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**Corrosion of Materials and Scaling  
in Low-Salinity East Mesa  
Geothermal Brines**

**By F. X. McCawley, S. D. Cramer, W. D. Riley,  
J. P. Carter, and P. B. Needham, Jr.**



**UNITED STATES DEPARTMENT OF THE INTERIOR**

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**UNITED STATES DEPARTMENT OF THE INTERIOR  
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**BUREAU OF MINES  
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# CORROSION OF MATERIALS AND SCALING IN LOW-SALINITY EAST MESA GEOTHERMAL BRINES

by

F. X. McCawley,<sup>1</sup> S. D. Cramer,<sup>2</sup> W. D. Riley,<sup>3</sup> J. P. Carter,<sup>4</sup>  
and P. B. Needham, Jr.<sup>5</sup>

## ABSTRACT

The Bureau of Mines, in pursuing its goal of extending the life span of strategic materials, conducted field corrosion studies at the East Mesa Known Geothermal Resources Area (KGRA) in the Imperial Valley, Calif., to determine the optimum materials of construction for use in geothermal mineral energy resource recovery plants. These studies included characterization of geothermal environments and in situ corrosion testing. The corrosion resistance of 10 alloys exposed to 5 brine and steam process environments was evaluated using the low-salinity, high-temperature brine from geothermal well Mesa 6-1. Of these alloys, Hastelloy C-276, Hastelloy S, Inconel 625, titanium-2nickel, and 316 L stainless steel had excellent resistance to corrosion in all of the process environments; E-Brite 26-1 and 430 stainless steel had fair resistance. Although general corrosion rates for 4130 steel and 1020 carbon steel were substantially higher than those of the other iron-base alloys, these two alloys could prove useful in low-salinity process environments because of their low cost. Aluminum alloy 5005 was the least corrosion resistant alloy and pitted severely. Scales formed on all of the alloys in every process environment. Calcite, aragonite, and an amorphous silicate were the major components of the scales.

## INTRODUCTION

One of the largest liquid-dominated hydrothermal resource areas in the United States is the Imperial Valley of California. A number of KGRA's (Known Geothermal Resource Areas), containing substantial quantities of recoverable metals and minerals and energy, are found there. Among these areas is the low-salinity, high-temperature area located on the East Mesa, known as the East Mesa KGRA. Brines from this area contain minerals at concentrations up to 3 percent total dissolved solids and reach temperatures up to 200° C. These

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brines are corrosive and, because of their mineral content, cause scaling of process equipment. In 1974, the Bureau of Mines, began laboratory and field research and testing to characterize and evaluate materials of construction for geothermal mineral and energy resource recovery plants in the Imperial Valley. To meet the objectives of this program, the Avondale Research Center (formerly College Park Metallurgy Research Center) conducted laboratory corrosion research (2, 7, 9,)<sup>6</sup>, thermodynamic studies (5-6), and field corrosion research and tests (3-4, 8) in geothermal brines. The purpose of the field-work was to determine the corrosion-resistant properties of commercially available metals and alloys in geothermal environments, the chemistry of flowing geothermal brines (10), and scale-deposition kinetics (1).

The Bureau's first extensive field test on geothermal materials began in July 1975 at the Mesa 6-1 geothermal well, a low-salinity, high-temperature well located on the East Mesa KGRA near Holtville, Calif. Mesa 6-1 is located at the U.S. Department of Energy (DOE) geothermal test site,<sup>7</sup> where desalination studies to produce potable water were being conducted (fig. 1). Materials were mounted for evaluation in a Materials Test Facility (MTF-1) that was connected via pipeline to Mesa 6-1, which is the only well involved in this study. Five process streams typical of those found in a geothermal resource recovery plant were produced in MTF-1. Onsite chemical analyses of the process streams were conducted in a large, well-equipped Mobile Chemistry Laboratory. MTF-1 was operated from April through September 1975 to conduct corrosion tests in brine from the well and for brine chemistry studies involving Mesa 6-1 and another low-salinity geothermal well nearby, Mesa 6-2 (10). The corrosion tests, originally scheduled for 60 days, were terminated when Mesa 6-1 failed after 22 days of the scheduled 60 day test due to plugging of the well with carbonate scale at a depth of 6,100 feet. This Bureau of Mines report presents corrosion tests conducted in the five brine and steam process streams, the chemical compositions of these streams, and a characterization of the scales and deposits that formed on the corrosion samples.

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<sup>6</sup>Underlined numbers in parentheses refer to items in the list of references at the end of this report.

<sup>7</sup>Prior to October 1, 1977, this facility was part of the Bureau of Reclamation, U.S. Department of the Interior.

