

Non-Condensable Gas Reinjection Test  
Conducted at the HGP-A Wellhead Generator Facility  
September 1, 1989 through December 10, 1990

Final Report

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## TABLE OF CONTENTS

I.	Introduction .....	1
II.	Test Stand Design .....	2
III.	Test Plan .....	5
IV.	Experimental Protocol .....	7
V.	Results and Discussion .....	12
	Brine/Condensate Mixing .....	12
	Gas Mixing .....	14
VI.	Conclusions and Recommendations .....	20
VII.	Recommendations for Additional Work .....	21

## Introduction

During the production lifetime of the HGP-A Wellhead Generator Facility, the two most significant technical problems encountered in its operation were the disposal of the high temperature liquid phase produced by the geothermal well and the abatement of the non-condensable gases present in the steam phase. Although early geothermal installations have been able to deal with these waste streams by surface disposal of liquid wastes and chemical treatment of the non-condensable gases, more recent developments in water dominated geothermal fields have applied new disposal methods that are based on reinjection of both the liquid and gaseous phases back into the geothermal reservoir. The environmental advantages of such a disposal method are evident: the potential for contamination of surface and shallow water supplies is eliminated, there are no hazardous wastes that have, in some cases, been generated by chemical treatment of the gases, and the proportion of the waste stream that can be disposed of is nearly 100%. However, the chemical composition of the geothermal fluids present in Hawaii are not identical to those found in the geothermal fields that have used gas reinjection and, hence, it was suggested that valuable design information could be obtained from a small scale evaluation of the gas reinjection process using Hawaii's geothermal fluids. The objectives of the study were to:

- 1) Identify optimum engineering design conditions for full scale application of the reinjection process;
- 2) Characterize the effects of gas injection on the chemistry of the liquid waste streams; and
- 3) Evaluate the metallurgical impacts of the recombined fluid chemistry.

In order to conduct a test to meet these objectives, a pilot gas injection test stand was fabricated and installed at the HGP-A Generator Facility. The system was designed to allow recombination of a continuous stream of geothermal brine, steam condensate, and non-condensable gases at proportions that would closely match the composition of the anticipated waste streams generated by a commercial geothermal generator facility. The system was also designed to allow for testing of the corrosion and deposition potential of the mixed phase fluids. Although the duration of the test using this apparatus was limited by the forced closure of the HGP-A Generator Facility prior to its planned shut-down date, sufficient data was obtained to allow us to evaluate the impacts of the recombination of the geothermal waste streams and to demonstrate that recombination of the fluids was not only feasible, but appeared to result in a more stable fluid, in terms of silica scale deposition, than occurred with the brine stream alone.

#### Test Stand Design

The test stand was designed to allow us to evaluate the effects of sequentially combining the discharge brine phase from HGP-A with steam condensate and with non-condensable gases from the power plant condenser. The specific design criteria that were included in the fabrication of the test stand were as follows:

- 1) Must be able to carry a continuous flow rate of the combined fluid streams of one cubic meter per hour (16.7 l/min; 4.4 gpm);
- 2) Allow recombination of the three fluid streams at a range of proportions and at a range of temperatures;
- 3) Permit the direct observation of the effects of fluid recombination on the dissolved solids present in the brine phase;

- 4) Provide direct sampling of the mixed phases;
- 5) Allow exposure of metallurgical and rock samples to the mixed phase fluids;

A line diagram of the design that was arrived at is presented in Figure 1. The system design is comprised of four basic units: the brine, condensate, and non-condensable gas inlet systems, and the mixed phase test system. The brine inlet consists of an insulated supply system taking brine at the plant operating pressure (nominally 150 psig) and temperature (nominally 353°F) and passing it through a single pass, tube-in-tube heat exchanger (COOLER, Fig. 1) and a check valve and into the mixed phase test system. Although temperature and pressure were monitored on this line, because of the high temperatures and high potential for scaling, neither flow metering nor pH measuring devices could be exposed to the brine. The condensate inlet consisted of a feed line taken off the condenser discharge ( $T = 124^{\circ}\text{F}$ ;  $P = 20$  psig), through a positive displacement pump, a single pass heat exchanger, a flow control valve, and a check valve, and then into the mixed phase system. Pressures in the line downstream of the positive displacement pump were controlled using a pump by-pass line. The lower temperatures and pressures in the condensate line allowed us to monitor the condensate pH and flow rate in addition to the temperature and pressure. The non-condensable gas line drew gas from the condenser off gas line ( $T = 100^{\circ}\text{F}$ ;  $P = 4$  psig), through a moisture separator, and into a compressor. The gas was compressed into an expansion tank and, from there, through a check valve and flow control valve into the mixed phase line. This line was also instrumented with pressure and flow metering devices.

The mixed phase line was designed to accept and mix the liquid and gas phases from the three inlet lines and to then allow us to evaluate the characteristics of the mixed phase fluid. The line consisted of a static mixer placed immediately downstream of the condensate and brine injection points, followed by temperature, pressure, pH, and flow measuring devices. The gas injection line entered the system immediately downstream of the liquid mixing and monitoring equipment, and was followed by a second static mixer element, a variable length "delay line," a view port, and a testing manifold and a discharge line. The intended function of the individual elements in this portion of the test stand were as follows:

Static Mixer: ensure that adequate contact surface area would be generated between the gas and the liquid phases in the line;

Delay Line: allow us to vary the contact time between the liquid and gas phases to determine the significance of possible kinetic effects controlling the reaction of the fluids to the gas injection;

View Port: enable us to make qualitative observations on the degree of gas dissolution and of solids precipitation;

Testing Manifold: provide ports for sampling and for installation of exposure chambers to test for corrosion and scaling potential of the mixed phase fluids;

Discharge system: carry fluids to the plant discharge system and allowed for treatment of the non-condensable gases by injection of cooling water and hydrogen sulfide abatement chemicals as needed.

In order to minimize the degree of corrosion of the test system and to limit contamination of the geothermal fluids with corrosion products from the test stand, the system was fabricated of type 316 stainless steel or stainless steel reinforced teflon. The only exceptions to this were

that the condensate and the non-condensable gas feed lines were fabricated of PVC pipe, the view port was of heavy-walled glass tubing, and, due to cost considerations, the non-condensable moisture separator and gas compressor were fabricated of mild steel. In order to maintain reasonable flow rates with acceptable pressure drops, all liquid flow lines were one inch (inside) diameter pipe except for the delay coils which were 3/4 inch stainless steel reinforced teflon flexible hose. In order to minimize heat loss from the fluid, all high temperature stainless steel lines were insulated with one-inch thick fiber glass. A detailed list of the major items of equipment and the manufacturers is presented in Table 1.

#### Test Plan

The objectives of the test were to determine the optimum conditions for the recombination of the geothermal waste streams prior to, or during, reinjection of the geothermal fluids, to determine the impacts of fluid recombination on the fluid chemistry, and to evaluate the metallurgical impacts of fluid recombination of the geothermal fluids. Because the results of this evaluation were of direct significance to the design of the Puna Geothermal Project reinjection system, the research plan was to begin the experimental work by testing the characteristics of a mixed fluid having a chemical composition similar to that which would be injected from a power plant using fluids from the Kapoho State 1A geothermal well on the Puna Geothermal Venture lease adjacent to the HGP-A site. The test plan was to then vary the composition of the reinjectate over an extended range to determine whether variations in the composition would yield a more easily handled fluid or one that would allow more heat to be extracted from the fluids prior to reinjection.

