/100$ ev). When this value is used to determine the energy requirements for the removal of 100 ppm of H_2S contained in a steam flow of 2×10^6 pph, 13.5 MW of energy results, or 12% of the plant output for a 110 MW geothermal plant. Because of zeroth order reaction kinetics, and the required energy is proportional to the concentration of H_2S , thus 27 MW would be necessary to remove 200 ppm of H_2S . These energy requirements are clearly prohibitive and imply no commercial feasibility. A better approach is to consider the application of the electron beam to the non-condensable gases exhausted by the off-gas ejector. This gas is primarily CO_2 , and the yield for destruction of H_2S in CO_2 is $G = 3.5$. A 2×10^6 pph steam flow containing 100 ppm H_2S and .8% CO_2 would result in 94,000 ppm H_2S in a 16×10^3 pph flow of CO_2 off gas. The energy needed to remove this H_2S is 3.8 MW.

We will therefore consider the installation of an E-beam treatment facility on the off gases of a 110 MW geothermal plant, which is the typical size of new plants. 3.8 MW is the energy required when the steam contains 100 ppm of H_2S . The costs for

an E-beam facility providing an input of 3.8 MW to the off gases will be determined. The costs for equipment needed for other H₂S concentrations will vary in proportion to the concentration. Assuming that 80% of the beam energy is absorbed by the gas, the total beam energy must be $3.8/.8 = 4.8$ MW. A beam energy of this magnitude can be economically applied only with megawatt sized power supplies and accelerator/scanner units. A system of this kind would be comprised of four 800 kV, 1500 ma power supplies, driving sixteen 800 kV, 375 ma accelerator/scanners. The estimated installed capital costs of such a system is given in Table 8.0-1.

Assuming operation for 7000 hours per year and an electricity cost of \$.045/kwhr, the E-beam electricity cost at 4.8 MW is \$1,512,000/yr. A 2% of capital cost maintenance charge is \$160,000/yr, and \$30/hr operating labor gives \$210,000/yr. Assuming a utility 50/50 equity to debt ratio, a 10% bond interest, 12% returns to stockholders and a 15 year straight line depreciation, the annual capital use charge becomes 15% of capital cost, or \$1,198,000/yr. The total annualized cost for a 110 MW plant is thus summarized in Table 8.0-2.

The costs are dominated by capital equipment and electricity usage. The annualized cost of 4.0 mill/kwhr is reasonable for H₂S control equipment on a generating station at the Geysers.

Table 8.0-3 compares these costs with those of the iron catalyst and Stretford process, where the same initial operational and utility cost assumptions have been made. Ninety percent abatement efficiency is expected from each process, although greater than 95% efficiency could be realized for the Stretford and the E-beam if supplemental H_2S scrubbing were applied to the condensate. It can be seen that the E-beam process is less costly than the iron catalyst but more costly than the Stretford process.

TABLE 8.0-1
INSTALLED CAPITAL COSTS

<u>EQUIPMENT CATEGORY</u>	<u>ESTIMATED COST</u> ⁴
4 High Voltage Power Supplies (800 kV, 1500 ma Rating)	\$2,800,000
16 Accelerator/Scanner Units (800 kV, 375 ma, 60" Scan.)	2,435,000
4 Module Controls	270,000
Peripheral Equipment	280,000
Equipment Spares	280,000
Installation of Above	1,079,000
Reaction Chamber & Building	843,000
TOTAL	\$7,987,000
	(\$72.6/kW)

TABLE 8.0-2

ANNUAL OPERATING COSTS

Electricity	\$1,512,000/yr
Maintenance	160,000/yr
Labor	210,000/yr
Capital Charge	1,198,000/yr
TOTAL ANNUALIZED COST	\$3,080,000/yr (4.0 mill/kwhr)

TABLE 8.0-3

COSTS COMPARISON

	IRON		
	CATALYST	STRETFORD	E-BEAM
Capital Cost, \$ x 10 ⁶	7.7	8.8	8.0
Capital Cost, \$/kW	70	80	73
Annualized Cost, \$ x 10 ⁶	4.7	1.9	3.0
Annualized Cost, Mill/kWhr	6.1	2.5	4.0

9.0 REFERENCES

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1961) p. 124-126.
3. Slater, R. C. and D. H. Douglas-Hamilton, J. Applied Physics
(1981) No. 52, p. 5820-5828.
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A-1 Definition of Terms

ev Electron volt

G-Value Number of molecules produced or destroyed per 100 eV
of total absorbed energy.

kWhr Kilowatt-hour

megarad Unit of absorbed radiation dosage equal to 10 joules
per gram of absorbing medium.

