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January 2, 1992

Maurice H. Kaya
Department of Business, Economic Development
& Tourism
335 Merchant St., Rm. 110
Honolulu, Hawaii 96813

Dear Mr. Kaya:

Thank you for the opportunity to review the draft final report for DOE Grant No. DE-FG07-88ID-12741, "Silica Control and Recovery in Geothermal Fluids" by Dr. Donald M. Thomas. From the structure of the report and your cover letter, it appears that this is more of an early draft than a near-final product. As such, it is hard to know exactly what the final report will look like, and many of my comments may be unnecessary or inappropriate.

Without a more formal report structure, Table of Contents, and with some missing pages (2-x), the report makes for difficult reading. In addition it seems to be presented as two reports "Silica Control and Recovery from Geothermal Fluids" and "A Test of Geothermal Brine pH Control by Non-Condensable Gas Reinjection". One report has references, the other does not. It is not clear how the two reports relate to each other, since neither is referred to in the other. The first report directly addresses the grant Statement of Work, except for task 4.4 "Fluid Characterization". The first report is very brief, and not very quantitative or detailed, while the second has considerable technical detail and some supporting tables and figures, but little quantitative chemistry. Two separate reports would be perfectly acceptable, but a second, more specific, report should be referenced and noted in the first, more general, report.

I think it is important to use a standard hierarchy for section headings and adequate subheadings to convey the report organization and information to the reader. A copy of a typical Table of Contents from another DOE State Team Final Report is enclosed for your information. Please note that the camera ready copy of the final report will be transmitted to the Office of Scientific and Technical Information (OSTI) for reproduction and distribution by the National Technical Information Service (NTIS).

Those of us familiar with the problems of high-silica geothermal fluids recognize the importance of Don Thomas' work and we know that Don has completed a careful, high-quality study. The final report should include enough data and quantitative chemistry to convey this to industry and to other scientists.

I understand that Don Thomas has many other demands upon his time, and lost considerable time due to his accident. Nevertheless, this final report is long overdue, and DOE is anxious to see a completed final report and to close out this grant.

Additional comments are enclosed, and noted in the margin of the text. Please call me at (801) 524-3444 if you wish clarification of any of these comments.

Please note that DOE will send the final report to a DOE office for Patent Clearance/Review. If it appears that the Principal Investigator or DBED intends to apply for any patents, this should be identified in a letter to the DOE Contract Officer and Project Manager.

Sincerely,

Howard P. Ross

Howard P. Ross
Project Manager/State Cooperative Program

encl.

cc: D. M. Thomas

REVIEW COMMENTS

SILICA CONTROL AND RECOVERY FROM GEOTHERMAL FLUIDS

1. Report needs a cover and title page, with DOE grant number.
2. Include a Table of Contents, showing major sections and subheadings.
3. Include a standard DOE disclaimer.
4. Include an acknowledgement of DOE support and grant number.
5. Include and Abstract for OSTI and NTIS use.
6. Page 2 (plus others?) was missing in draft reviewed.
7. References- some are cited but not listed; some are listed but not cited. Please check for accuracy and completeness.
8. Several parts of the text are awkward because of the long, complex sentence structure. This can be easily corrected with shorter, less involved sentences.
9. The section "Preliminary (more accurately 'conceptual'?) Design of Pilot Scale System) could benefit from a flow chart or schematic diagram to clarify the discussion.
10. Task 4.4, Fluid Characterization, does not seem to be specifically addressed in the report, except for portions of the second report. Could you include some tables of residual fluid compositions, particle size, and settling rates?
11. Task 4.7, Preliminary Evaluation of the Applicability ..to Other Geothermal Systems, would benefit from a table listing some of the other geothermal fluids reviewed, showing basic fluid chemistry, temperature, geothermal field, references, etc.
12. The report needs more quantitative chemistry, i.e. data and formulations, etc. expressing the reactions taking place. Is it not well enough understood at present for this experimental work?
13. The report needs to show the data used to develop the conclusions and the results in graphic form. It should include analyses of brines, preflash and postflash.
14. Were any changes observed in the basalt chips?
15. Several photomicrographs are presented as supporting data. More discussion of the significance of the photomicrographs is needed.

Typical SCP report format

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STATE OF HAWAII
1959

JOHN WAIHEE
Governor

MURRAY E. TOWILL
Director

BARBARA KIM STANTON
Deputy Director

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DEPARTMENT OF BUSINESS, ECONOMIC DEVELOPMENT & TOURISM

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December 6, 1991

Rec. 12/12/91
HPR

Ms. Mary Wilcox
U.S. Department of Energy
785 DOE Place
Idaho Falls, Idaho 83402

Dear Ms. Wilcox:

Attached is the draft Final Technical Report required under Grant No. DE-FG07-88ID-12741, "Silica Control and Recovery in Hawaiian Geothermal Fluids."