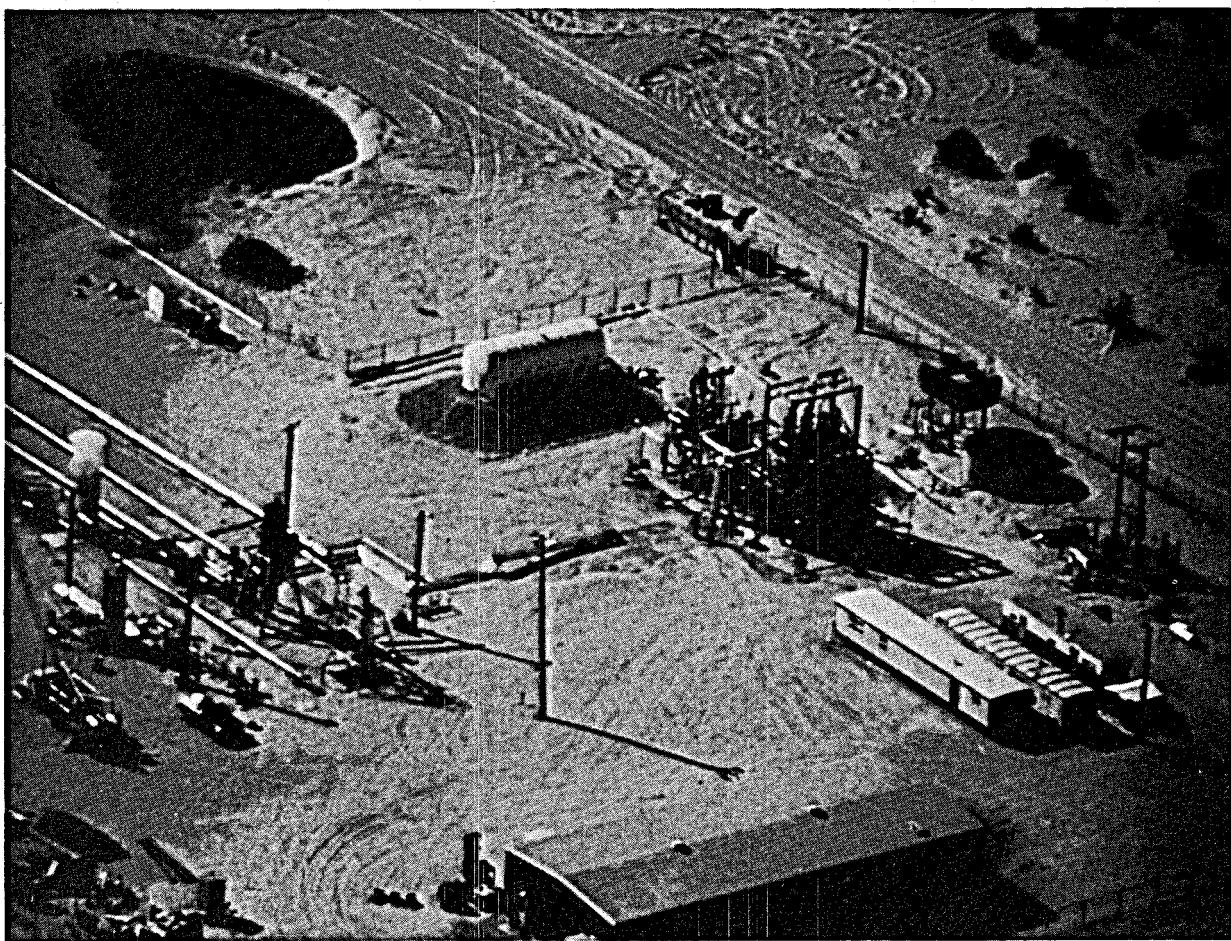


FIGURE 1. - Aerial view of Bureau of Reclamation geothermal test site, East Mesa KGRA, Imperial Valley, Calif.

#### ACKNOWLEDGMENTS

The authors express their gratitude for the cooperation and assistance provided by Bureau of Reclamation personnel at their former facilities on the East Mesa KGRA. The knowledge of geothermal process equipment and the welding skills of U. Kelly were invaluable in conducting the field tests.

#### EXPERIMENTAL EQUIPMENT AND PROCEDURES

##### Materials Test Facility

MTF-1 was constructed on a flatbed truck at the Avondale Research Center and moved to the DOE geothermal site on the East Mesa in early 1975. The facility (figs. 2-3) consisted of (1) corrosion test packages for five brine and steam process streams, (2) two steam separators for flashing some of the brine to steam and separating it at elevated pressures, (3) an atmospheric pressure separator, and (4) flow-control valves with their associated pressure control systems. MTF-1 was constructed entirely of 1020 carbon steel.

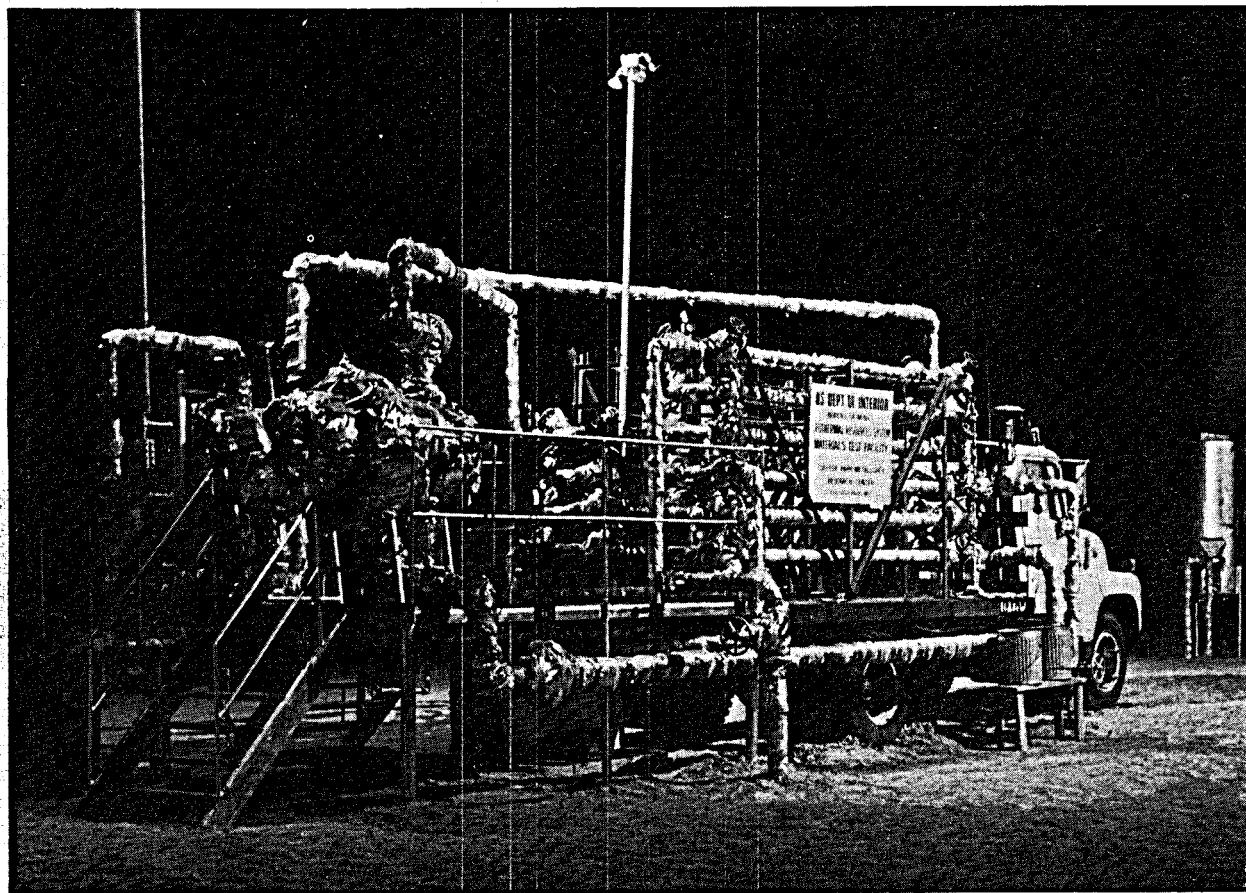


FIGURE 2. - Bureau of Mines Materials Test Facility (MTF-1).