MW Megawatt

ppmV Concentration in parts per million by volume.

pph Pounds per hour of steam

A-2 Dosimetry

Dosimetry is the determination of an absorbed radiation dose. Dose is measured in terms of energy absorbed per unit mass of absorbing medium. The special unit of absorbed dose is the rad, where $1 \text{ rad} = 100 \text{ erg/gm}$. There are several methods of determining absorbed dose, which include ion chambers, colorimeters, power input measurements, and calibrated chemical reactions. In general, the radiated energy is not uniformly absorbed by the target medium, and the dose can vary by orders of magnitude at different locations within the medium. Because of the non-uniformity of absorbed energy, the method must be one which measures dose at several locations within the experimental chamber. These samples can then be spacially averaged in order to determine average dose.

The radiation bleaching of blue methylene impregnated cellophane was used for point to point dose measurement. This cellophane is available from duPont and Far Western Technology, and its opacity has been calibrated to absorbed radiation dose, i.e. higher doses decrease opacity. The cellophane is distributed within the cell volume and the cell is then irradiated in normal fashion. In the case of the FX-35 a given number of pulses is applied, and in the case of the Resotron machine, a specified electron current over a given time period. For the 2.6 liter cell, a sheet of cello-

phane was placed just under the window and a sheet at the back wall, as shown in Figure 10.2-1. Subsequent to irradiation, the cellophane is removed and its opacity measured at positions 1 through 10. These readings then give the dose received by the cellophane at each position. A correction must be made to these dosages in order to take into account the difference in stopping power between the cellophane films and that of a gas. Radiation dose is given by the equation:

$$D = N/A (dE/dx)$$

where

N = number of electrons

A = area of electron flux

dE/dx = electron stopping power of the media

then

$$D_{\text{gas}} = D_{\text{film}} (dE/dx)_{\text{gas}} / (dE/dx)_{\text{film}}$$

FIGURE A-2.1
DOSIMETRY VOLUMES

When the gas dosages are then determined at points 1 through 10, then the average dose to the cell can be calculated by dividing the cell into concentric zones as shown in the Figure. Then the average dose is given by:

$$\bar{D} = 1/V \sum \bar{D}_i V_i$$

$$= \sum \phi_i \bar{D}_i$$

where

$\bar{D}_i$ = average dose in zone i

V_i = volume of zone i

ϕ_i = volume fraction of zone i

and for Figure A.2-1

$$\bar{D}_1 = (1+2)/2 \qquad \phi_1 = .111$$

$$\bar{D}_2 = (3+4+5+6)/4 \qquad \phi_2 = .333$$

$$\bar{D}_3 = (7+8+9+10)/4 \qquad \phi_3 = .555$$

As an example, five pulses from the FX-35 produced the following dosages in the cellophane.

	Film	Gas (Air)	$\bar{D}_i$
1	9.8 Mrad	8.8	$\bar{D}_1 = 10.0$
2	12.4	11.1	
3	$4.5 \times 1.68 / 1.88 =$	4.0	$\bar{D}_2 = 5.4$
4	8.8	7.9	
5	4.8	4.3	
6	6.0	5.4	$\bar{D}_3 = 2.3$
7	2.6	2.3	
8	2.6	2.3	
9	2.4	2.1	
10	2.6	2.3	

Then $\bar{D} = \sum_i \bar{D}_i$

$$= (.111)(10) + (.333)(5.4) + (.555)(2.3) = 4.2 \text{ Mrad.}$$

Thus for this dosimetry trial, each pulse yielded an average dose of .84 Mrad to the air contained within the cell.

A-3 Analysis of Hydrogen Sulfide (H₂S)

A-3.1 Analytical Method

Analyte: Hydrogen Sulfide

Matrix: Air, Nitrogen, and Steam

Range: 0.003 ppm to 100 ppm

100 ppm dilution required

Procedure: Absorption in SAOB (II) solution. Measurement of sulfide ions using calibrated Orion sulfide ion electrode and 901 Orion ion analyzer meter.