In order to reduce processing time, we are reviewing and commenting on this report, prepared by Dr. Donald M. Thomas, concurrent with your review.

We are retaining the single set of original photographs, figures 2 through 7, for inclusion in the final edition of the report.

Sincerely,

Maurice H. Kaya
Energy Program Administrator

MHK/GOL:jms:272

Attachment

cc: Howard Ross

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Attachment

cc: Howard Ross

Joe

A Test of Geothermal Brine pH Control by Non-Condensable Gas Reinjection.

CONTENTS

Joe

Silica Control and Recovery From Geothermal Fluids

CONTENTS

13/12

Silica Control and Recovery From
Geothermal Fluids
Draft Final Report

Introduction

The HGP-A geothermal well, drilled in 1976 to a total depth of 1966 m on the East Rift Zone of Kilauea Volcano, has one of the highest bottomhole temperatures of any geothermal well ~~that has been put into~~ used for commercial production. As a result of the high temperatures, the fluids produced by the well have higher concentrations of silica than those in most other geothermal fields around the world. In 1981, a 3 MWe wellhead generator was installed on the HGP-A well in an effort to determine whether it was technically feasible to produce electrical power from the silica- and H_2S-rich fluids found in the Kilauea East Rift Zone. This generator facility was able to produce power for approximately eight years with an availability factor in excess of 90%. ~~but~~ It also showed that the high concentrations of both silica and H_2S required extraordinary maintenance efforts in order to allow ~~the generator facility to~~ operat~~e~~ion in an efficient and environmentally acceptable fashion.

Operation of the facility showed that deposition of silica scale in the well casing and piping system upstream of the separator was relatively modest but that, after discharge from the separator, scale deposition within the brine disposal system constantly fouled the pipe walls and the control valves. Scale deposition within this system required constant maintenance and forced replacement of equipment on a far more frequent basis than would otherwise have been necessary.

Although the higher maintenance requirements generated by deposition within the brine system would have had a substantial impact on the economics of power generation in this geothermal field, the silica deposition rates found in the brine disposal

pg. 2+ missing

6) characterization of the silica byproduct recovered from the brine phase;

7) evaluation of the feasibility of applying the treatment system developed to other geothermal systems in North America.

Although work was conducted on all of the planned subtasks, a combination of experimental difficulties and external events prevented our pursuing all of the planned studies to their ultimate conclusion. The most significant of the external circumstances was that, during the course of our study, it became apparent that operation of the HGP-A geothermal well would be terminated sooner than we had anticipated. Because this well represented our only source of geothermal brine, a decision was made to focus on those experiments that required a continuous stream of brine and that would provide the most practical returns in the shortest amount of time. Hence, a decision was made to abbreviate the basic investigation of the kinetics of silica polymerization in the brine phase as well as the batch precipitation studies and to concentrate instead on the testing of continuous treatment of hot brine. This decision was based on the assumption that demonstration of a successful continuous treatment system would have greater utility to the geothermal industry than a detailed study of silica kinetics that could prove to be applicable primarily to geothermal fluids from HGP-A and not to other wells in Hawaii or to other geothermal fields.

RESULTS

Silica Polymerization Studies

The silica polymerization studies were intended to investigate the changes in the rate of silica polymerization in the geothermal brines as a function of brine pH and as a function of changes in the concentration of various metal ions and other industrial reagents added to the geothermal brines. The experimental plan called for rapid chilling of brine in a heat exchanger and immediate addition of the reagents followed by rapid analysis of the brine for dissolved silica using the molybdate blue method. The latter method was chosen because it is sensitive to dissolved silica only and not to silica that has polymerized and remains suspended in the fluid in a colloidal state.

any reference or more detail ?

Preliminary experiments showed that addition of caustic to the brine rapidly accelerated the rate of silica precipitation; similarly, the addition of trace quantities of iron and aluminum appeared to further accelerate the deposition. However, these investigations also showed that the presence of hydrogen sulfide dissolved in the brine phase interfered with the polymerization effect since it competed with the silica by the formation and precipitation of iron sulfide thereby preventing its binding to the silica polymer.

Effect of pH

Our interpretation of the effect of pH on the precipitation of silica from the geothermal fluids is that polymerization of silica, although highly favored at low temperature, is severely impeded by the formation of short chain silica polymers that carry a very high surface charge. Growth of the short chain polymers is controlled by the high surface charge and hence, as the concentration of dissolved silica falls, the polymerization rate is retarded due to the reduction in the chemical potential of the silica hydrate. However, it has been shown (Iler,1976) not in refs. that the surface charge of the silica polymer is a function of pH and that, at elevated as well as at very low pH, the surface charge is lost and polymerization can proceed at a far more rapid rate.