Although it would have been extremely difficult to artificially formulate a reinjectate fluid having a composition identical to KS1-A, by controlling the flow rates of brine, condensate, and non-condensable gas into the test system, a mixed fluid could be produced for which the temperature, the concentrations of silica and hydrogen sulfide, and other key reactive species would be nearly identical to KS1-A reinjectate. The design parameters for the planned binary power generation system using KS1-A fluids were calculated to yield a reinjectate having a temperature of approximately 210°F, a silica concentration of approximately 340 mg/kg, and a hydrogen sulfide concentration of 1000 mg/kg. Because the dissolved solids concentrations in the brines were higher, and the proportion of brine produced was greater in the KS1-A well than in any of the other wells drilled on the Puna Geothermal Venture lease, it was considered that this reinjectate would represent a "worst case" situation for fluid disposal. However, the test plan also allowed for variations in compositions to be tested in order to determine both the optimum design parameters as well as the design limits of gas/brine/condensate injection approach to fluid disposal.

Evaluation of the physical and chemical response of the fluids to mixing included assessment of the following:

Variations in pH of the mixed phases;

The extent of homogeneous (fluid phase) precipitation of silicates and sulfides;

The extent of heterogeneous precipitation of silicates and sulfides (onto metal and basaltic substrates);

The rate and degree of dissolution of the mixed gas into the reinjectate liquid phase;



The corrosivity of the mixed phases on various alloys of stainless and mild steel.

In order to evaluate pH changes in the fluids, the test stand, as described above, was instrumented with high pressure and temperature pH probes downstream of the liquid and gas phase injection and mixing points. A sampling port allowed us to obtain samples of fluid through a filtration device to determine the extent of homogeneous precipitation of sulfides; a pair of exposure tanks allowed us to pass the mixed fluids through a bed of rock chips and over a set of metal samples to determine both the rates of heterogeneous deposition of precipitates and the corrosivity of the mixed fluids. A delay coil and a view port were installed in the test system that were to be used to determine the rate and degree of dissolution of the gases in the mixed phase. The delay coil, consisting of a set of flexible woven stainless steel-reinforced teflon lines that could be connected together, to allowed us to pass the fluid through lengths of tubing ranging from approximately 3 meters to approximately 20 meters and extend the contact time of the gas and liquid from approximately 5 seconds to approximately 40 seconds. Observation of the mixed phase downstream of the the various lengths of delay coil allowed us to make a gross determination as to whether gas dissolution increased substantially with the increase in contact time.

#### Experimental Protocol

Two experimental runs were conducted: the first evaluated the impacts of mixing the brine and steam condensate streams and the second evaluated the results of mixing all three streams, brine, condensate, and non-condensable gases, together. Although additional experimental runs were planned, shut-down of the HGP-A Generator facility limited the time

available and thus precluded the evaluation of different fluid compositions and temperatures.

Preparation of the system for a brine/condensate mixing run included the following procedures:

The exposure tanks used for heterogeneous precipitation of solids from the fluid were loaded: one with fine basalt chips and the other with pre-weighed metal coupons. The basalt chips were sized to dimensions of 3 mm or less and were washed both prior to and after loading into the exposure tank. The metal coupons used for the exposure experiments were supplied by Puna Geothermal Venture, and were fabricated from SAF 2205 and SS 316L alloys.

The exposure tanks were installed on the system to allow a parallel flow of mixed fluid through both tanks for the duration of the mixing run.

The system was then pressure tested using steam condensate to confirm that any leaks within the system were of a manageable size. (Because the system was fabricated of threaded stainless steel components, a completely leak proof system was not considered to be reasonably achievable.)

Start-up of the system was initiated by pressurizing the flow line and establishing fluid flow through the pumped condensate injection system. Condensate flow was initially set at approximately 3 gpm, at a pressure of 150 psig, through manual manipulation of a pump by-pass system, the inlet valves, and the system discharge valve manifold. After temperature and flow equilibrium were achieved with condensate alone, brine was admitted into the system and flow was gradually increased until the brine flow rate provided the appropriate temperature and silica concentration in the mixed phase. Although the experimental plan was to determine the brine flow by difference between the measured condensate and

mixed flow sensors, we encountered difficulties with the mixed-line flow sensor and were required to use an alternate method to determine brine flow that utilized the heat balance among the brine, condensate, and mixed phases. Because heat is a conservative parameter under the experimental conditions, this presented no difficulty and, in some respects, was a more certain measure of the liquid flow rates because mechanical errors are not a consideration in performing the measurement. It should also be noted here that care was required in establishing brine flow into the system in order to balance the flow rate and pressure at a point where the brine could be admitted to the system without allowing it to flash to steam. Prevention of brine flashing was considered critical to both the integrity of the system - due to hammering of the steam as it was condensed in the mixed phase line - as well as in the prevention of scale nucleation that is triggered by the boiling process.

During the initial start-up phase of the experiment, we found that both the temperature and fluid flow rates showed a cyclic behavior that was induced by the operating characteristics of the plant separator level control valve; as the valve opened to discharge brine from the separator, the pressure and brine injection rate in our feed line fell, allowing more condensate to be injected into the line; as the level control valve closed, the reverse happened. Because we could not maintain a constant pressure in the plant brine system without risking plant operational problems, the inlet and discharge system were set to minimize the flow rate variations and the testing was continued with temperature excursions spanning a range from approximately 196°F (91.1°C) to 220°F (104.4°C). The brine and condensate flow rates and the silica and chloride concentrations that correspond to these temperatures are presented in

Table 2. During this phase of the test we also encountered a number of problems with the condensate pump tripping its electrical supply breaker. As a result the initial test run was terminated after seven hours. After arranging for a twenty-four hour watch over the system to ensure that loss of condensate pressure would not allow undiluted brine to pass through the test system the test was restarted.

On restarting the continuous flow test on November 26, and establishing as stable a flow as possible at approximately 5 gpm and a temperature of about 210°F, flow through the system was partially diverted to a bypass line that allowed us to observe the fluid through the viewport to determine whether significant precipitation was occurring. Further evaluation of precipitation rates were also undertaken by installing a pressurized filter system on a side stream of the mixed phase flow. The filters employed were 90 mm diameter and 0.45 micron pore size and were allowed to pass up to 200 liters of mixed fluid to determine the mass of precipitate present in the volume of fluid passed. The unfiltered stream was split and allowed to flow through two parallel lines into the exposure tanks to allow solids deposition onto both the metal substrate and onto the basalt chips. The fluid from the exposure tanks was then discharged through the fluid disposal system into the brine sump.

Continuous fluid flow during this phase of the test was maintained until December 4. There were, however, two periods during which flow conditions were modified substantially due to loss of the condensate pump breaker. During the interruptions, the system was allowed to flow only condensate at a reduced pressure and flow rate for periods of 3 hours and 5 hours, respectively, during which time the pump breaker was reset and the system was brought back up to operating pressure and to stable flow.