A-3.2 Principle of Method

Hydrogen sulfide was converted to sodium sulfide by bubbling the gas through SAOB(II) 1:1 solution. The gases from the reaction chamber were forced out by means of nitrogen. The sulfide ion (sodium sulfide) was measured by a calibrated sulfide ion electrode and a 901 Orion ion analyzer meter. The analysis was completed within 10 minutes following the collection of the sample.

A-3.3 Reagents

A-3.3.1 10M Sodium Hydroxide: Dissolve 200 gms of sodium.

(Hydroxide (A.C.S. certified) in 500 ml of distilled deaerated water)

A-3.3.2 L. Ascorbic acid, A.C.S.. certified.

A-3.3.3 Disodium EDTA ethylenedinitrils tetracetic acid disodium salt. Analytical reagent meets A.C.S. specification.

A-3.3.4 Sulfide antioxidant buffer (SAOB II) 1:1 Solution.

In a two liter volumetric flask, add 1000 ml of distilled deaerated water. To this add ml of 10M sodium hydroxide, 35 gms of L-ascorbic acid and 67 gms of disodium EDTA. Swirl the mixture to dissolve the solids. Make up to 2 liter mark using distilled deaerated water. Fresh SAOB (II) solution color will range from clear to pale yellow brown. When SAOB (II) turns dark, it has been oxidized, therefore discard the solution.

NOTE: During this project every morning fresh SAOB (II) was prepared and kept in a dark brown tightly stoppered bottle.

A-3.4 Reagent for standardization and standard solution.

A-3.4.1 Lead perchlorate standard 0.1M Orion Research. Inc.
#94-82-06

A-3.4.2 Stock solution of saturated sodium sulfide (sulfide standard) preparation:

Dissolve 100 gms of sodium sulfide (Fisher Scientific - reagent grade) in 100 ml of distilled deaerated water in a beaker. Shake well and stand overnight. Store in a tightly stoppered bottle in a hood.

Prepare 1000 ppm of weekly sulfide standard solution by pipetting 3.2 ml of stock solution of saturated sodium sulfide into a 200 ml volumetric flask containing 1:1 SAOB (II) solution: Make up the volume to 200ml mark by 1:1 SAOB (II) solution. This is weekly sulfide standard solution.

Prepare daily stock sulfide solution by pipetting 25 ml of above solution into a 250 ml volumetric flask and dilute to the mark with 1:1 SAOB (11) solution. Determine the exact sulfide concentration of this solution by titrating 100 ml of this solution by lead perchlorate (0.1M) using 901 Orion analyzer and sulfide electrode along with double junction electrodes.

$$C_S \text{ (ppm)} = 3206 (V_t/V_s)$$

C_S = concentration of ppm sulfide

V_t = volume of titrant at end point

V_s = volume of standard solution used (100 ml)

$$C_{H_2S} = C_S \times 1.0625$$

Prepare other sulfide standard daily by serial dilution of the above solution.

A-4 Data

The data is presented in chronological order. Major headings are:

Cell 1 = 2.6 liter (See Section 4.1)

2 = 0.21 liter (See Section 4.1)

E-Beam 1 = FX-35 Pulse Type (See Section 4.2)

2 = Resotron DC (See Section 4.2)

Gas This is the host gas. Unless otherwise noted in comments, steam conditions are 10 atm and 190°C. All other gases at 1 atm and 20°C.

Dose This is the absorbed dose in Mrads

H₂S IN This is the weight of the H₂S in the cell prior to irradiation, mg.

H₂S OUT This is the weight of the H₂S in the cell subsequent to irradiation, mg.