Addition of Metal Ions

The acceleration of polymerization by the addition of metal ions operates on a similar basis. The surface charge of the silica polymer is strongly negative; in the presence of a strong positively charged metal ion, the silica polymer will rapidly scavenge a metal ion, which will locally neutralize the surface charge and will enable additional silica hydrate species to attach to the polymer. The strong effect of even trace quantities of metal ion (5 ppm) in the presence of several hundred ppm of silica strongly suggests that the neutralization of surface charge enabled not only the silica hydrate to attach to the polymer but that cross linking of already formed polymers was the primary mode of formation of the silica gels promoted by the metal addition.

At the conclusion of our preliminary investigations, we attempted to do a more detailed analysis of the polymer formation rates using an automated analyzer that could provide silica analyses in very short times after the addition of reagent to the brines. Unfortunately, we found that the presence of sulfide in the fluids apparently had an adverse effect on the analysis method and yielded silica values much lower than were present in the geothermal fluids. Although we attempted to circumvent this problem by treatment of the brine phase with peroxide to convert the H_2S to sulfate, this was not successful and, due to the limitations on the time available to pursue this study, we suspended, and ultimately were forced to terminate this investigation until such time as we can gain access to fluids from an operating geothermal well.

<u>Low Temperature Brine Treatment System/Bench Scale Treatment System</u>

Because of the similarity of the objectives of these two subtasks, a single, continuous-treatment system was fabricated that was capable of treating both low temperature and high temperature fluids (Fig. 1). This system was designed to allow us to inject reagents into hot, untreated brine, cooled brine, or brine diluted with condensate. The most significant feature of the system was that it also allowed us to add geothermal non-condensable gases to the fluid as a pH control reagent. Our decision to use non-condensable gases for pH control was based on several considerations:

1) our literature survey had indicated that pH control was a critical factor in the strength of the surface charge developed by the silica polymer;
2) our polymerization kinetics study indicated that the surface charge effects were the major factor controlling the formation of silica scale and silica gels from the geothermal brines;
3) although maintenance of a slightly acid pH in the fluids was expected to give the greatest silica stability, addition of too much acid, or a too strong acid, also had the potential for destabilizing the silica polymers in solution.

Hence, it was apparent that the addition of a buffer or a weak acid would be able to maintain the brine pH in the optimum range without running the risk of forcing the brine pH to too low a value with resultant silica precipitation. Because both carbon dioxide and