In anticipation of the imminent shut-down of the HGP-A facility, it was decided that adequate data had been collected after approximately eight days of brine/condensate mixed flow and this phase of the experiment was terminated on December 4. Immediately after completion of the test run, the corrosion coupons were retrieved and samples of the basalt chips were recovered from the exposure tanks. The corrosion coupons were reweighed and stored in plastic bags; the basalt chips were saved for later microscopic examination.

Prior to the initiation of the second experiment, the sample exposure tanks were rinsed and re-loaded with weighed stainless steel coupons and with a fresh charge of basalt chips. On December 5, 1989 condensate and brine flow through the test system were reestablished as described for the first experimental run. After flow stabilization was achieved, gas injection into the liquid flow stream was initiated. This attempt to inject gas was almost immediately aborted, however, as it was discovered that a substantial amount of water was being carried over to the compressor from the power plant gas ejection system. In order to alleviate this problem, it was necessary to re-configure the non-condensable gas feed system to allow the majority of the water to be removed at the knock-out drum upstream of the incinerator system. After this work was completed, the gas injection system was restarted on December 7. In spite of a number of difficulties encountered with gas pressure stability and injection rates into the mixed flow line, we were able to inject gas into the liquid phase system for a period of approximately 48 hours before failure of the gas metering device forced us to terminate the gas injection phase of the experiment. At the conclusion of the gas injection test, the metal coupons and samples of the basalt

chips were recovered from the exposure tanks. Over the course of this run samples of filtered fluid were also recovered following an identical protocol to that used in the fluid mixing experiment.

### Results and Discussion

Even though the time available for experimental work on the test system was severely constrained due to the premature shut-down of the HGP-A facility, the work that was accomplished was far more successful than anticipated. The results of the brine/condensate/non-condensable gas recombination experiments clearly demonstrate that recombination of the three fluid streams did not generate chemical changes in the mixed fluid that are considered likely to affect our ability to reinject waste fluids from Hawaii's geothermal resource. The mixed fluid produced under the anticipated reinjection conditions for the PGV design showed only trace amounts of homogeneous precipitation of sulfide minerals and even smaller quantities of silicate deposition. More surprisingly, the mixed fluids showed a marked increase in stability, with respect to silica deposition, rather than any indication of a decrease in stability; silica deposition from the mixed fluids were negligible even after aging for several days at ambient temperatures.

#### Brine/Condensate Mixing

During the course of the brine and condensate mixing experiment, visual observation of the fluid streams indicated no detectable precipitation or turbidity increase in the mixed phase fluids. Filter samples taken of the brine/condensate mix showed that sample volumes of one hundred liters or more, when passed through a 0.45 micron filter immediately after mixing, produced virtually no visible precipitate on the filter and no indication of an increased pressure drop across the filter.

Field measurements of the weights of the filters after passing the mixed fluids were not detectably different from their weights taken prior to the filtration experiments. More precise measurements taken at a later date showed that the weight of solids deposited ranged from 11 mg to 42 mg on a given filter. Calculated deposition rates, based on the amount of solid recovered and the volume of fluid passed by the filter ranged from 0.073 mg to 0.21 mg per liter of fluid (Table 3). Twenty liter samples of mixed fluid, after nucleation and aging periods of 24 and 72 hours were re-filtered to determine the stability of the mixed fluids with respect to silica precipitation. The second filtration again yielded less than 10 mg of solids. The visual appearance of the fluids was consistent with these findings: samples immediately after mixing and, later, after aging showed no evidence of turbidity or suspended solids (Figures 2 and 3).

The pH of the mixed fluids were near neutral ranging from 5.7 to 6.3 depending on the proportion of brine to condensate. These values suggest that the buffering capacity of the brine is adequate to tolerate the injection of substantial amounts of condensate without having the pH fall to levels that are at equilibrium with carbonic acid present in the condensate.

Analysis of the corrosion coupons indicated that there was no scale deposition detectable and that no clear evidence of corrosion was apparent. The sample weights taken after exposure to the mixed fluids were, within the error limits of the balance, identical to the sample weights taken before exposure (Table 4). Scanning electron micrographs of the metal coupons further substantiate these results, showing no apparent difference between the untreated samples and those exposed to the mixed brine condensate streams (Figures 4 and 5); the samples show only very

small amounts of scale deposition and no indication of pitting or generalized surface corrosion. The basalt chip samples showed no detectable difference between the exposed and unexposed samples when examined under a light microscope.

#### Gas Mixing

Although the injection of the non-condensable gases into the fluid stream encountered a number of operational problems, the results of the injection experiment will enable us to address several issues regarding a larger scale gas injection effort. Among the questions that were of greatest concern are the following:

- 1) Are the non-condensable gases soluble in the fluid phase at pressures normally encountered in surface equipment;
- 2) What are the effects of the gas injection on fluid pH; and
- 3) Will the injection of hydrogen sulfide or carbon dioxide cause substantial amounts of precipitation of sulfide or silicate minerals.

Observations made of the mixed gas and liquid flow stream showed that, at the pressures of the experiment, a residual gas phase remained in the flow lines at virtually all gas addition rates (Figure 6). However, pH observations showed that equilibrium between the carbon dioxide and hydrogen sulfide were rapidly achieved in the liquid phase. Although it was not possible to sample the residual gases, the relatively high solubility of carbon dioxide and hydrogen sulfide in water at these pressures and the much lower solubility of nitrogen and hydrogen suggest that the residual phase was largely comprised of the latter gases.

The pH of the mixed fluid and non-condensable gases showed a clear correlation between the amounts of gas injected and the aqueous phase pH. Moderate amounts of gas (5 to 10 stp l/m) injection yielded a drop in pH



of the fluid from approximately 5.8 to 4.5. An increase in the gas injection rate to approximately 20 stp l/m further decreased the fluid pH to 3.6. Although these values are lower than expected, subsequent to completion of the experiment, we discovered what may have caused the apparent anomaly. Disassembly of the equipment showed that a substantial amount of elemental sulfur (as well as sulfide minerals) had been deposited in the compressor head and in the pressurized injection line. Atmospheric oxygen entry into the condenser system could account for the oxidation of hydrogen sulfide to produce both elemental sulfur as well as sulfur dioxide and sulfuric acid. The presence of atmospheric oxygen was later confirmed when several leaks were found in the condensate hot-well of the plant subsequent to shut down of the facility several days after the completion of this experiment. The size and location of these leaks would have allowed substantial amounts of air to be entrained in the non-condensable gas that reacted with hydrogen sulfide in the compressor to produce sulfur and acid sulfur gases. Hence, the lower pH values are believed to have been the result of the addition of the more acid oxidized sulfur species. Exclusion of oxygen from the reinjected gases, as would occur with a commercial geothermal facility, would allow the mixed fluids and non-condensable gases to maintain a pH in the range of approximately 4 to 4.5, the pH of the condensate.