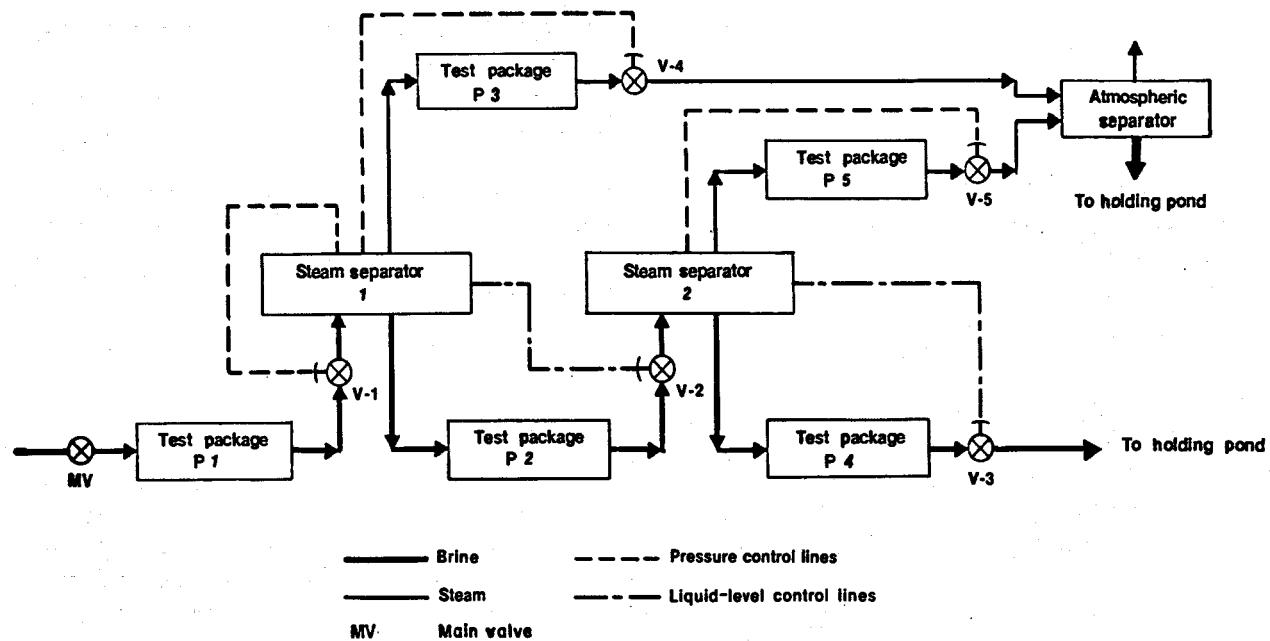


FIGURE 3. - Schematic diagram of MTF-1.

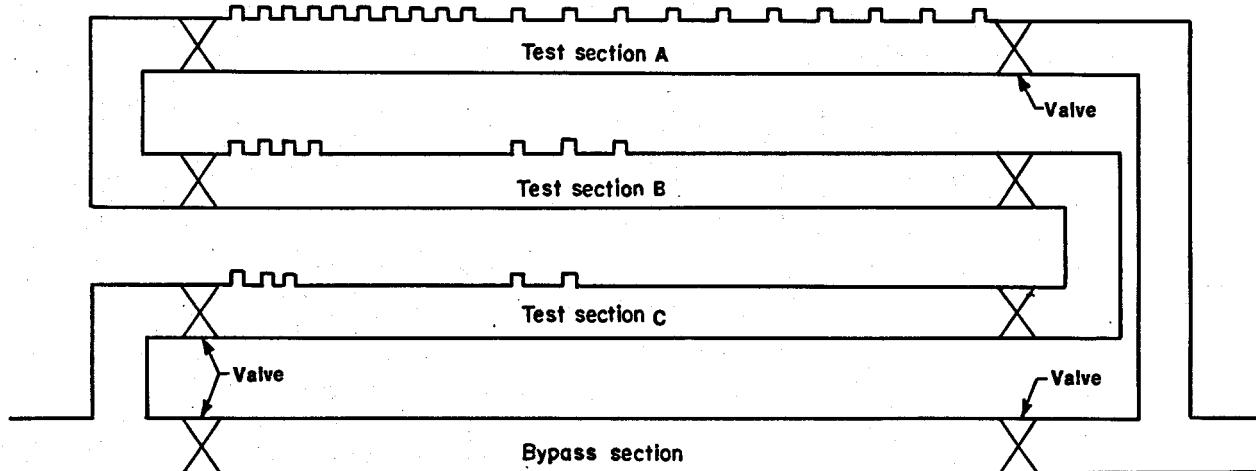


FIGURE 4. - Diagram of in situ corrosion test packages.

Each of the five corrosion test packages (P1 through P5) consisted of three 10-foot-long test sections in which samples were mounted, and a bypass section for routing the brine around the test sections (fig. 4).

The test sections were constructed from 2- and 3-inch-diameter schedule 80 pipe. Three-inch pipe was used in P1 to transport the wellhead brine, and in P5 to transport the large volumes of low-pressure steam from the second-stage steam separator. Each of the test sections held 20 corrosion samples. Individual sample holders were mounted on vertical ports (approximately 2 inches high) constructed from 2-inch diameter pipe welded at right angles to the test-section pipe (fig. 5). Ten of the ports were spaced 4 inches apart for mounting samples with their faces normal (at right angles) to the flow of brine or steam (fig. 4). The remaining 10 ports were spaced 8 inches apart for mounting samples with their faces tangential (parallel) to the flow. A 3/8-inch-diameter rod formed part of each sample holder. The corrosion sample was secured to the rod with a stainless steel screw, and was electrically insulated from the rod and screw by a Teflon<sup>8</sup> gasket and ceramic insulator (fig. 5). Each rod was welded to a 2-inch-diameter cap and the cap was clamped to the ports during the tests. Teflon or asbestos gaskets were used to seal the sample ports and other flanges on the test sections.

Two steam and two concentrated-brine process streams were produced by the two steam separators. These plus the input brine flowing directly from the well formed the five different environments in which the corrosion tests were conducted. The steam separators were 2 feet in diameter by 4 feet long, and were certified in accordance with the American Society of Mechanical Engineers (ASME) code for pressure vessels to operate at 200 psig at a temperature of 300° C. Brine entering the separator was projected horizontally towards one end by means of the input pipeline passing vertically through the bottom wall and making a right-angle bend at the centerline. The steam

<sup>8</sup>Reference to specific trade names is made for identification only and does not imply endorsement by the Bureau of Mines.