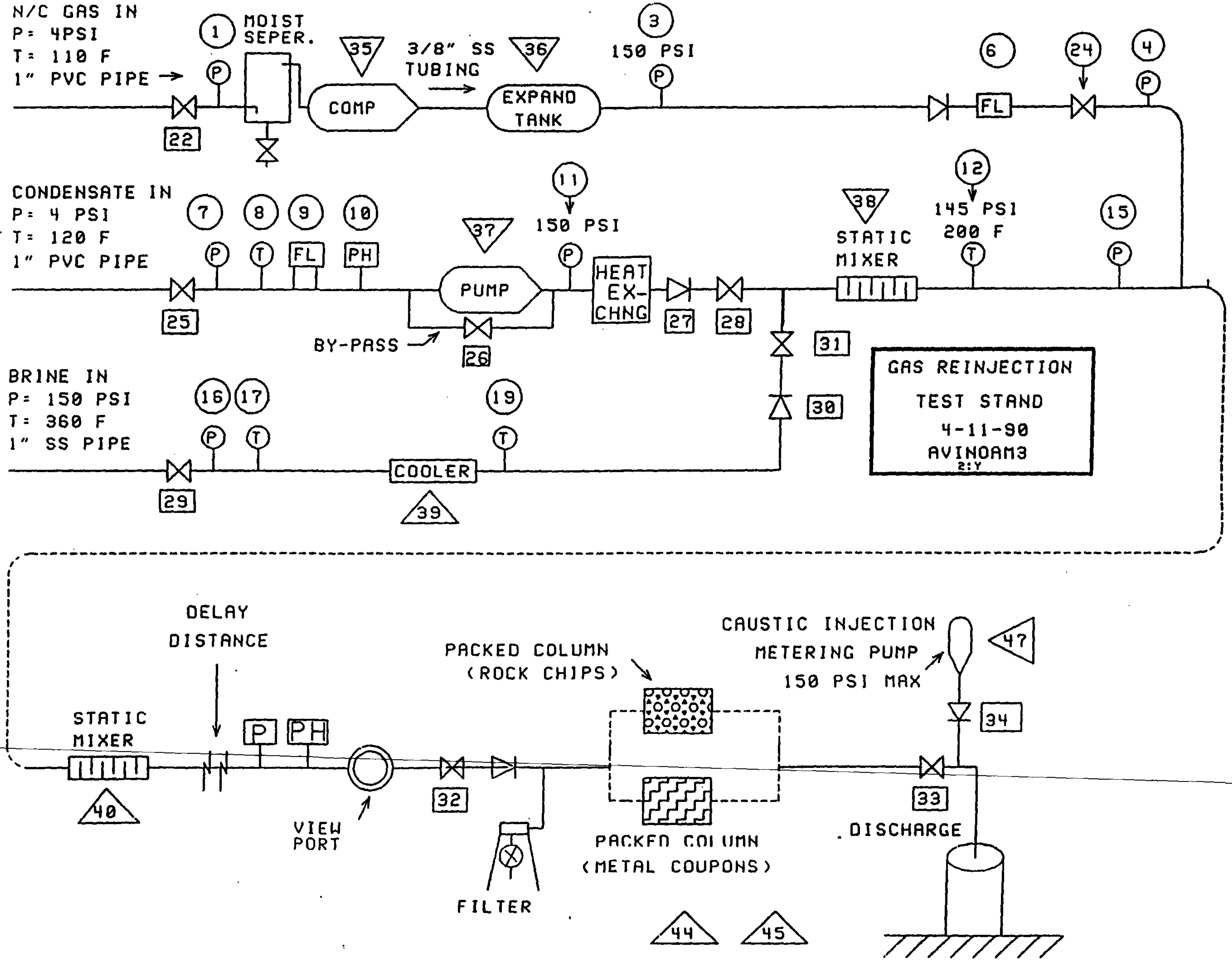

Figure 1. Line diagram of gas reinjection test stand.

hydrogen sulfide form weak acids in aqueous solutions, and because both were readily available, pH modification using N-C gases appeared to provide a potentially cost effective means of controlling silica precipitation.

Other features of the brine test system included: refer to ident or position on Fig 1

1) heat exchangers to allow us to control the temperature of the brine and the condensate; ( )

2) static mixers to give immediate mixing of the brine, condensate, and N-C Spell out gases after addition to the system; ( )

3) a delay coil, consisting of a set of steel reinforced TFE flexible tubes that could be connected in series and thereby allow us to vary the retention time of the fluid in our treatment system; ( )

4) a flow-through sight glass that allowed us to observe the mixed fluid and qualitatively assess the balance among the solid, liquid, and gas phases present in the mixed fluids; ( )

5) a filtration system that allowed us to withdraw a side-stream of mixed fluid to quantitatively determine its solids load and its tendency to foul a filtration system;

6) exposure chambers that allowed the mixed fluid to contact metal coupons, to test for corrosion potential, as well as basalt chips to determine whether the solids generated within the mixed phase system would have a strong tendency to precipitate out in a reinjection well.

During the fabrication and testing period of the above test system, a public controversy developed over the continuation of operations of the HGP-A geothermal facility. The result of this controversy was that the owner of the well was required to terminate operations prior to the originally planned shut-down of the facility in mid-1990. Although this premature shut-down forced us to shorten our planned experiments at the facility, we were able to conduct approximately two weeks of tests on the brine system. Because of the short time available to us, our testing was limited to treatment of the high-temperature brine with condensate and non-condensable gases. The results of this testing, described in detail in the attached report, can be summarized as follows:

1) addition of weakly acid condensate to the brine phase can

substantially reduce the rate of precipitation of silica from the discharged fluids;

2) filtration experiments showed that minimal silica scale or gel was formed in the liquid phase when brine and condensate were mixed;

Spell out

3) addition of N-C gases did not appreciably alter the amount of solids precipitated although trace quantities of sulfide minerals were present in the filtrate;

4) the brine/condensate mixture showed minimal amounts of silica precipitation over periods of more than 24 hours even when allowed to stand at ambient air temperature (30°C);

5) the brine/condensate/N-C gases, when maintained in a sealed, gas tight container, showed no detectable silica precipitation for periods of up to four months;

Preliminary Design of Pilot Scale System

The results of these experiments strongly suggest that treatment of the brine phase with condensate and/or non-condensable gases can substantially reduce the rate of silica fouling of reinjection wells and of surface piping. Although it is clear that recombination of N-C gases with brine in surface equipment will require a substantial increase in pipeline capacity (due to the increased frictional losses associated with two phase flow) addition of condensate to the brine phase appears to be far more cost-effective. Our recommended design for a pilot system is, therefore, to add condensate to the brine phase immediately after separation of the brine from the steam phase. This approach is also based on our observations at the HGP-A facility which indicated that the pH changes associated with boiling of the brine phase was a key factor in the formation of silica scale and that, because the brine discharged from the separator was at saturation, boiling was occurring throughout the brine piping system. Hence, the addition of condensate immediately after separation would have the dual effect of adding a weak acid to the brine and would reduce its temperature to below steam saturation and hence substantially reduce the potential for boiling and silica scaling within the control valving system. Addition of the N-C gases at the reinjection wells will further inhibit the silica scale/gel formation rate and may further protect the capacity of the reinjection well.

