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**SCALING CHARACTERISTICS IN THE
GEOHERMAL LOOP EXPERIMENTAL FACILITY
AT NILAND, CALIFORNIA**

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SCALING CHARACTERISTICS IN THE GEOTHERMAL LOOP EXPERIMENTAL FACILITY AT NILAND, CALIFORNIA

Abstract

The San Diego Gas & Electric Company - U.S. Energy Research and Development Administration joint Geothermal Loop Experimental Facility (GLEF), located at Niland in the Imperial Valley, California, began operation in May 1976. The GLEF incorporates a sequential four-stage flash process to successively lower temperatures and pressures with a binary fluid energy-conversion cycle. Approximately 300 hr of intermittent operation were logged before shutdown of the facility on June 16 for inspection and maintenance. Samples of the brine, suspended solids, and scale deposits were analyzed for bulk composition and mineralogy, but correlation with temperature and pressure is vague.

In general, a galena-rich scale is observed in valves and piping ahead of the first-stage separator, becoming much less abundant beyond that point. The bulk of the scale consists of an increasing proportion of an iron-rich amorphous silica

with process progression. Trace crystalline phases, such as akaganeite, kutnahorite, and sphalerite and/or wurtzite, have been detected or are strongly suspected in the scales. Halite and sylvite are found primarily as a result of numerous facility shutdowns and subsequent cooling of the retained brine in the equipment. Barite is frequently present when irrigation water (used for priming the wells) containing $\text{SO}_4^{=}$ is mixed with the brine. Calcite and/or aragonite is also found whenever separated steam condensate in contact with CO_2 is recombined with the brine. Corrosion products, magnetite and hematite, form an integral part of the scale adjacent to steel walls. The scales are layered with bands of widely differing material. The color, texture, hardness, and thickness of the deposits also vary considerably within locations in the GLEF.

A new method of in-process scale buildup surveillance based on radiography was successfully verified.

Introduction

Operation of the GLEF began in mid-May 1976 with the activation of a single well. Brine flow through the facility was approximately one-half of the design capacity. Magmamax No. 1 was the production well; Magmamax No. 3 was the injection well. Over a month-long period, approximately 300 hr of operation were logged before shutdown. Brine flow was interrupted a number of times over this period because of problems in liquid level control, pump operation, erosion and failure of parts, and the usual problems associated with starting up a new test facility.

During the final 100 hr of operation, when the facility was operating under relatively stable conditions, numerous brine and steam samples were collected from various locations. Following shutdown, samples of scale and solid deposits were scraped from the inside walls of pipes, flash drums, scrubbers, pump housings, reinjection lines, and other points from which solid samples could provide useful information in evaluating plant performance.

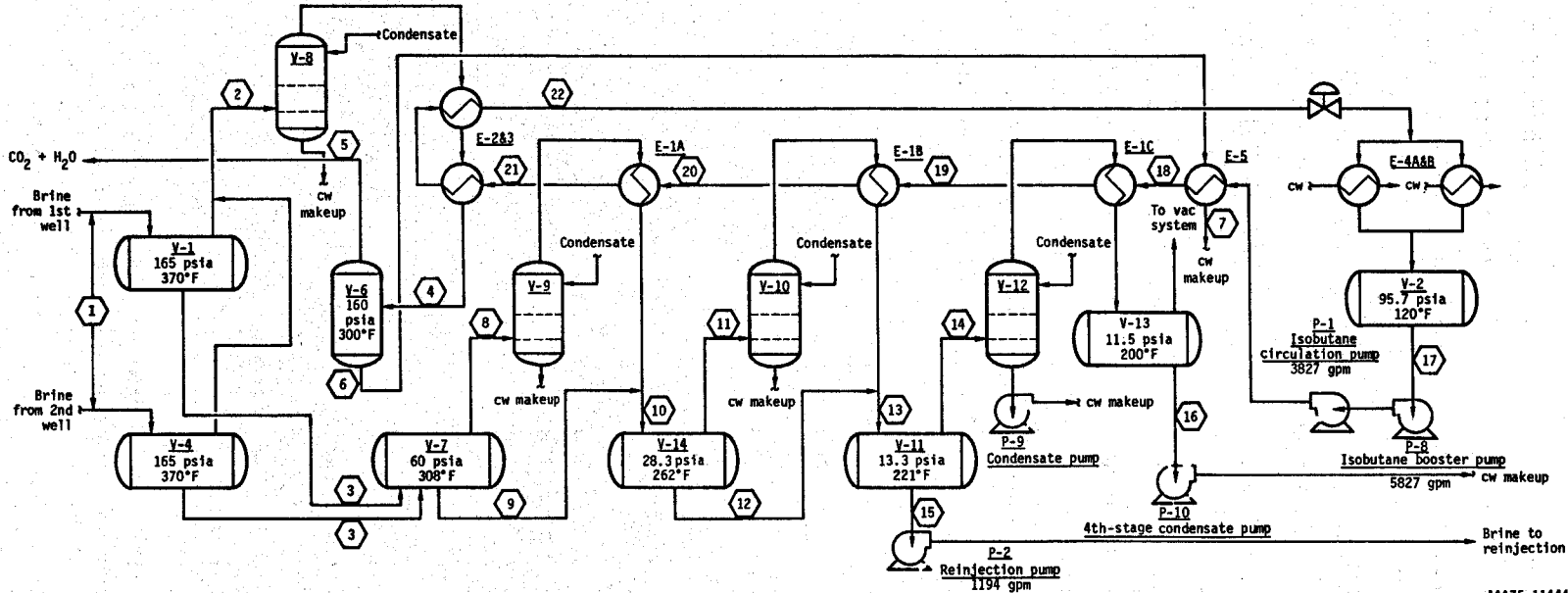
As a completely external means of surveying the buildup of scale within pipes and on components, radiographs were taken during operation at certain locations in the facility. These locations were preselected on the basis of anticipated