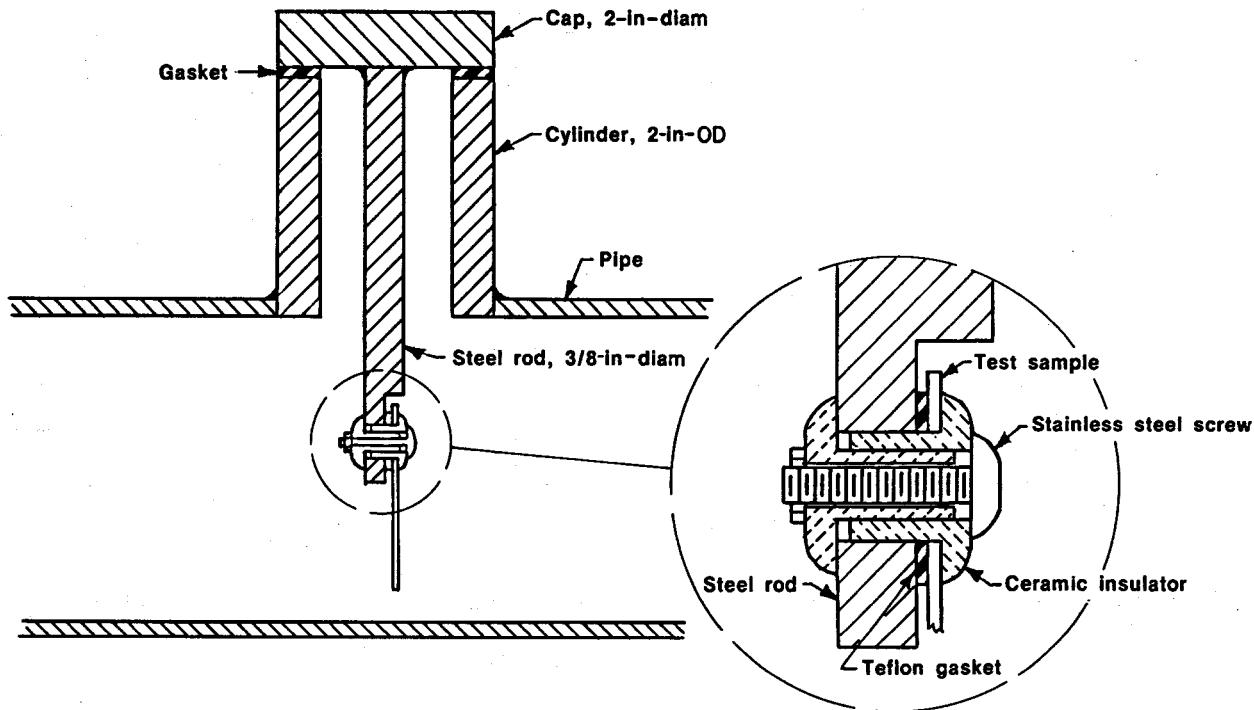


FIGURE 5. - Corrosion sample holder.

separators converted roughly 10 percent of the brine into steam at each stage of flashing. The concentrated brine exited from the bottom of the separators and the steam from the top.

Five pneumatically operated flow-control and pressure-actuated valves controlled the overall operating conditions of MTF-1 (fig. 3); that is, they determined the rate at which brine flowed from the well, the pressures in each of the test packages, and the amount of steam removed from the brine in each steam separator. Valves V-1, V-2, and V-3 were flow-control valves; V-4 and V-5 were pressure actuated. Valves V-2 and V-3 were controlled by ultrasonic liquid-level sensors mounted in each of the steam separators.

The average operating conditions for the corrosion test packages are given in table 1. Test package P1 contained input brine that flowed directly from the well at a pressure slightly lower than that of the wellhead owing to viscous losses. Packages P2 and P3 contained brine and steam produced at 85 psig in steam separator 1. Packages P4 and P5 contained brine and steam produced at 50 psig in steam separator 2 from the concentrated brine flowing through package P2. Brine in the steam separators was maintained at a level that provided a brine-mist carryover, producing "dirty" steams; that is, steams containing significant amounts of chlorides. After passing through MTF-1, all liquids, including brine and condensate, were discharged into a brine-holding pond.

TABLE 1. - Mean operating conditions and composition of process environments in MTF-1 and at wellhead during first 7 days of corrosion tests<sup>1</sup>

Test environment	Temp, ° C	Pressure, psig	pH	Concentrate, ppm					
				Cl	Na	Ca	Si	K	Ba
Wellhead brine.....	152	98	5.6	11,800	6,153	771	129	613	16.8
Input brine (P1).....	152	96	5.2	11,000	5,850	700	115	613	15.2
Brine, separator 1 (P2)	140	85	6.8	12,062	5,867	795	125	645	15.9
Brine, separator 2 (P4)	132	50	8.1	12,735	6,667	850	135	645	18.8
Steam, separator 1 (P3)	140	85	5.2	3,000- 5,000	2,803	300	44	323	16.3
Steam, separator 2 (P5)	132	50	5.7	200- 500	10	<10	<10	82	<.1

<sup>1</sup> Flow rate 35 gpm.

Special ports were mounted on each test package to collect samples of the brine or steam (as condensate) for analysis (fig. 6). These samples were cooled to ambient temperature by passing them through a water-cooled stainless steel heat exchanger. No effort was made to preserve dissolved gases in the samples.

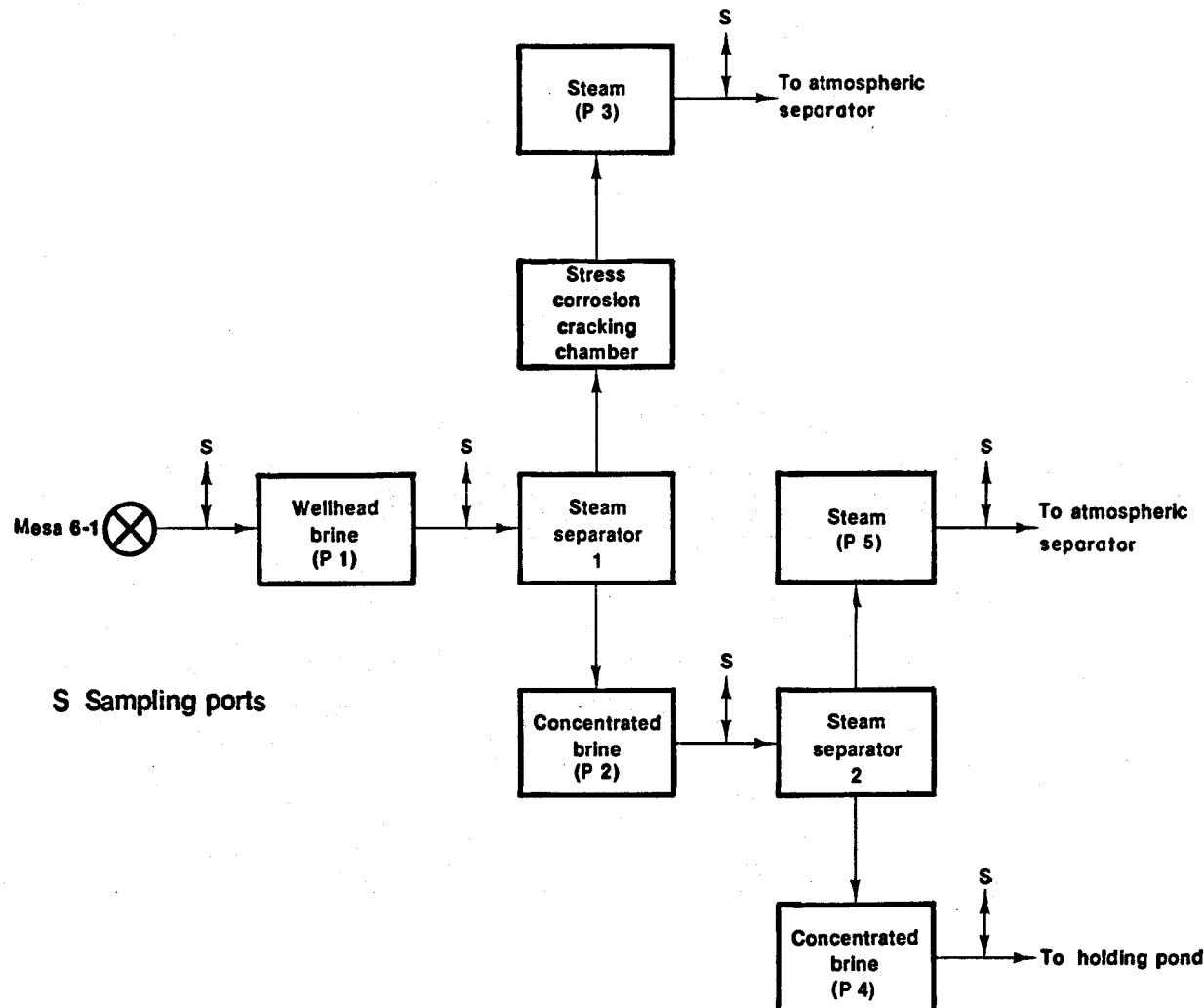


FIGURE 6. - Location of sample ports on MTF-1 and wellhead of the geothermal well (Mesa 6-1).