There is, however, a very important caveat to the above design. If substantial amounts of dissolved transition metal ions (e.g. iron, copper, lead, silver, etc) are present in the brine phase, the precipitation of metal ion sulfides can generate a high solids load within the reinjected fluid. Hence, an alternative designs includes the capacity to inject small amounts of gas upstream of a filtration system capable of removing the metal sulfides prior to reinjection of the mixed fluid/gas phase. The amount of gas addition required upstream will depend on the metals load in the mixed phase and will have to be determined based on the fluid compositions produced from the geothermal field.

By-product Characterization

The by-product characterization study was intended to determine the physical and chemical characteristics of the solid material precipitated from the geothermal fluid. As the work evolved, our objective became an effort to develop recovery methods that would optimize the commercially valuable characteristics of the silica. These characteristics were determined to be purity and particle size/surface area.

In our earlier investigations, we had found that the key reagents in precipitating silica from solution were caustic, for pH control, and iron and aluminum to accelerate the polymerization rate and to improve the characteristics of the recovered material.

The silica precipitation experiments performed were largely batch precipitations followed by various methods of treatment of the recovered solids. The primary constituent of the recovered raw gel was water which made up more than 90% of the filtered or centrifuged gel. The solids within the gel material ~~was~~ were composed predominantly of silica with small amounts of calcium carbonate formed as a result of increased fluid pH. The high water content contained in the gel also resulted in substantial amounts of entrained salts and trace metals derived from the brine. ~~Although~~ Washing with distilled water removed some of the soluble salt content of the gel, and acid washing was capable of removing the majority of the calcium carbonate, ~~although~~ trace metals appeared to be more tightly bound than could be removed by dilute acid (see Table 1 below). The results of the batch experiments also showed

Awk

that the time delay between cooling the brine and the addition of flocculating agent had little effect on the amounts of the major

Define sample # scheme)

Table 1
Major and Trace Constituents of Precipitated Geothermal Silica

Sample No.	Al mg/g	Ba mg/g	Ca mg/g	Fe mg/g	Mg mg/g	Na mg/g
Fe-0	11.4	0.873	127	2.44	0.144	61.7
Fe-1	9.76	0.401	97.6	2.02	0.122	58.4
Fe-4	9.04	0.234	59.9	1.29	0.072	63.8
Fe-17.5	11.4	0.512	110	2.23	0.102	95.6
Al-0	11.4	0.43	87.8	0.448	0.131	50
Al-1	10.2	0.341	101	0.371	0.142	54
Al-4	12.7	0.316	70.8	0.51	0.096	1.55
Al-17.5	11.1	0.295	65.3	0.374	0.125	72.5
US-1 (acid washed)	11.4	0.138	7.4	0.357	0.255	14.2
US-1 (removed by acid)	0.032	0.34	48.9	0.014	0.073	84.3
Fe-17.5 (acid washed)	0.716	0.048	10.6	0.716	0.049	1.55
Fe-17.5 (removed by acid)	0.356	0.465	99.7	1.51	0.005	94.1

constituents entrained in the gel. Samples exposed to immediate treatment with flocculating agent show virtually the same contaminant concentrations as those experiencing delay times of 17.5 hours of nucleation time. Similarly, the contaminants showed no substantial differences in concentration as a result of using iron or aluminum as the cross-linking agent.

Because surface area was one of the key considerations in the value of the recovered material, a number of variations on sample recovery methods were attempted. These included:

1) Varying times of silica nucleation prior to addition of
indent flocculating agent;
2) Varying the concentration of the flocculating agent;
3) Recovery followed by immediate washing with distilled
indent water and then immediate drying;

Align

4) Varying the temperature of drying;
5) Recovery followed by removal of water using a polar organic wash and then drying;
6) Recovery followed by freeze drying;
7) Recovery, followed by a polar organic wash and supercritical carbon dioxide drying.

The various treatment methods generally resulted in silica having a highly variable dried surface area in the range of from 50 square meters per gram (m^2/gm) to approximately 125 m^2/gm. The exceptions to this were samples that were dried using the supercritical carbon dioxide. These samples showed a substantial increase in surface area over those that received other treatments and were air dried (Table 2).

Table 2 Title? Dried with supercritical carbon dioxide (?)

Spike Addition	Nucleation Time (hr)	Surface Area Oven Dry (m^2/gm)	Surface Area Critical Pt. Dry (m^2/gm)
Al-5 mg/g	0	68.2	163, 168
Al-5 mg/g	1 ~~hr~~	90.1	342, 364
Al-5 mg/g	4 ~~hr~~	71.3	122, 177
Al-5 mg/g	16	91.6	179
Fe-5 mg/g	0	82.1	147
Fe-5 mg/g	1	94.6	158
Fe-5 mg/g	4	100	172
Fe-5 mg/g	16	96.2	224
Fe-3.5 mg/g	0		145, 180
Fe-3.5 mg/g	1		214
Fe-3.5 mg/g	4		363
Fe-3.5 mg/g	16		197
Unspiked	0	67.2	95.6

The results of these studies clearly indicate that the key factors in the formation of high surface area solids are both the nucleation time allowed prior to addition of flocculating agents and the post-recovery treatment. Clearly the optimum method of producing high surface area product is to first de-water the gel using a polar organic solvent followed by critical point drying of the organic-saturated gel.