process conditions most likely to result in the production of scale.

GLEF Process Design

A condensed process flow diagram (Fig. 1) shows the design temperatures and pressures, the stream flow rates, and enthalpies. The GLEF incorporates a sequential four-stage flash process. As indicated in Fig. 1, feed to the facility is expected to be brine flow from two wells, each supplying 400,000 lb/hr at first-stage temperatures and pressures of 370°F and 165 psia. Temperature and pressure at the wellhead will be slightly higher, with dropoff occurring as the brine flows through surface piping between the wellhead and the first stage. The brine flashes in the production casing and, in principle, no additional flashing is necessary in the first-stage separator ("flash drum" and "separator" will be used interchangeably). All the separators consist of large cylindrical vessels mounted horizontally. Separation of the steam (and noncondensable gases) from the brine is achieved by gravity. The steam is scrubbed in bubble-cap tray towers and then directed toward heat exchangers where the heat is transferred to a secondary working fluid. All four stages operate similarly, except that the input brine is flashed across intake-

Y-1 1st-stage brine flash drum 78 in. diam x 20 ft-0 in. T-T
Y-4 1st-stage brine flash drum 66 in. diam x 20 ft-0 in. T-T
Y-6 Vent gas separator 36 in. diam x 10 ft-0 in. T-T
Y-7 2nd-stage brine flash drum 72 in. diam x 20 ft-0 in. T-T
Y-8 1st-stage steam scrubber 84 in. diam x 14 ft-0 in. T-T
Y-9 2nd-stage steam scrubber 66 in. diam x 14 ft-0 in. T-T
Y-10 3rd-stage steam scrubber 66 in. diam x 14 ft-0 in. T-T
Y-11 4th-stage brine flash drum 90 in. diam x 30 ft-0 in. T-T
Y-12 4th-stage steam scrubber 66 in. diam x 19 ft-0 in. T-T
Y-13 Condensate tank 42 ft diam x 12 ft-0 in. T-T
E-1A 2nd-stage exchanger 32.9 MM Btu/hr
E-1B 3rd-stage exchanger 268 MM Btu/hr
E-1C 4th-stage exchanger 23.0 MM Btu/hr
E-5 1st-stage condensate cooler 14.2 MM Btu/hr
E-2A3 1st-stage exchangers 94.9 MM Btu/hr
E-4A&B Condensers 191.8 MM Btu/hr
V-2 Isobutane accumulator 114 ft diam x 30 ft-0 in. T-T



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	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
Fluid	Total brine both wells	Steam + CO ₂	Brine	Cond + CO ₂ +H ₂ O	CO ₂ +H ₂ O	Cond	Cond	Steam	Brine	Brine	Steam	Brine	Brine	Steam	Brine	Cond	i C ₄	i C ₄	i C ₄	i C ₄	i C ₄	i C ₄
M lb/hr	800	132	668	132	30.7	101.3	101.3	35.9	632.1	668	28.3	639.7	668	23.6	644.4	23.6	1000	1000	1000	1000	1000	1000
gpm (ACFM)	1544	(5882)	1289	-	(786)	220	207	(4219)	1205	1250	(6852)	1197	1237	(12 501)	1194	49.1	3827	3974	4261	4732	5755	(2884)
*F	370	370	370	300	300	300	160	293	308	262	247	262	221	207	221	200	120	143	176	211	246	300
psia	165	165	165	160	160	160	150	60	60	28.3	28.3	28.3	13.3	13.3	13.3	11.5	95.7	540	530	520	510	500
p, lb/ft ³	64.6	0.374	64.6	-	0.656	57.3	61.0	0.142	65.4	66.6	0.0688	66.6	67.3	0.0315	67.3	60.0	32.6	31.4	29.3	26.3	21.7	5.78
MM Btu/hr	-	-	-	-	-	27.2	13.0	-	-	-	-	-	-	-	-	-	0	14.2	37.2	64.0	96.9	191.8