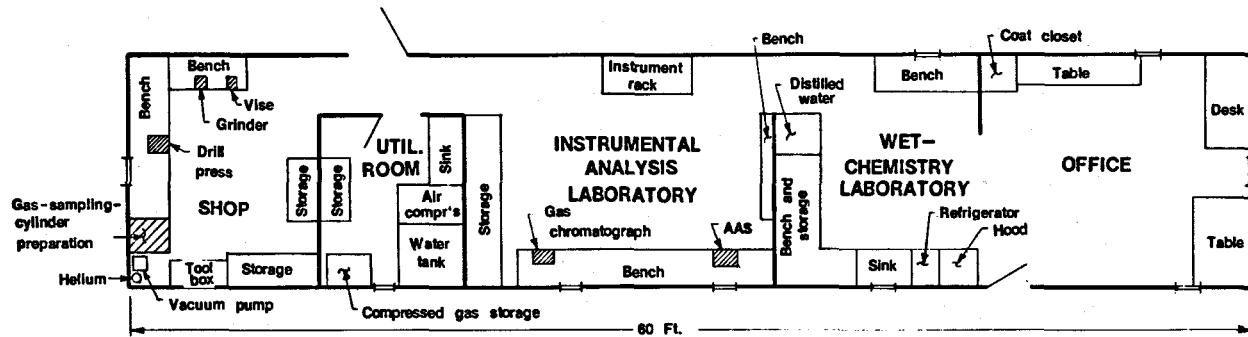


FIGURE 7. - Floor diagram of Mobile Chemistry Laboratory.

#### Mobile Chemistry Laboratory

The Mobile Chemistry Laboratory was a converted mobile-home trailer containing five basic service areas (fig. 7), including instrumental- and wet-chemistry analytical laboratories, an office area, a small machine shop, and a utility room (tap  $H_2O$ , distilled  $H_2O$ , compressed air, vented-gas storage, and vacuum pumps). The instrumental analysis laboratory was equipped with an atomic absorption spectrophotometer (AAS), gas chromatograph (GC), and a pH-ion meter. The wet-chemistry laboratory was used primarily for carbonate and chloride determinations. The laboratory, used for onsite analyses of geothermal brines and steams, was located at the Bureau of Reclamation geothermal test site on the East Mesa from December 1974 until January 1976, when it was moved to a site at the Salton Sea KGRA.

#### Materials Preparation and Evaluation

The 10 commercially available alloys used in the corrosion tests and their nominal compositions are given in tables 2-4. These alloys, selected on the basis of laboratory corrosion studies (2, 7), were evaluated for their resistance to general, crevice, and pitting corrosion in the five process streams. In addition, a set of stress-corrosion samples was exposed to the steam from steam separator 1 in a chamber connected directly to the separator and through which all the steam to package P3 flowed.

TABLE 2. - Nominal composition of ferrous alloys used in the corrosion tests, weight-percent<sup>1</sup>

Element	1020 carbon steel	4130 steel	430 stainless steel	E-Brite 26-1	316 L stainless steel
Carbon.....	0.2	0.3	0.12	0.001	0.03
Chromium.....	0	.95	16-18	27.6	16-18
Columbium....	0	0	0	0.1-.2	0
Copper.....	0	0	0	.02	0
Manganese....	.45	.5	1	.02	2
Molybdenum...	0	0.12	0	1.0	2-3
Nickel.....	0	0	0	.01	10-14
Phosphorus...	.04 max.	.04 max.	.04 max.	.01	.045 max.
Silicon.....	0	.3 max.	1 max.	.27	1
Sulfur.....	.05	.04 max.	.03 max.	.01	.03 max.

<sup>1</sup> The balance of the composition is iron.

TABLE 3. - Nominal composition of nickel alloys used in the corrosion tests, weight-percent<sup>1</sup>

Element	Hastelloy S	Hastelloy C-276	Inconel 625
Cobalt.....	0.61	2.5	0
Columbium + tantalum.....	0	0	3.7
Chromium.....	16.7	15.5	21.5
Iron.....	1.8	5.5	2.5
Manganese.....	0	1.0	0
Molybdenum.....	14.6	16	9
Tungsten.....	.22	3.75	0

<sup>1</sup> The balance of the composition is nickel.

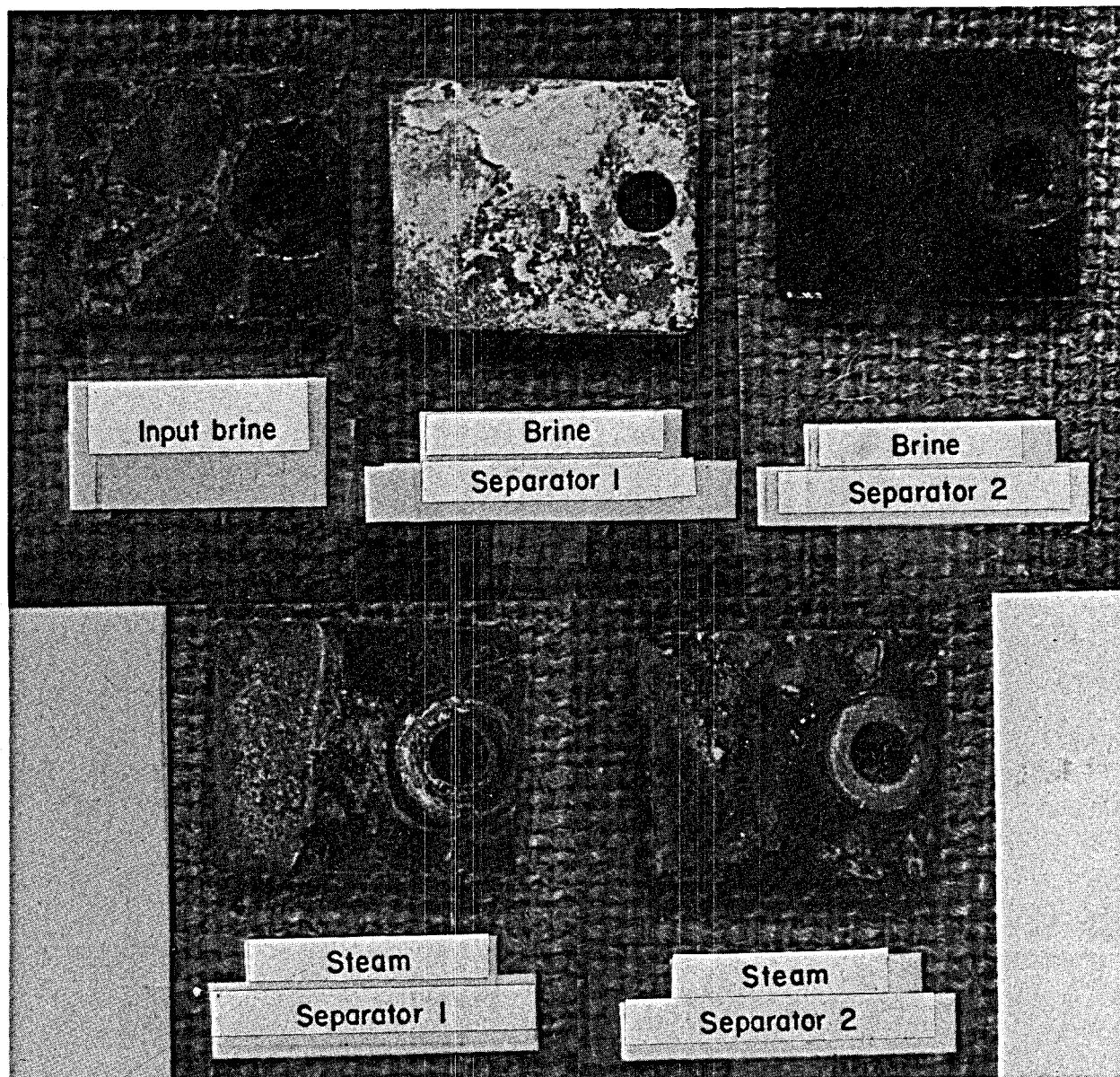
TABLE 4. - Nominal composition of titanium and aluminum alloys used in the corrosion tests, weight-percent