In general, these results are very encouraging. In our prior discussions with commercial suppliers of silica, we were informed that development of a method to reliably recover silica having surface areas of more than 150 m^2/gm would be of substantial commercial interest and hence there appears to be potential for development of an industrial scale recovery process for removal of silica from these geothermal fluids. However, it is also clear that more work could be done to further refine the recovery method for the geothermal silica and to better characterize the recovery process in order to optimize both the characteristics of the product and to optimize the economics of the process.

Evaluate the feasibility of applying treatment system to other geothermal systems in North America

In our review of other possible geothermal systems in which brine treatment such as that developed in Hawaii could be applied for control or removal of silica from the geothermal fluids, we assessed geothermal systems in the western United States, Mexico, and Central America. The results of our experimental work indicated that a treatment system such as that developed for the Kilauea fluids would need to have both of the following characteristics:

1) The silica concentrations in the geothermal fluids must be high enough to precipitate within the power plant system or in the disposal system;
2) The fluids generated from the geothermal system must have a moderate-to-low concentration of transition elements that are reactive with hydrogen sulfide.

The first requirement restricts the treatment to those systems in which it is economically feasible to modify the plant design in order to improve operations or reduce maintenance requirements. The latter restriction limits the processes to those geothermal fields in which rates of metal sulfide precipitation would be low enough to allow reinjection of the N-C gas treated fluids. Furthermore, the presence of high concentrations of metal ions would also preclude external control of fluid nucleation times that is essential to the optimization of the surface area characteristics of the recovered silica product.

The above requirements preclude the use of our treatment

Need a Table of brine chemistry - metals, TDS, temp, SiO_2, etc for other fields considered to support this discussion. ✓

system at most of the geothermal systems in the western United States. The Geysers, being a dry steam field, has no brine disposal system for treatment. Geothermal brines from the Salton Sea field typically have high concentrations of transition metals and, hence, would not be likely candidates for treatment with N-C gases containing carbon dioxide or hydrogen sulfide due to the potential for precipitation of metal carbonates and sulfides. Other geothermal fields in the western U.S., such as Dixie Valley, typically suffer from carbonate, rather than silica, scaling and would again be inappropriate for our treatment system.

However, there are high-temperature geothermal fields in Mexico and Central America in which silica scaling has been a long standing problem. The most important of these that our survey identified were Cerro Prieto, in Mexico, and Ahuachapan in El Salvador. The high temperature fluids produced by both Cerro Prieto and Ahuachapan both carry a substantial load of silica that precludes effective reinjection programs at either field. The fluid compositions at both fields also appear to have low enough concentrations of transition metals to allow either recovery of high surface area silica or treatment of the pressurized brine with condensate and N-C gases, and reinjection of both back into the reservoir. Although further on-site testing would have to be performed to confirm the feasibility of brine treatment at these systems, both appear to have a great enough need for silica treatment to justify further investigation.

Summary and Conclusions

The results of the work performed under this contract have demonstrated that treatment of silica supersaturated geothermal brines with geothermal condensate and Non-Condensable gases can substantially reduce the rate of precipitation of silica from the aqueous phase. If the sulfide-reactive metals concentration of the brines are low enough, this approach is suggested as the least cost method of inhibiting silica precipitation from geothermal fluids to allow them to be reinjected back into the reservoir formation.

This work has also demonstrated that recovery of high surface area silica solids from geothermal fluids can be achieved by precipitation of silica gels from the fluid phase followed by treatment to remove soluble salts and water and drying using a supercritical fluid. Although the economic feasibility of this process remains to be proven, the results of this work have demonstrated that high surface area solids can be reliably recovered from geothermal fluids.

Finally, an analysis of the applicability of this research to other commercial geothermal fields has indicated that the two most promising candidate fields in North/Central America for application of this technology are the Cerro Prieto field in Mexico and the Ahuachapan field in El Salvador.

REFERENCES

18 p text

A Test of Geothermal Brine pH Control by Non-Condensable Gas Reinjection

Final Report

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 significantly different from those found in the geothermal fields that have used gas reinjection. It was therefore considered prudent to conduct a small scale evaluation of the gas reinjection process using Hawaii's geothermal fluids in order to:

1) Determine optimum engineering design specifications 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 commercial geothermal generator facilities at the Kilauea (Puna?) geothermal system. 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 included in the fabrication of the test stand were as follows:

1) Continuous flow capacity 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 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, no. 39, Fig. 1) and check valve 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°F; P = 20 psig), through a positive displacement pump, a single pass heat exchanger, a flow control valve, and 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°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 allow 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 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, could be connected together to allow 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 systemn 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 in diameter with a 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 flow through the system during this phase of the test was maintained until December 4 (eight days). There were, however, two periods during which fluid flow conditions were modified substantially due to loss of power to the condensate pump. During the interruptions the system was allowed to flow only condensate at a reduced pressure and flow rate, for periods of approximately 3 hours and 5 hours. during ~~which~~ this time the pump breaker was reset and the system was brought back up to operating pressure and to stable flow.