As noted above, different volumes of gases were injected into the flow line to determine both the pH effects of the gas concentrations as well as to obtain an indication of the relative proportion of gases present as a separate phase in the flow line. The results of this effort indicated that a separate gas phase was present at every injection rate of N-C gases that was attempted. The relative proportions of the gas phase

changed appreciably as the rate of gas injection was varied. Studies of carbon dioxide and hydrogen sulfide solubilities in aqueous phases (Kohl and Risenfeld, 1979) clearly show that the equilibrium saturation concentrations of these gases under our experimental temperature and pressure conditions are substantially higher than the amounts of gas injected into the brine condensate mixture. This suggests that over contact periods of 20 seconds or less, equilibrium between the gas and the liquid phases is not achieved. This is consistent with laboratory studies of carbon dioxide dissolution in aqueous phases which show that the dissolution process for this gas is relatively slow. Extension of the delay line from approximately 10 meters to 20 meters had no clearly detectable effect on the relative proportion of the gas to the liquid phase suggesting that gas contact times of several minutes may be required to obtain complete dissolution at 150 psia. However, it should be noted that, at higher pressures, the relative volume of gas should decrease and the rate of dissolution will increase substantially.

Although the data obtained during this phase of the experiment were quite limited, the implications of the results are clear. At the pressures and temperatures of the anticipated process conditions for a commercial geothermal facility, mixing of the N-C gases with the brine/condensate stream will yield a two phase mixture in a surface transmission pipeline. Because of the increased pressure losses that would result from transporting a two phase mixture over a substantial distance on the surface, it may be advisable for the gas and liquid phases to be transported separately to the reinjection well where they could be combined at the wellhead or even downhole. If the mixed waste fluids are reinjected into the formation at a depth of approximately 4000 ft.,

contact between the two phases as they move downhole into a progressively higher pressure environment (~1500 to 1800 psi), should enable the non-condensable gases to completely dissolve to form a single phase fluid at the point of reinjection into the formation.

Analysis of the mixed phase fluids for precipitation of sulfides and silicates showed only very small amounts of sulfide were precipitated from solution. A filtration sample volume of 100 l, on filtration through a 0.45 micron filter, yielded a slight darkening of the filter surface. The mass of the solids recovered on the filter was approximately 77 milligrams for a precipitation rate of 0.769 milligrams of solid per kilogram of fluid. The mass of solid recovered has also clearly been impacted by the mixing of air with the N-C gases. Energy dispersive x-ray analysis and x-ray diffraction analysis of the filters showed that the major component of the solids recovered is elemental sulfur with much smaller amounts of iron sulfides and silica.

Examination of the metal coupons exposed to the mixed phase fluids also showed a small amount of solids deposition. The scale was present as a fine, powdery, film that was easily removed by gentle abrasion of the surface. The ease of removal of the scale suggests that the material was physically deposited on the surface of the metal rather than chemically deposited on the metal substrate. Scanning electron micrographs of the metal coupons show that the thickness of the sulfide scale layer on the metal coupons was approximately 10 microns thick (Figure 7a and 7b). Energy dispersive x-ray analysis of the scale found predominantly sulfur with lesser amounts of iron sulfides and other transition metal sulfides. Silicate deposition was found to be a minor component of the solids deposited on the coupons.

The scanning electron micrographs of the metal coupons that were exposed to the mixed phase fluids show no detectable evidence of metal loss or corrosion: coupon samples exposed to the geothermal fluids show no detectable difference from samples that were held as unexposed controls. The only evidence of corrosion found was what appears to have been sulfide embrittlement in a stainless steel sponge used as a solids trap in one of the exposure tanks. Prior to exposure, the metal, which resembled fine lathe turnings, was very flexible; after exposure to the mixed brine/condensate/N-C gases the turnings became very brittle and fragile. A similar sample of sponge that was exposed to the brine/condensate mix did not show an equivalent alteration in character. The grade of the steel from which the sponge was fabricated was 430 stainless steel.

Although the relatively small amount of scale deposition from the mixing of the liquid and gas phases indicates that mixing of the liquid and gas waste streams does not generate significant amount of solids, it is also clear that the amount of solids deposited in this experiment may be substantially higher than would be produced from mixing pure N-C gases with the liquid phase. As noted above, oxygen and water in the non-condensable discharge allowed the formation of elemental sulfur (and oxidized sulfur compounds) in the compressor system that was carried over into the mixed fluid portion of the test stand. This is believed to account for the predominance of elemental sulfur (identified by x-ray diffraction) as well as for a significant portion of the iron sulfides. The latter are believed to have been generated by sulfur and carbonic acid attack of the compressor and expansion tank. This hypothesis is supported by the occurrence of periodic bursts of black sulfide particulate that

were observed to pass through the view port on system during the gas injection experiment. Although the source of the scale was not immediately recognized, on disassembly of the test stand we found significant amounts of sulfides present in the gas injection line and as well as corrosion and sulfur deposition in the (mild steel) compressor head and valves. Hence, in an oxygen free system, where compression of the N-C gas can be accomplished using stainless steel equipment, the load of sulfide minerals present in the reinjectate may be significantly lower than indicated by the results of the mixed phase testing completed here.

The final observation made on the gas combination experiment relates to the potential for silica deposition from the mixed fluid phase. As note above, filter samples of the mixed fluids taken immediately after the fluids were mixed showed no detectable silica deposition. Samples of fluid were also preserved at room temperature in closed containers for a period of several weeks after the experiment was concluded. During this period of storage, the turbidity of the mixed brine/condensate remained very low and only gradually began to show evidence of colloidal silica formation by the development of a faint bluish cast to the samples. The stored samples of brine/condensate/N-C gases showed even greater stability with no clear evidence of colloidal light scattering developing even after several weeks of storage. This result suggests that the rate of polymerization and deposition of silica from the weakly acid geothermal fluids was much slower than has been observed in untreated geothermal fluids that are either flashed to atmospheric pressure or rapidly cooled and allowed to stand at neutral pH. Hence, the results of this part of the experiment suggests that addition of the weakly acid condenser off-gases stabilize the dissolved silica present in the geothermal brine phase.

## Conclusions and Recommendations

In spite of the limited duration of the geothermal fluid recombination tests conducted at the HGP-A facility, the results of this work clearly demonstrate that mixing of geothermal brine, condensate, and non-condensable gases having compositions similar to those from the KS1-A well and at the temperatures and pressures used in this experiment produce only trace amounts of solid precipitates. These results demonstrate that the optimum conditions under which full-scale reinjection of the geothermal waste fluids to occur are within the range of 150 psig and 200°F to 225°F. The marked contrast between the silica precipitation rate of the mixed fluids and that of the geothermal fluids discharged at the HGP-A facility also suggests that the physical and chemical changes induced by the boiling process (such as occurred in the HGP-A discharge line) may be a key factor in the prevention of scale deposition from the geothermal fluids produced by the Kilauea East Rift Zone.

The results of these experiments also suggest that optimal design of the recombination system may entail the transmission of separate liquid and gas phases to the reinjection wellhead in order to minimize frictional pipeline losses associated with two phase transport of a mixed fluid. Theoretical and laboratory data indicate, however, that the solubility of the individual components of the N-C gases are high enough that the gas phase will completely dissolve at the temperature and pressure conditions that are likely to occur in the formation around a reinjection well.