	Titanium-2 nickel	Aluminum alloy 5005
Aluminum.....	0	Balance
Carbon.....	.02	0
Chromium.....	0	.1
Copper.....	0	.2
Hydrogen.....	.006	0
Iron.....	.03	.7
Magnesium.....	0	0.5-1.1
Manganese.....	0	.2
Nickel.....	1.35	0
Nitrogen.....	.005	0
Oxygen.....	.062	0
Silicon.....	0	.4
Titanium.....	Balance	0
Zinc.....	0	.25

The flat samples for general, crevice, and pitting corrosion tests measured 1 by 1-1/4 inches and were approximately 1/16 inch thick. They were cut slightly oversize by shearing and then ground to the correct size on an 80-grit wet-belt sander to remove burrs and distorted metal. After grinding, 8 of the 10 alloys were degreased in methanol, washed in distilled water, dried, and weighed. The two remaining alloys, 1020 carbon steel and 4130 steel, were pickled at 60° C. in 12 volume-percent  $H_2SO_4$  containing 2.5 milliters per liter of Rhodine 95 inhibitor to remove mill scale, then washed, dried, and weighed. The flat samples were mounted as shown in fig. 5. The stress-corrosion samples were U-bends prepared from flat 1- by 2-inch samples. The U-bend samples were cleaned in the same way as the flat samples. To introduce stress, they were bent approximately 175° around a 1-inch-diameter steel mandrel, and the legs were forced into grooves cut 1 inch apart in an alumina plate.

The test program originally called for four 15-day, two 30-day, and one 60-day exposure of corrosion samples. The first 15-day exposure was completed for the five process streams. However, the second 15-day exposure had to be halted on the 7th day when the well (Mesa 6-1) failed. The results presented here are those for (1) the first 15-day exposure, (2) the subsequent 7-day exposure (samples from the second 15-day test), and (3) two 22-day originally intended as the 30-day and 60-day tests.

The samples were removed from the test packages, examined, and photographed. The appearance of the carbon steel and 316 L stainless steel samples after the 22-day exposure to the steam and the brine process streams is shown in figures 8 and 9, respectively. Scale samples scraped from the corrosion coupons were analyzed using X-ray diffraction and emission spectrography analyses. Tightly adherent scale and corrosion product were chemically removed from the samples by immersion in either inhibited 12 percent sulfuric acid (1020 carbon steel, 4130 steel, and aluminum alloy 5005 samples) or 60 percent nitric acid containing, if necessary, a few drops of hydrofluoric acid to facilitate removal (all other samples). The sulfuric and nitric acid cleaning solutions were used at 60° C. Between successive immersions in the acid cleaning solutions, the samples were vigorously rubbed with a rubber stopper to remove loose scale and corrosion product. The cleaned samples were examined with an optical microscope for localized corrosion such as pits, crevice attack, and stress-corrosion cracking. General corrosion rates were determined from weight-loss data, and the value reported is the average from at least four samples.



**FIGURE 8.** - Carbon steel corrosion samples exposed to five process environments using brine from the geothermal well.