Fig. 1. Process flow diagram, Geothermal Loop Experimental Facility, Niland, California. After the Ben Holt Company diagram for the San Diego Gas & Electric Company.

control valves of the second-, third-, and fourth-stage separators. The train of heat exchangers operates in a countercurrent mode.

In the present operation, water is used as the working fluid and is expanded across a throttling valve to simulate the pressure drop across a turbine. About 10 MW of power is a design possibility at full flow of 800,000 lb of brine per hour. The expanded working fluid is condensed in tube and shell heat-exchangers with the heat rejected to the atmosphere via a conventional spray pond. The

steam condensate can be either cascaded to the next stage, reinjected together with the spent brine (unflashed portion of the geothermal brine), or used for spray-pond makeup. Figure 2 is a view of the facility from the west.

Geothermal Well Data

The GLEF is designed to be supplied by two wells, Magmamax No. 1 and Woolsey No. 1, while Magmamax No. 2 and Magmamax No. 3 would serve as reinjection wells. Figure 3 illustrates the geographical

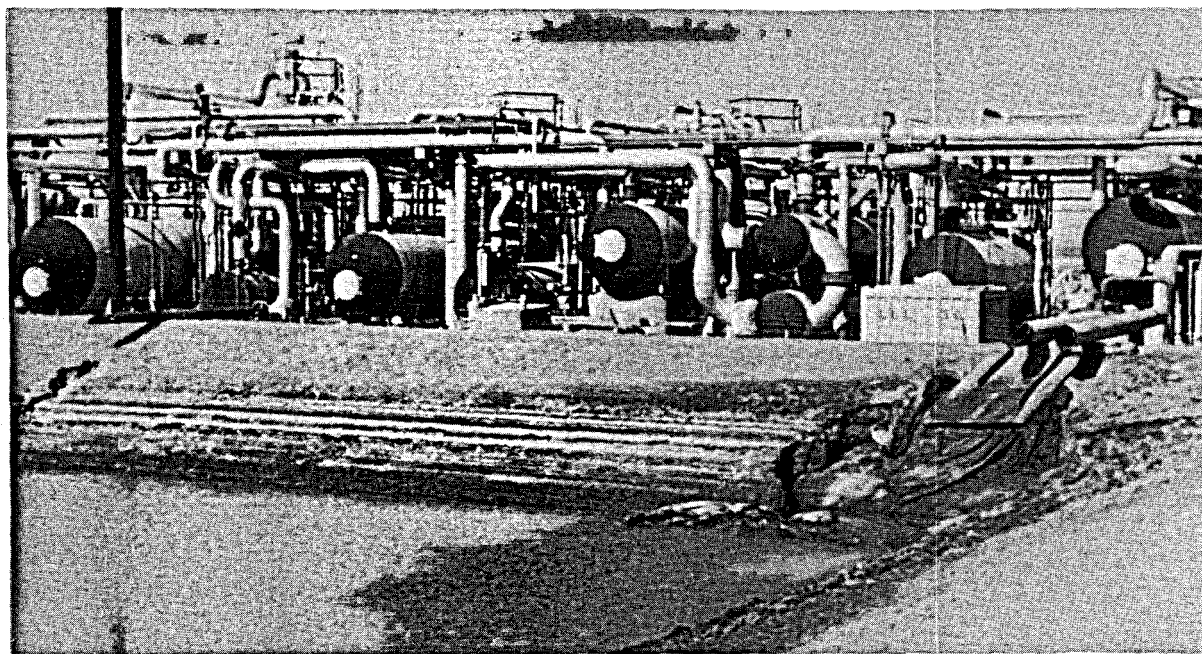


Fig. 2. San Diego Gas & Electric Company - ERDA Geothermal Loop Experimental Facility (GLEF). Foreground shows emergency brine pond. First-stage separator is on right, followed by second-, third-, and fourth-stage separators, right to left. Heat exchangers are located between separators. Steam scrubbers are located behind separators. Working fluid condenser, accumulator, and chemical cleaning equipment are hidden in the background.