The remarkable increase observed in the stability of silica with respect to polymerization and precipitation in response to the addition of steam condensate indicate that a similar approach could be very valuable if applied on a commercial scale. If steam condensate can be added to the

brine phase as soon as it is separated from the steam phase, many of the operational problems encountered in the brine handling system at the HGP-A Generator Facility (fouling of valve stems and seats and fouling of flow monitoring equipment) might be avoidable, with a concomitant improvement in plant reliability and reduction in maintenance costs.

#### Recommendations For Additional Work

Although the tests of the corrosivity of the mixed fluids toward stainless steel coupons showed no detectable corrosion, the short duration of the test renders any conclusions from this aspect of the test somewhat speculative. It is recognized that the availability of geothermal fluids will delay further corrosion and gas recombination testing until after completion of design and construction of the first commercial geothermal facility in Hawaii. However, after commercial production of geothermal fluids is initiated, additional corrosion testing could be done in order to both confirm the results of this work as well as to conduct a broader survey of alloys and composite materials in an effort to economically optimize the installation and operation of future geothermal facilities. Hence we would recommend that a second series of gas recombination and corrosion tests be conducted over a longer term and over a broader range of fluid compositions than was possible during the present experimental work. Such an effort could provide additional data on the realistic design limits of the gas injection process and assist in the design of least-cost waste fluid reinjection systems.

Table 1  
Major Equipment Manufacturers

Item	Manufacturer
N-C Gas Compressor	Corken Model D191AM9FDBA
Condensate Pump	Oberdorfer Model 9156C
Sensing Equipment	Omega Engineering
pH Meter	PHTX-92
pH Probe	PHE 5431-10
High Temp. Liquid Flow Meter	FP-5210
Low Temp. Liquid Flow Meter	FP-5300
Gas Flow Meter	FMA-5700
Particle Filter	Cole Parmer Inst. Supply Model N-02927-50
Caustic Metering Pump	Ryan Herco Model A141-155
Cooling Water Pump	Little Giant TE-7-MD-HC
Pressure Transducers	National Semiconductor Model LX1430
Valves and Fittings	Swagelok



Table 2  
Range of Key Fluid Parameters During Fluid Mixing Experiments

Mixed Phase Temperature	196°F (91.1°C)	220°F (104.4°C)
Brine Flow	1.48 gpm (5.6 lpm)	2.05 gpm (7.76 lpm)
Condensate Flow	3.26 gpm (12.3 lpm)	2.85 gpm (10.79 lpm)
Chloride Concentration	3100 mg/kg	4200 mg/kg
Silica Concentration	2.63 mg/kg	3.57 mg/kg

Table 3  
Filter Weight Changes for Fluid Samples

Date	Weight Change (Milligrams)	Liquid Volume (Liters)	Ppt. Mass Per Liter (mg/l)
11/26/89	10.7	77	0.139
11/28/89	35.2	ND	-
12/2/89	4.21	200	0.2105
12/3/89	35.2	180	0.196
12/3/89*	1.7	20	0.085
12/5/89	17.4	240	0.0725
12/8/89	76.9	100	0.769

\* 24 hour nucleation time

Table 4  
Metal Coupons Sample Weights

Sample Code <sup>#</sup>	Weight Before	Weight After	Change in Weight
BC-R-1	77.17	77.23	0.06
BC-BR-1	27.62	27.71	0.09
BC-BR-2	24.85	24.89	0.04
BC-F-1	12.55	12.56	0.01
BC-F-2	9.32	9.30	0.02
BC-F-3	7.86	7.90	0.03
BCNC-R-1	75.70	75.86	0.16
BCNC-BF-1	31.62	31.68	0.06
BCNC-F-1	7.65	7.69	0.04
BCNC-F-2	9.80	9.82	0.02

# BC = Brine/Condensate  
 BCNC = Brine/Condensate/Non-Condensable Gas

- Figure 1. Test Stand Line Diagram
- Figure 2. Photograph of brine immediately after mixing
- Figure 3. Photograph of brine after 24 hour nucleation time
- Figure 4a. Scanning electron micrograph of metal coupon control sample at a magnification of 260X.
- Figure 4b. Scanning electron micrograph of metal coupon control sample at a magnification of 4000X.
- Figure 5a. Scanning electron micrograph of metal coupon sample after exposure to brine and condensate at a magnification of 260X.
- Figure 5b. Scanning electron micrograph of metal coupon sample after exposure to brine and condensate at a magnification of 4000X.
- Figure 6. Photograph of mixed phase fluid in sight tube showing separate gas phase
- Figure 7a. Scanning electron micrograph of metal coupon sample after exposure to brine, condensate and non-condensable gases at a magnification of 100X.
- Figure 7b. Scanning electron micrograph of metal coupon sample after exposure to brine, condensate and non-condensable gases at a magnification of 1640X.