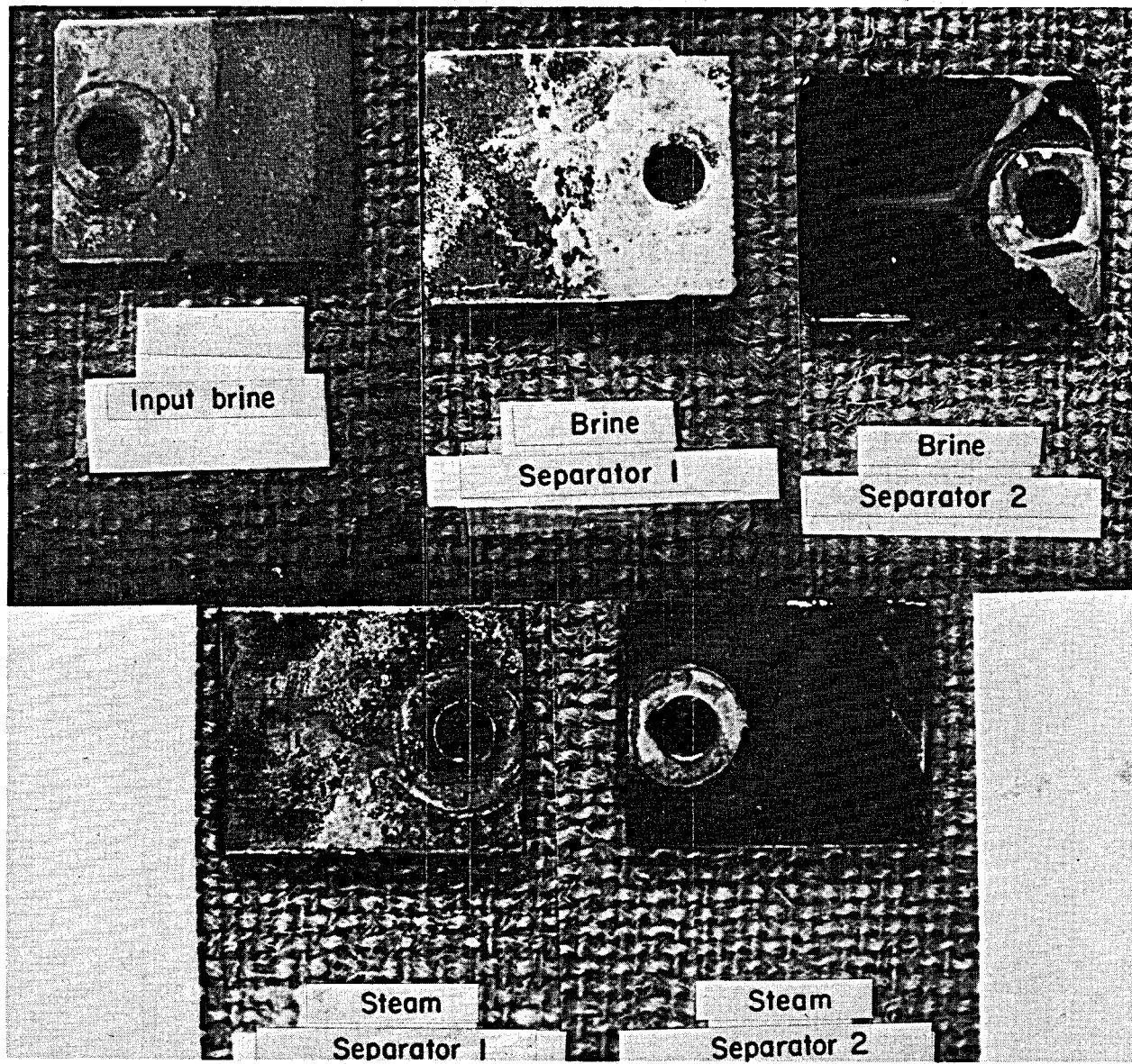


FIGURE 9. - Type 316 L stainless steel corrosion samples exposed to five process environments using brine from the geothermal well.

## RESULTS

Corrosion Tests

General corrosion rates are given in table 5 for 1020 steel, 4130 steel, 430 steel, 430 stainless steel, E-Brite 26-1, and aluminum alloy 5005 exposed to the five brine and steam process streams for exposure periods of 7, 15, and 22 days. Hastelloy C-276, Hastelloy S, Inconel 625, titanium-2 nickel, and 316 L stainless steel had excellent resistance to general corrosion in these five environments, with corrosion rates less than 0.1 mil per year and, therefore, were not listed in table 5; however, only Hastelloy C-276 exhibited no evidence of corrosion as determined by optical microscopy. For example, 316 L stainless steel and Inconel 625 were susceptible to localized corrosion in the form of pits too shallow to measure with an optical micrometer, and titanium-2nickel and Hastelloy S exhibited a slight roughening of their surfaces.

TABLE 5. - General corrosion rates<sup>1</sup> in five process environments  
using Mesa 6-1 brine, mils per year<sup>2</sup>

Exposure, days.	Input brine (P1)			Brine, separator 1 (P2)			Brine, separator 2 (P4)			Steam, separator 1 (P3)			Steam separator 2 (P5)		
	7	15	22	7	15	22	7	15	22	7	15	22	7	15	22
1020 carbon steel.....	11.5	3.2	2.8	1.0	2.4	2.1	3.4	3.4	1.2	16.6	2.0	2.4	18.2	3.1	4.5
4130 steel....	10.2	1.9	2.3	1.1	1.6	2.1	2.1	1.1	1.0	15.3	1.3	1.9	9.2	2.5	2.8
430 stainless steel.....	6.1	.1	1.9	.0	.5	.9	.2	.2	.2	.3	.0	.1	.5	.0	.2
E-Brite 26-1...	9.8	.0	2.2	.3	.0	.2	.2	.1	.2	1.6	.0	.1	.5	.1	.2
Aluminum alloy 5005.....	72.0	57.0	18.0	5.0	21.4	11.4	4.1	2.7	3.2	41.5	29.1	10.2	2.2	3.0	2.8

<sup>1</sup>Corrosion rates were less than 0.1 mil per year for 316 L stainless steel, Hastelloy S, Hastelloy C-276, Inconel 625, and titanium-2nickel.

<sup>2</sup>To convert mils to micrometers, multiply by 25.4.

E-Brite 26-1 and 430 stainless steel had excellent resistance to corrosion in the separated brine and steam environments (P2 through P5), but had only fair resistance to corrosion in the input brine (P1). Corrosion rates for these alloys in input brine varied widely for the three exposure periods. They were appreciably greater for the 7- and 22-day tests, which began after or continued past the first 15 days of operation, suggesting that a substantial change in brine chemistry occurred during the second exposure period. This change will be discussed in the "Brine Chemistry" section of this report. Microscopic examination of the 430 stainless steel samples showed that shallow pitting, similar to that observed on the 316 L stainless steel samples, occurred in all five environments. Shallow pitting was also observed on E-Brite 26-1 samples exposed to input brine and to concentrated brine from steam separator 1. There was no evidence of corrosion on E-Brite 26-1 samples exposed to the steam environments and to the concentrated brine from steam separator 2.

Both 1020 carbon steel and 4130 steel had fair resistance to general corrosion in the five environments. These steels showed no evidence of pitting or crevice corrosion attack when examined by optical microscopy.

Aluminum alloy 5005 had poor resistance to general corrosion in the input brine and in the brine and steam from separator 1, and the corrosion resistance was only fair in the brine and steam from separator 2. In addition to high general corrosion rates in packages P1 through P3, the aluminum alloy 5005 samples were severely pitted and showed a high susceptibility to crevice corrosion.

General corrosion rates for the 10 alloys were not affected by sample orientation (normal or tangential) in the flow of brine or steam.

None of the U-bend samples exposed for 22 days in the steam from separator 1 showed evidence of stress corrosion cracking when examined by optical microscopy. Furthermore, no cracks were exposed when the legs of the U-bend samples were compressed together.

#### Scale Characterization

Scaling occurred on test samples exposed in each of the five process streams. The major crystalline phases in the scales were identified by X-ray diffraction as aragonite and calcite. These crystalline components were accompanied by substantial amounts of amorphous material. The composition of the scale formed on the alloys, with the exception of aluminum alloy 5005 was shown by emission spectroscopic analysis to depend on the process environment. Scale formed in input brine and in the steam and concentrated brine from separator 1 had calcium as the major constituent, iron as a secondary constituent, and minor amounts of Al, Ba, K, Mn, Na, Pb, Si and Sr. In addition, zinc was detected in trace amounts in the scale formed in the concentrated brine from separator 1. Scales formed in the steam and concentrated brine from separator 2 had silicon as the major constituent, iron and calcium as secondary constituents, and minor amounts of Al, Ba, Mn, Mo, Na, Pb, and Zn. The scales formed on aluminum samples in the five process environments contained aluminum as the major constituent, with all other elements present in minor or trace amounts.

#### Brine Chemistry

The well had been flowing continuously for 3 weeks at an average input brine flow rate of 115 gallons per minute prior to the corrosion tests. During the tests, the flow rate of the well was 35 gallons per minute. Fluid samples were taken for chloride, pH, and carbonate determinations at 4-hour intervals from ports located on MTF-1 at positions labeled "S" in figure 6. Samples for atomic absorption spectroscopy and gas chromatography were obtained at 8-hour intervals.