<u>DATE</u>	<u>CELL</u>	<u>E-BEAM</u>	<u>GAS</u>	<u>DOSE</u>	<u>H₂S IN</u>	<u>H₂S OUT</u>	<u>COMMENTS</u>
3/9/82	1	1	N ₂	0	8.44	7.80	Procedures Check
	1	1	N ₂	0	8.44	7.76	Procedures Check
	1	1	N ₂	0	8.44	7.70	Procedures Check
3/10/82	1	1	N ₂	0	8.44	7.82	Procedures Check
	1	1	N ₂	0	8.44	7.54	Procedures Check
	1	1	N ₂	0	8.44	7.60	Procedures Check
	1	1	N ₂	0	8.44	7.92	Procedures Check
	1	1	Steam	0	8.44	4.80	Procedures Check
3/11/82	1	1	Steam	0	8.44	5.80	Procedures Check
	1	1	Steam	0	8.44	6.34	Procedures Check
	1	1	Steam	0	8.44	6.66	Procedures Check
	1	1	Steam	0	8.44	6.22	Procedures Check
	1	1	Steam	3.0	8.44	6.24	
3/12/82	1	1	Steam	0	8.44	6.20	
	1	1	Steam	0	8.44	5.64	
	1	1	Steam	.75	8.44	6.62	
	1	1	Steam	0	8.44	5.84	
	1	1	Steam	3.0	8.44	3.08	

<u>DATE</u>	<u>CELL</u>	<u>E-BEAM</u>	<u>GAS</u>	<u>DOSE</u>	<u>H₂S IN</u>	<u>H₂S OUT</u>	<u>COMMENTS</u>
3/17/82	1	1	Air	0	8.44	7.20	
	1	1	Air	0	8.44	7.00	
	1	1	Air	1.5	8.44	6.40	
	1	1	Air	3.0	8.44	5.98	
	1	1	Air	6.0	8.44	4.58	
3/18/82	1	1	Air	3.0	8.44	3.72	
	1	1	Air	0	8.44	6.88	
	1	1	Air	0	8.44	.01	Chamber Heated
	1	1	Steam	3.0	8.44	3.70	
	1	1	Steam	6.0	8.44	3.60	
3/22/82	1	1	Steam	0	8.44	4.52	
	1	1	Steam	1.5	8.44	4.74	
	1	1	Steam	3.0	8.44	3.86	
3/22/82	1	1	Steam	0	8.44	3.52	
3/23/82	1	1	Steam	0	8.44	5.28	
	1	1	Steam	0	30.0	19.4	
	1	1	Steam	0	30.0	20.0	
	1	1	Steam	1.5	30.0	18.3	
	1	1	Steam	3.0	30.0	17.4	

	<u>DATE</u>	<u>CELL</u>	<u>E-BEAM</u>	<u>GAS</u>	<u>DOSE</u>	<u>H₂S IN</u>	<u>H₂S OUT</u>	<u>COMMENT</u>
76	3/24/82	1	1	Steam	6.0	30.0	13.5	
		1	1	Steam	0	30.0	19.1	
		1	1	Steam	1.5	30.0	19.8	
		1	1	Steam	11.25	30.0	16.2	
		1	1	Steam	0	30.0	23.8	
		1	1	Steam	0	16.0	13.5	
		1	1	Steam	3.0	16.0	9.14	
	3/25/82	1	1	Steam	6.0	16.0	6.90	
		1	1	Steam	0	16.0	8.24	
		1	1	Steam	0	16.0	10.7	
		1	1	Steam	6.0	16.0	5.40	
		1	1	Steam	9.0	16.0	4.82	
		1	1	Steam	0	16.0	9.80	
		1	1	Steam	12.0	16.0	1.05	
	3/26/82	1	1	Steam	0	8.44	3.14	
		1	1	Steam	12.0	8.44	1.62	
		1	1	Steam	12.0	8.44	1.22	
		1	1	Steam	0	8.44	3.72	
		1	2	Steam	4.0	8.44	2.70	
	4/5/82	1	2	Steam	4.0	8.44	2.70	

<u>DATE</u>	<u>CELL</u>	<u>E-BEAM</u>	<u>GAS</u>	<u>DOSE</u>	<u>H₂S IN</u>	<u>H₂S OUT</u>	<u>COMMENTS</u>
4/6/82	1	2	Steam	0	8.44	5.40	
	1	2	Steam	0	16.0	11.7	
	1	2	Steam	4.0	16.0	11.4	
	1	2	Steam	8.0	16.0	9.50	
4/7/82	1	2	Steam	0	16.0	9.36	
	1	2	Steam	0	16.0	10.6	
	1	2	Steam	8.0	16.0	7.78	
	1	2	Steam	12.0	16.0	7.38	
77 4/8/82	1	2	Steam	10.0	30.0	16.5	
	1	2	Steam	20.0	30.0	11.4	
4/16/82	1	2	Air	0	7.4	6.50	
	1	2	Air	4.0	7.4	4.90	
	1	2	Air	8.0	7.4	2.30	
	1	2	Air	12.0	7.4	0.15	
	1	2	Air	0	18.5	16.1	
	1	2	Air	8.0	18.5	12.3	
	1	2	Air	12.0	18.5	9.90	
	1	2	Air	16.0	18.5	8.90	
4/20/82	1	2	Air	12.0	18.5	10.9	Lab Air
	1	2	Air	12.0	18.5	10.2	Dry Air