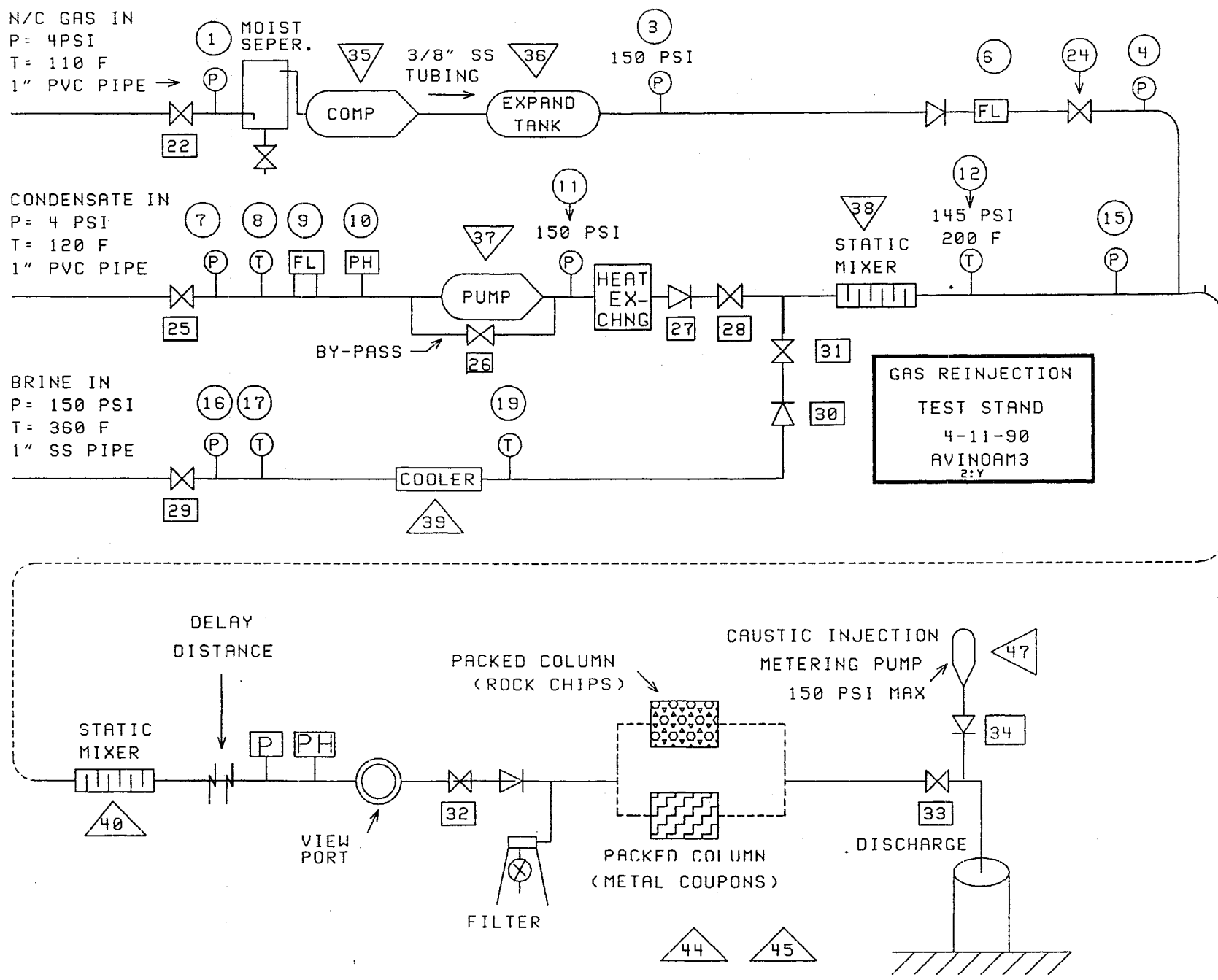


Figure 1. Line diagram of gas reinjection test stand.

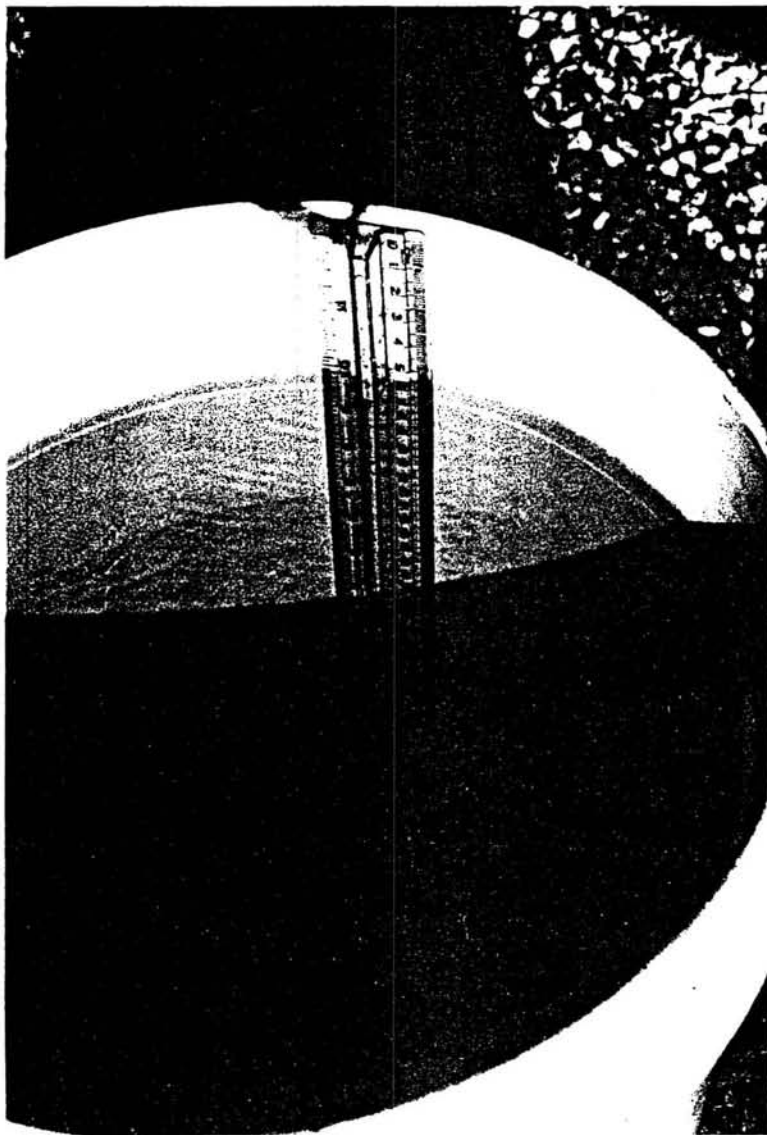


Figure 2. Brine/Condensate mixed phase immediately after mixing.

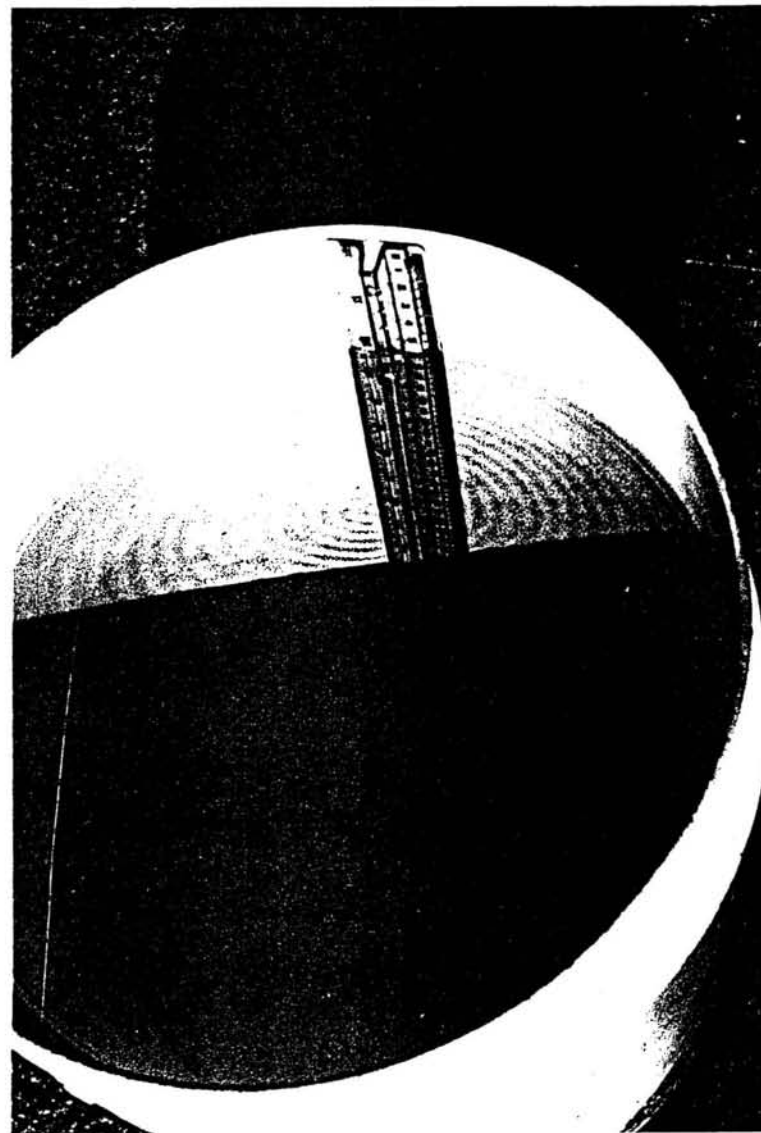


Figure 3. Brine/Condensate mixed phase twenty four hours after mixing.