Auk.

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.

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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 typical power plant 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.

what test results support these Tables 3 & 4? elaborate with more discussion

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 Experiment

Although the injection of the non-condensable gases into the fluid stream encountered a number of operational problems, the results of the injection experiment did 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.

how fast?

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~~ uc these values are lower than expected, and subsequent to completion of the experiment, we discovered that significant amounts of air were entrained in the gas stream due to air leakage into the condenser system. Dissassembly of the equipment showed that elemental sulfur (as well as sulfide minerals) had been deposited in the compressor head and in the pressurized injection line. This suggest~~ing~~s that atmospheric oxygen entry into the condenser system oxidized 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. 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 whose 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. (1220 m), 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~~ kg, 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 attached to the metal substrate. Scanning electron micrographs of the metal coupons show that the thickness of the scale layer coupons was approximately 10 microns thick (Figures 7 and 8) and 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 present.

No Fig. 8 — 7a and 7b(?)

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 on? of the compressor and expansion tank. This hypothesis is supported by periodic bursts of black sulfide particulate that were observed to pass through the view port on the system during the gas injection experiment. ~~Although~~ u.C the source of the scale was not immediately recognized, but upon ~~on~~ disassembly of the test stand ~~we found~~ significant amounts of sulfides were found ~~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.

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Effect of O2

The final observation made on the gas combination experiment relates to the potential for silica deposition from the mixed fluid phase. As noted 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 dissolved 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 relatively short duration of the geothermal fluid recombination experiments conducted at the HGP-A facility, the results obtained show that recombination of the geothermal brine, condensate, and non-condensable gases at a pressure of 150 psig and at a temperature of 200°F to 225°F should produce no major difficulties. The results of the experiments suggest that optimal design of the recombination system may entail the transmission of separate liquid and the 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 also suggest that a similar approach could be very valuable if applied on a commercial scale. If steam condensate can be added to the brine 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) could be avoided with a concomitant improvement in plant reliability and reduction in maintenance costs.

Recommendations ~~for further work~~

Although the tests of the corrosivity of the mixed fluids toward stainless steel coupons showed no detectable corrosion, the very short duration of the test renders any conclusions from this aspect of the test somewhat speculative. ~~Although 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. Nonetheless, additional corrosion testing of coupons having similar metallurgy to those already exposed would enable us to confirm the preliminary results of this experiment and would allow us to conduct a broader survey of, possibly less expensive, alloys that could be considered for use in future geothermal facilities in Hawaii. 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.

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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 Model 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

Columns scrambled

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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 (milligrams)