<u>DATE</u>	<u>CELL</u>	<u>E-BEAM</u>	<u>GAS</u>	<u>DOSE</u>	<u>H₂S IN</u>	<u>H₂S OUT</u>	<u>COMMENTS</u>
	1	2	Air	12.0	18.5	9.70	Humid Air
4/22/83	1	2	CO ₂	0	284	254	
	1	2	CO ₂	20.0	284	248	
	1	2	CO ₂	100.0	284	116	
4/28/82	1	2	Air	0	16.0	15.4	Viton "O" Rings
	1	2	Air	0	16.0	14.9	Replaced with Teflon
	1	2	Air	0	16.0	15.2	
	1	2	Air	0	16.0	15.2	
4/29/82	1	2	Air	4.0	16.0	13.8	
	1	2	Air	8.0	16.0	12.0	
	1	2	Air	12.0	16.0	9.8	
4/30/82	1	2	Steam	0	8.44	6.24	
	1	2	Steam	4.0	8.44	2.24	
	1	2	Steam	4.0	8.44	5.04	
5/3/82	1	2	Steam	8.0	8.44	4.35	
5/4/82	1	2	Steam	0	8.44	5.81	
	1	2	Steam	12.0	8.44	3.24	
5/5/82	1	2	N ₂ +NH ₃	0	8.44	7.32	
	1	2	N ₂ +NH ₃	0	8.44	6.66	
5/6/82	1	2	Steam + NH ₃	0	8.44	4.88	

<u>DATE</u>	<u>CELL</u>	<u>E-BEAM</u>	<u>GAS</u>	<u>DOSE</u>	<u>H₂S IN</u>	<u>H₂S OUT</u>	<u>COMMENTS</u>
5/6/82	1	2	Steam + NH ₃	0	8.44	5.44	
	1	2	Steam + NH ₃	4.0	8.44	4.08	
	1	2	Steam + NH ₃	8.0	8.44	4.71	
	1	2	Steam + NH ₃	0	8.44	6.46	
5/7/82	1	2	Air	4.0	8.0	4.50	Plastic in cell
	1	2	Air	0	8.0	6.18	Plastic in cell
5/11/82	1	2	Comments	0	8.3	5.30	Steam + CO ₂ + NH ₃ +
5/12/82	1	2	Comments	0	8.3	4.60	C ₄ H ₁₀ + CO ₂ + NH ₃ +
5/12/82	1	2	Comments	4.0	8.3	3.62	"
	1	2	Comments	8.0	8.3	3.87	"
	1	2	Comments	12.0	8.3	3.51	"
	1	2	Comments	0	8.3	5.50	"
5/13/82	1	2	Comments	0	8.3	4.08	Steam+CO ₂ + C ₄ H ₁₀
	1	2	Comments	4.0	8.3	4.40	"
5/18/82	1	2	Comments	0	8.3	4.12	"
	1	2	Comments	4.0	8.3	4.04	"
	1	2	Comments	8.0	8.3	4.46	"
	1	2	Comments	12.0	8.3	5.20	"