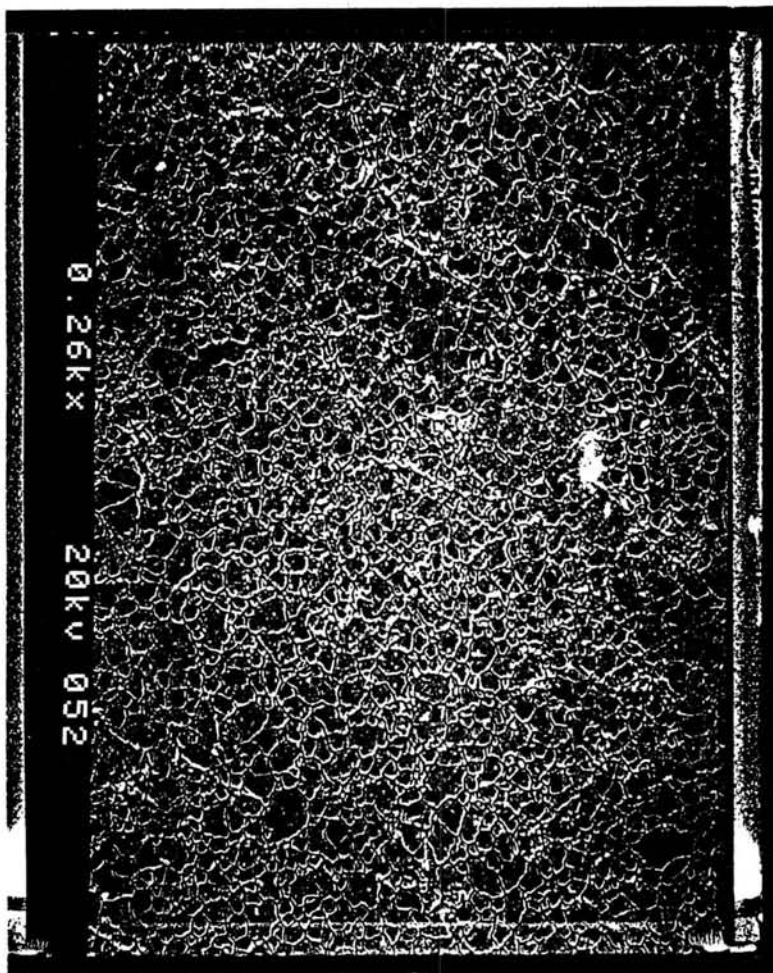


Figure 4a. Scanning electron micrograph of metal coupon control sample (unexposed to geothermal fluids). Mag. = 260X

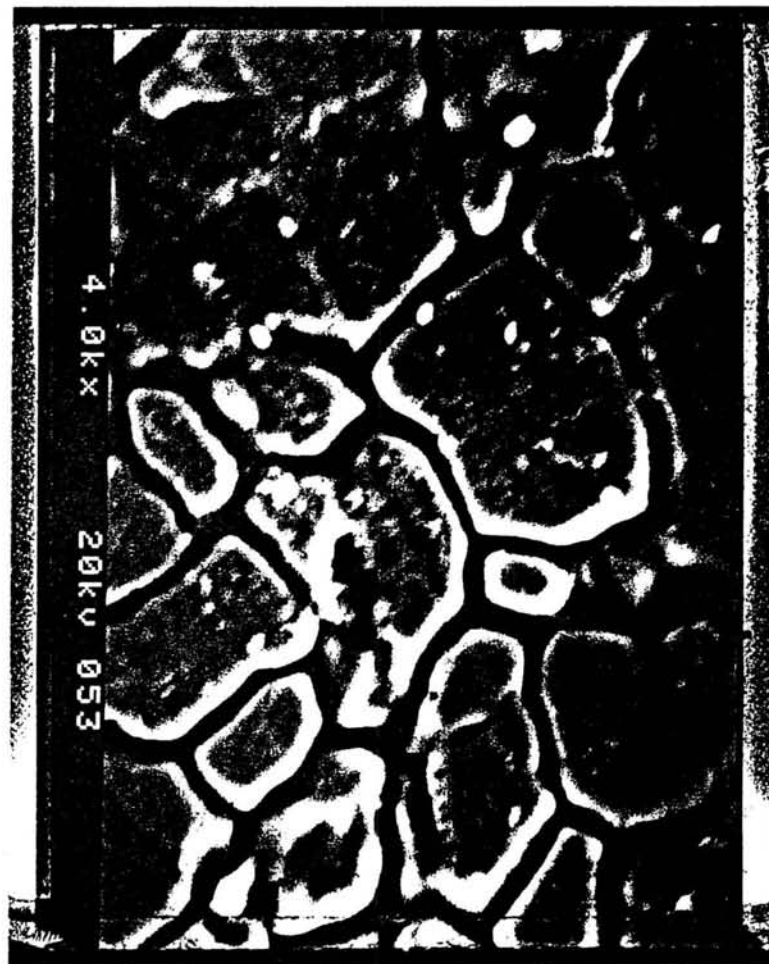


Figure 4b. Scanning electron micrograph of metal coupon control sample. Mag. = 4000X

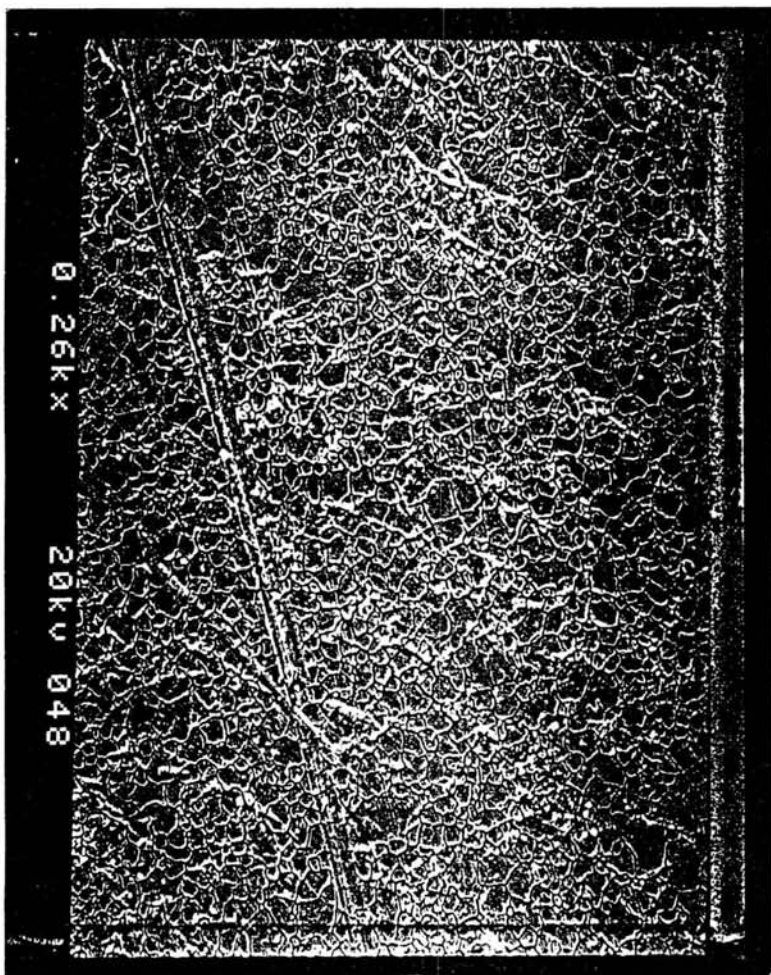


Figure 5a. Scanning electron micrograph of metal coupon exposed to Brine/Condensate mixture. Mag. = 260X