A major portion of the dissolved carbon dioxide was removed in separator 1. The loss of the carbon dioxide substantially increased the pH of the separated brine. The higher pH of the brine from separator 2 (table 1) indicates that additional carbon dioxide was removed from the brine in the second steam separation.

Variations in the concentration of several components of the input brine over the 22 days of the tests are illustrated in figure 10. The operating conditions and chemical composition of the environments in each of the five corrosion test packages were stable within  $\pm 10$  percent for the first 7 days. Mean values for these variables are given in table 1. On the eighth

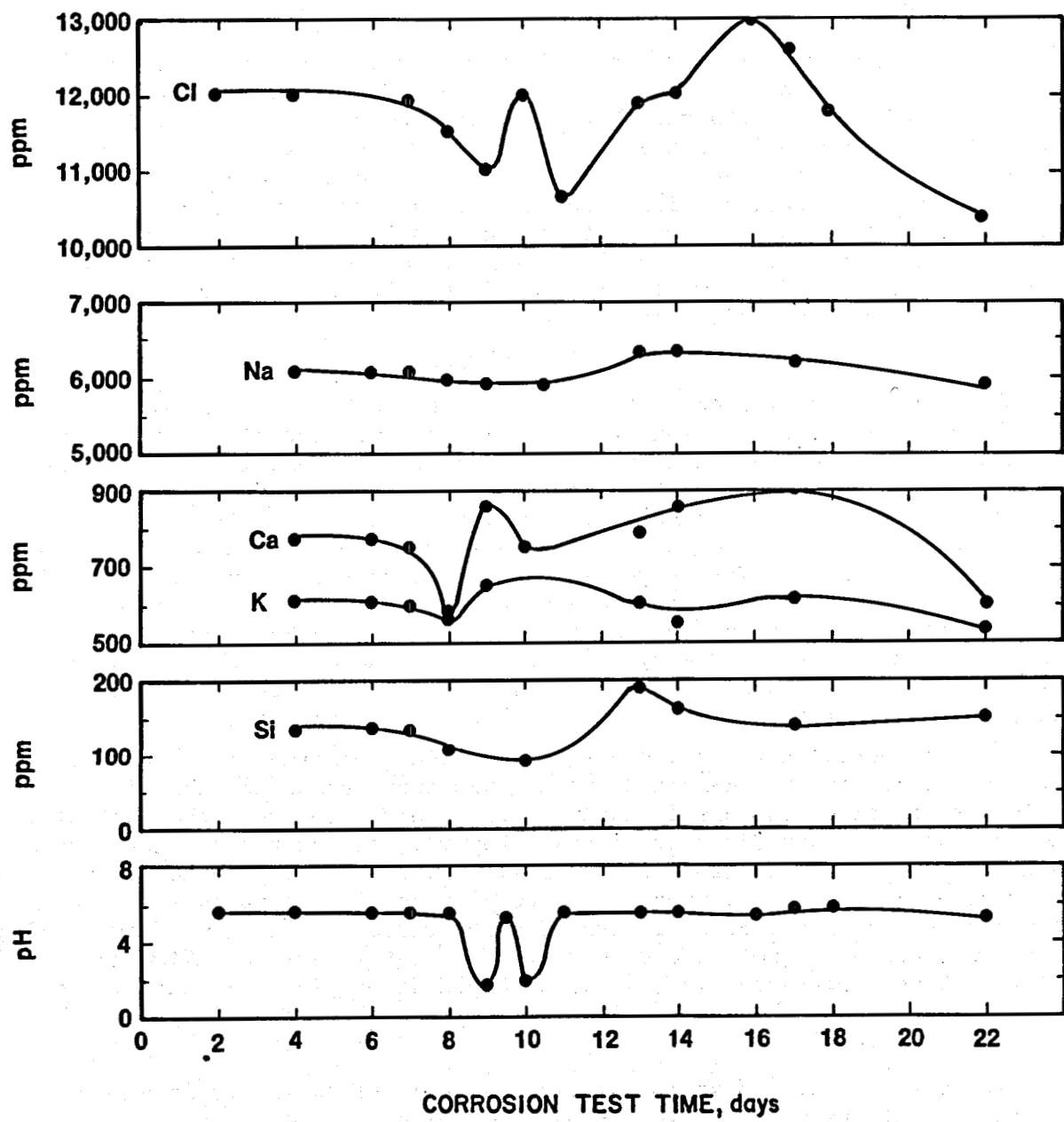


FIGURE 10. - Fluctuations of pH and several components of the wellhead brine during 22 days of tests, July-August 1975.

day, a ground tremor resulted in changes in the input-brine composition.<sup>9</sup> Because these changes persisted, a stable input-brine composition was not reestablished during the remainder of the tests from the 8th through the 22d day. Variations occurred in the concentrations of all major dissolved species, but calcium and chlorine were affected the most. Similar variations occurred in the composition of the fluids forming each of the process environments.

Corrosion rates for most materials were higher for the 7-day exposure coming near the end of the 22-day test period. This increase apparently reflected the chemical changes that had occurred in the brine after the ground tremor. Corrosion rates for materials exposed 22 days were also higher than rates observed in the initial 15-day test. However, the increase was less than that for materials exposed 7 days, probably owing to the buildup of scale on samples prior to the change in brine composition. Flow from the well ceased on the 22d day of the scheduled 60-day test. Subsequent redrilling of the well removed a large plug of carbonate scale that had formed 6,100 feet below the surface.

#### SUMMARY AND CONCLUSIONS

Although the corrosion tests conducted at the East Mesa KGRA lasted only 22 days owing to plugging of the well, data were obtained on the performances of some commercially available alloys in low-salinity geothermal brines. These data are essential in the selection of materials of construction for geothermal resource recovery facilities. Onsite monitoring was useful for promptly detecting changes in the composition of the geothermal environments. Variations in the corrosion rates for different exposure periods seemed to correlate with changes in the chemistry of the input brine. For example, corrosion rates for E-Brite 26-1 and 430 stainless steel in the 7- and 22-day exposures were generally higher than those for the 15-day test, reflecting chemical changes that occurred in the input brine after the ground tremor on the eighth day of the test.

In the low-salinity, near-neutral chloride geothermal environments, ferritic steels such as E-Brite 26-1 and 430 stainless steel were less resistant to corrosion, particularly pitting corrosion, than the austenitic steels and nickel and titanium alloys. However, all of these alloys appear suitable for use as construction materials in low-salinity geothermal environments. The 1020 carbon steel and 4130 steel also appear useful as construction materials since their corrosion rates were not excessively high in the process environments and they are low-cost materials. Aluminum alloy 5005 does not appear suitable for applications in low-salinity geothermal environments because of its low resistance to general, pitting, and crevice corrosion.

These tests were of short duration. Longer tests involving a more thorough examination of stress-corrosion cracking are recommended.

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<sup>9</sup> In the opinion of Bureau of Reclamation personnel, the tremor opened a "zone of lost circulation" that released drilling muds and acids into the well.

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