<u>DATE</u>	<u>CELL</u>	<u>E-BEAM</u>	<u>GAS</u>	<u>DOSE</u>	<u>H₂S IN</u>	<u>H₂S OUT</u>	<u>COMMENTS</u>
5/20/82	1	2	Air	0	16.0	13.0	Glass Wool in Cell
	1	2	Air	4.0	16.0	11.5	Glass Wool in Cell
	1	2	Air	8.0	16.0	7.5	Glass Wool in Cell
	1	2	Air	12.0	16.0	7.2	Glass Wool in Cell
6/3/82	1	2	Air	0	16.0	15.1	
	1	2	Air	4.0	16.0	11.6	
	1	2	Air	8.0	16.0	8.90	
	1	2	Air	0	16.0	14.8	
7/7/82	1	2	CO ₂	50	284	222	
	1	2	CO ₂	0	284	250	
	1	2	CO ₂	50	284	218	
	1	2	CO ₂	100	284	202	
	1	2	CO ₂	0	284	250	
7/8/82	1	2	CO ₂	100	284	170	
	1	2	CO ₂	0	284	244	
	1	2	CO ₂	200	284	173	
7/12/82	1	2	CO ₂	0	284	234	Stir Gas During Irradiation
	1	2	CO ₂	50	284	214	"
	1	2	CO ₂	50	284	198	"

	<u>DATE</u>	<u>CELL</u>	<u>E-BEAM</u>	<u>GAS</u>	<u>DOSE</u>	<u>H₂S IN</u>	<u>H₂S OUT</u>	<u>COMMENTS</u>
	7/13/82	1	2	CO ₂	0	284	228	Stir Gas During
		1	2	CO ₂	100	284	189	Irradiation
		1	2	CO ₂	200	284	132	"
		1	2	CO ₂	0	284	222	"
	7/14/82	1	2	CO ₂	0	284	230	Humidity Added
		1	2	CO ₂	50	284	226	Humidity Added
		1	2	CO ₂	50	284	218	Humidity Added
		1	2	CO ₂	0	284	292	Humidity Added
		1	2	CO ₂	50	284	236	Air Added
	7/15/82	1	2	CO ₂	0	284	272	Air Added
		1	2	CO ₂	50	284	246	Air Added
	11/22/82	2	2	Air	6.9	.297	.0037	
		2	2	Air	6.6	.297	.0009	
		2	2	Air	6.9	.297	.0008	
		2	2	Air	5.1	.297	.0060	
	11/23/82	2	2	Air	2.0	.297	.114	
		2	2	Air	3.0	.297	.063	
		2	2	Air	3.0	.297	.063	

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<u>DATE</u>	<u>CELL</u>	<u>E-BEAM</u>	<u>GAS</u>	<u>DOSE</u>	<u>H₂S IN</u>	<u>H₂S OUT</u>	<u>COMMENTS</u>
11/23/82	2	2	Air	4.0	.297	.029	
	2	2	Air	0	.297	.250	
	2	2	Air	5.0	.297	.021	
	2	2	Air	6.0	.297	.010	
	2	2	Air	0	.297	.310	
	2	2	Air	4.0	.104	.005	
	2	2	Air	0	.104	.069	
	2	2	Air	2.0	.104	.016	
11/30/82	2	2	Air	6.0	.297	.0476	
	2	2	Air	6.0	.297	.0474	
12/1/82	2	2	Air	0	0	0	U V Check
	2	2	Air	0	0	0	U V Check
	2	2	N ₂	0	0	0	U V Check
	2	2	Air	6.0	.594	.0965	
	2	2	Air	6.0	.594	.0733	
	2	2	Air	0	.594	.590	
	2	2	Air	0	.594	.570	
	2	2	Air	6.0	.594	.0548	

<u>DATE</u>	<u>CELL</u>	<u>E-BEAM</u>	<u>GAS</u>	<u>DOSE</u>	<u>H₂S IN</u>	<u>H₂S OUT</u>	<u>COMMENTS</u>
12/1/82	2	2	Air	6.0	.594	.113	
	2	2	Air		.594	.0490	
	2	2	Air	6.0	.594	.102	
	2	2	Air	10.0	.594	.016	
12/2/82	2	2	Air	0	.144	.144	
	2	2	Air	4.4	.144	.0014	
	2	2	Air	6.0	.144	.0004	
	2	2	Air	1.6	.144	.0157	
	2	2	Air	4.0	.144	.0098	
	2	2	Air	0	.144	.119	
12/8/82	2	2	Air	0	.149	.169	
	2	2	Air	10.0	.149	.023	
	2	2	Air	5.0	.149	.175	
	2	2	Air	0	.149	.348	
12/9/82	2	2	Air	0	.137	.131	
	2	2	Air	6.0	.137	.003	
	2	2	Air	3.0	.137	.010	
	2	2	Air	0.8	.137	.0095	
	2	2	Air	6.0	.137	.002	
	2	2	Air	3.0	.137	.011	