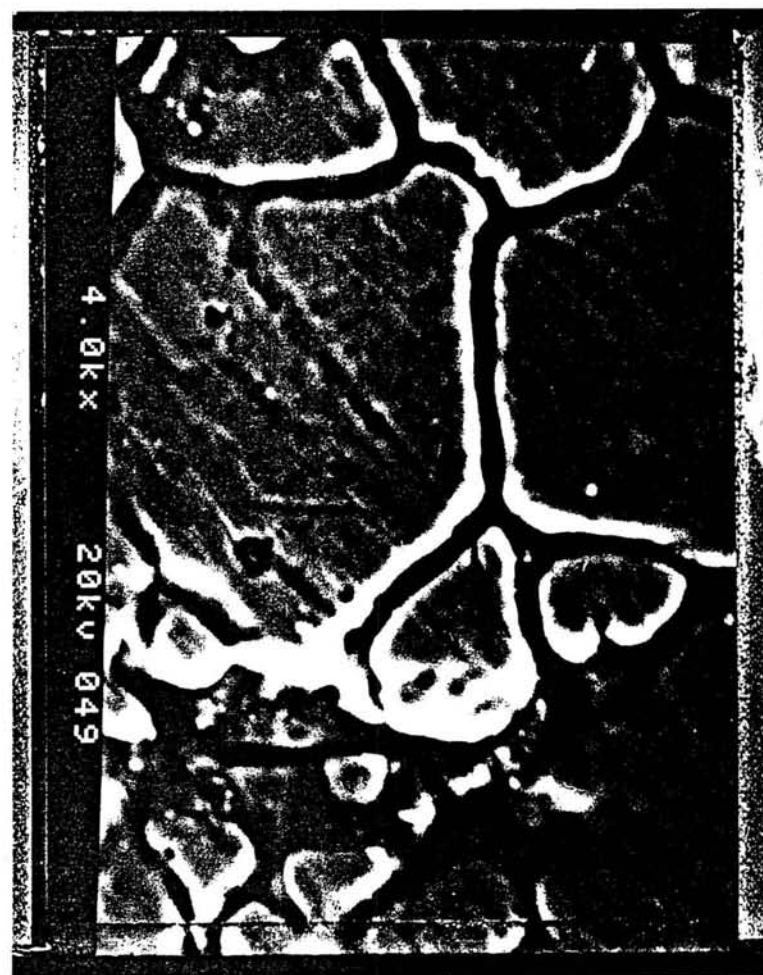


Figure 5b. Scanning electron micrograph of metal coupon exposed to Brine/Condensate mixture. Mag. = 4000X

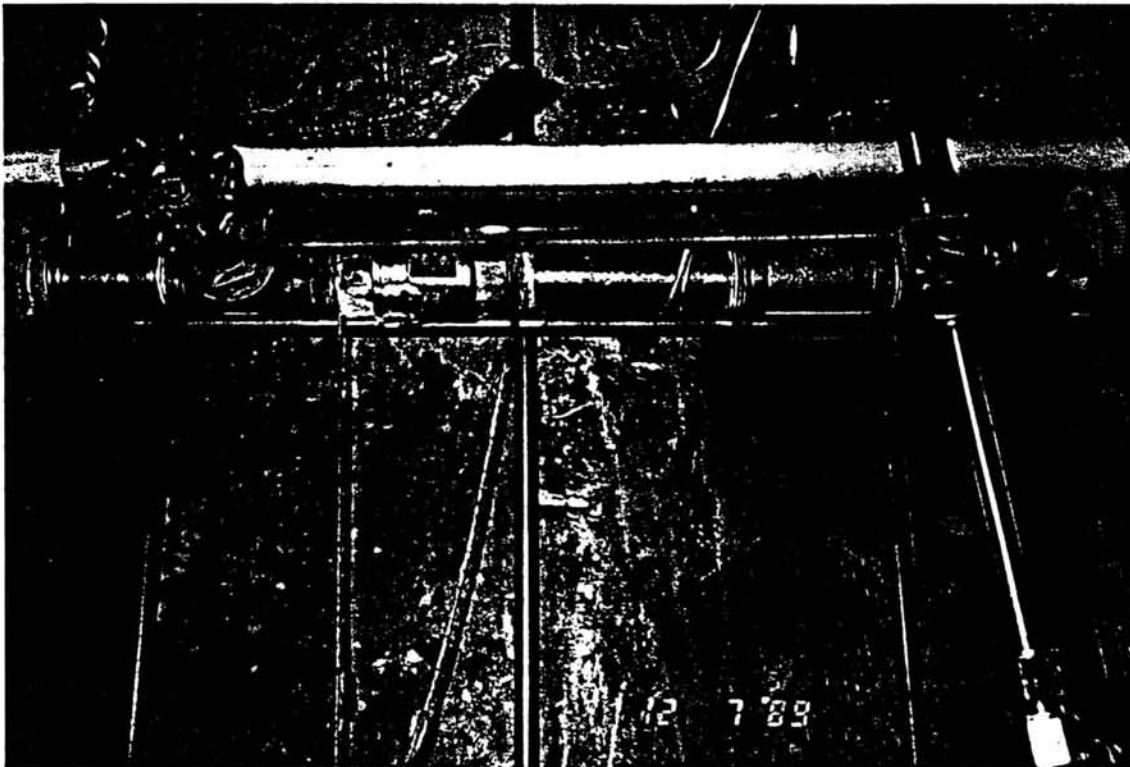


Figure 6. Photograph of mixed Brine/Condensate/Non-Condensable gas phases in sight tube. (Note the dispersion of small gas bubbles in the predominantly liquid phase.)





Figure 7a. Scanning electron micrograph of metal coupon sample after exposure to Brine/Condensate/Non-condensable gas mixture.  
Mag. = 100X



Figure 7b. Scanning electron micrograph of metal coupon sample after exposure to Brine/Condensate/Non-condensable gas mixture.  
Mag. = 1640X

## Bibliography and References

- Iovanitti, J.L., and W.L. D'Olier, 1985, Preliminary results of drilling and testing of the Puna Geothermal Reservoir, Proc. Stanford Geothermal Workshop, 1985.
- Kohl, A., and A. Riesenfeld, 1979, Gas Purification, Gulf Publishing Company, Houston, TX, 825 pg.
- Thomas, D., 1987, A geochemical model of the Kilauea East Rift Zone, Chapter 56 in Volcanism in Hawaii, R. Decker, T. Wright, and P. Stouffer eds., pp. 1507-1525.