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

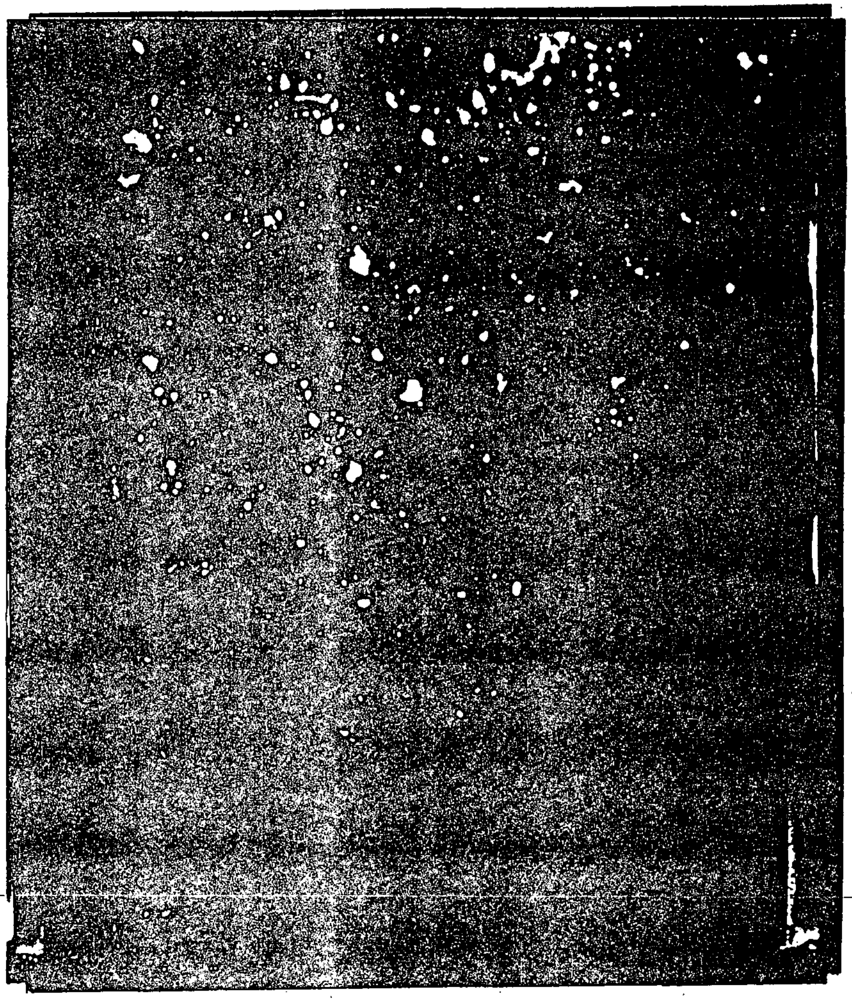

Figure 7b. Scanning electron micrograph of metal coupon sample after exposere to Brine/ Condensate/Non-condensable gas mixture.
Mag. = 1640X

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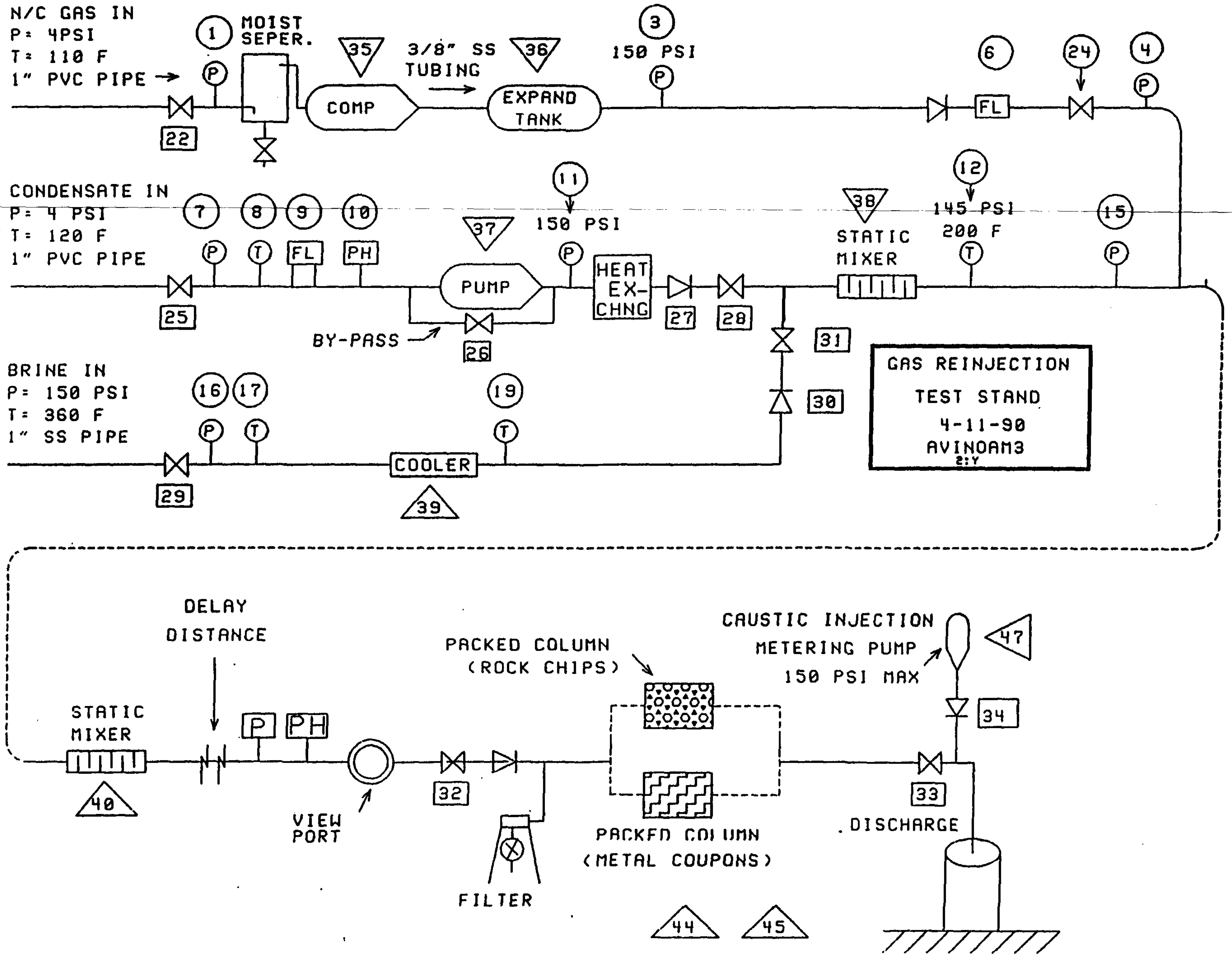

Figure 1. Line diagram of gas reinjection test stand.