<u>DATE</u>	<u>CELL</u>	<u>E-BEAM</u>	<u>GAS</u>	<u>DOSE</u>	<u>H₂S IN</u>	<u>H₂S OUT</u>	<u>COMMENTS</u>
	2	2	Air	1.2	.131	.05	
	2	2	Air	6.0	.131	.001	
	2	2	Air	3.0	.131	.004	
	2	2	Air	0	.131	.143	
	2	2	Air	1.2	.131	.038	
	2	2	Air	6.0	.131	.0015	
	2	2	Air	3.0	.131	.005	
	2	2	Air	0	.131	.157	
12/10/82	2	2	Air	6.0	.891	.350	
	2	2	Air	3.0	.891	.610	
	2	2	Air	0.8	.891	.860	
	2	2	Air	6.0	.891	.780	
	2	2	Air	6.0	.891	.780	
	2	2	Air	3.0	.891	.670	
	2	2	Air	1.2	.891	.820	
	2	2	Air	6.0	.891	.380	
	2	2	Air	3.0	.891	.670	
1/12/83	2	2	CH ₄	0	.355	.355	

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<u>DATE</u>	<u>CELL</u>	<u>E-BEAM</u>	<u>GAS</u>	<u>DOSE</u>	<u>H₂S IN</u>	<u>H₂S OUT</u>	<u>COMMENTS</u>
1/12/83	2	2	CH ₄	1.1	.355	.330	
	2	2	CH ₄	3.3	.355	.185	
	2	2	CH ₄	6.6	.355	.212	
	2	2	CH ₄	11.0	.355	.0039	
1/13/83	2	2	CH ₄	0	1.88	1.88	
	2	2	CH ₄	11.0	1.88	1.36	
	2	2	CH ₄	22.0	1.88	.941	
6/3/83	2	2	Air	0	.287	.287	
	2	2	Air	2.0	.287	.100	
	2	2	Air	1.0	.287	.118	
	2	2	Air	1.0	.287	.143	
6/6/83	2	2	Steam	0	.180	.18	
	2	2	Steam	2.0	.180	.18	
	2	2	Steam	0	.706	.706	
	2	2	Steam	2.0	.706	.674	
	2	2	Steam	0	1.34	1.34	
	2	2	Steam	10.0	1.34	1.12	
	2	2	Steam	0	1.76	1.76	
	2	2	Steam	10.0	1.76	1.35	

<u>DATE</u>	<u>CELL</u>	<u>E-BEAM</u>	<u>GAS</u>	<u>DOSE</u>	<u>H₂S IN</u>	<u>H₂S OUT</u>	<u>COMMENTS</u>
6/6/83	2	2	Steam	0	1.25	1.25	
	2	2	Steam	0	1.15	1.15	
	2	2	Steam	0	2.13	2.13	
	2	2	Steam	20.0	1.90	.011	
6/7/83	2	2	N ₂	0	.281	.281	
	2	2	N ₂	6.0	.281	.0181	
	2	2	N ₂	3.0	.281	.125	
	2	2	N ₂	2.0	.281	.156	
	2	2	CO ₂	0	.695	.695	
	2	2	CO ₂	10.0	.695	.377	
	2	2	CO ₂	20.0	.695	.232	
	2	2	CO ₂	0	.695	.695	
	2	2	CO ₂	10.0	.695	.377	
	2	2	CO ₂	20.0	.695	.232	
6/8/83	2	2	Steam	0	.487	.487	Syringe Injection
	2	2	Steam	6.0	.487	.396	"
	2	2	Steam	0	.326	.326	"
	2	2	Steam	0	1.15	1.15	
	2	2	Steam	20.0	1.15	.743	
	2	2	Steam	20.0	1.15	.644	

<u>DATE</u>	<u>CELL</u>	<u>E-BEAM</u>	<u>GAS</u>	<u>DOSE</u>	<u>H₂S IN</u>	<u>H₂S OUT</u>	<u>COMMENTS</u>
6/10/83	2	2	N ₂	0	.421	.421	
	2	2	N ₂	6.0	.421	.110	
	2	2	N ₂	0	.421	.380	
	2	2	CO ₂	0	.665	.665	
	2	2	CO ₂	6.0	.665	.329	
	2	2	CO ₂	6.0	.665	.287	
	2	2	CO ₂	0	.667	.667	
	2	2	Steam	0	.326	.326	
	2	2	Steam	6.0	.326	.270	
	2	2	Steam	0	.336	.336	
	2	2	Steam	10.0	.336	.395	
	2	2	Steam	6.0	.336	.240	
	2	2	Steam	20.0	.336	.293	
	2	2	Steam	0	.257	.257	
6/15/83	1	2	Steam	0	8.44	4.83	140 psig 550°F
	1	2	Steam	85.0	8.44	2.46	90 550
	1	2	Steam	127.5	8.44	2.91	100 400
	1	2	Steam	0	8.44	5.83	100 380
	1	2	Steam	127.5	8.44	2.73	95 380
6/16/83	1	2	N ₂	0	8.44	8.37	0 psig 85°F

<u>DATE</u>	<u>CELL</u>	<u>E-BEAM</u>	<u>GAS</u>	<u>DOSE</u>	<u>H₂S IN</u>	<u>H₂S OUT</u>	<u>COMMENTS</u>	
6/16/83	1	2	N ₂	25.5	8.44	.28	0 psig	85° F
	1	2	N ₂	25.5	8.44	.47	40	85°
	1	2	N ₂	25.5	8.44	.60	75	85°
	1	2	N ₂	0	8.44	7.43	0	275°
	1	2	N ₂	25.5	8.44	.42	0	275°
	1	2	N ₂	25.5	8.44	.39	40	275°
	1	2	N ₂	25.5	8.44	.416	75	275°
	1	2	N ₂	0	8.44	5.96	0	375°
∞ 6/21/83	1	2	N ₂	25.5	8.44	.71	0	375°
	1	2	N ₂	25.5	8.44	.19	75	375°
	1	2	N ₂	8.5	8.44	3.98	0	375°
6/22/83	1	2	Steam	0	8.44	5.62	50	375°
	1	2	Steam	1.7	8.44	5.49	95	375°
	1	2	Steam	4.25	8.44	5.18	50	375°
	1	2	Steam	8.5	8.44	4.28	50	375°
	1	2	Steam	8.5	8.44	3.89	50	375°
	1	2	Steam	8.5	8.44	4.37	65	375°

<u>DATE</u>	<u>CELL</u>	<u>E-BEAM</u>	<u>GAS</u>	<u>DOSE</u>	<u>H₂S IN</u>	<u>H₂S OUT</u>	<u>COMMENTS</u>
6/22/83	1	2	Steam	25.5	8.44	2.63	60 psig 375° F
	1	2	Steam	25.5	8.44	3.32	60 375°
6/23/83	1	2	Steam	25.5	8.44	2.60	75 375°
	1	2	Steam	25.5	8.44	3.22	75 375°
12/8/82	2	2	Air	6.0	.495	.030	
	2	2	Air	3.0	.495	.28	
	2	2	Air	.8	.495	.44	
	2	2	Air	6.0	.495	.09	
	2	2	Air	3.0	.495	.27	
	2	2	Air	1.2	.495	.40	
	2	2	Air	6.0	.495	.12	
	2	2	Air	3.0	.495	.21	

<u>DATE</u>	<u>CELL</u>	<u>E-BEAM</u>	<u>GAS</u>	<u>DOSE</u>	<u>H₂S IN</u>	<u>H₂S OUT</u>	<u>COMMENTS</u>
6/22/83	1	2	Steam	25.5	8.44	2.63	60 psig 375 ^o F
	1	2	Steam	25.5	8.44	3.32	60 375 ^o
6/23/83	1	2	Steam	25.5	8.44	2.60	75 375 ^o
	1	2	Steam	25.5	8.44	3.22	75 375 ^o
12/8/82	2	2	Air	6.0	.495	.030	
	2	2	Air	3.0	.495	.28	
	2	2	Air	.8	.495	.44	
	2	2	Air	6.0	.495	.09	
	2	2	Air	3.0	.495	.27	
	2	2	Air	1.2	.495	.40	
	2	2	Air	6.0	.495	.12	
	2	2	Air	3.0	.495	.21	

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