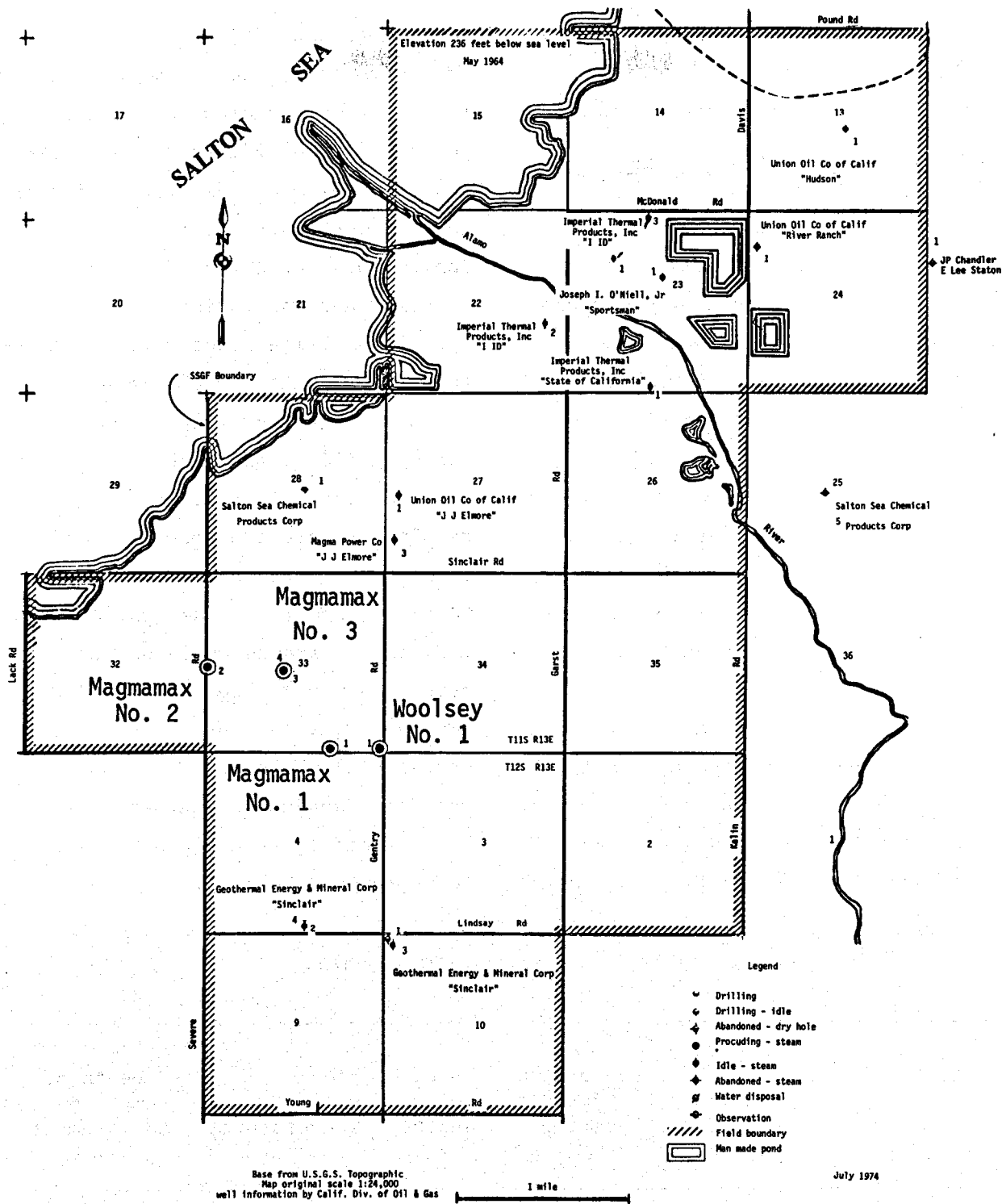


Fig. 3. Geothermal well locations at Niland, Imperial Valley, California.

layout of these wells (from Palmer¹). Geothermal well data are listed in Table 1 in accordance with Palmer.¹

GLEF Process Conditions During First Operational Phase

During the first 300 hr of operation, there were frequent interruptions for the above-mentioned reasons. The longest continuous period of operation was 101 hr, which occurred at the end of the first operational phase. Prior to this, the longest continuous period was 59 hr. About midway through the first operational phase, the third stage was bypassed completely because of weakened supports under the third-stage separator.

Pressures and, to a lesser degree, temperatures cycled continuously over a range which varied from stage to process stage. The frequency of these oscillations was

related to the off/on process control system, the ultimate cause of these periodic cycles (estimated period of about 1/2 to 2 min). The temperatures and pressures listed in Table 2 were obtained from GLEF instruments during the final 101 hr continuous operation.

Input brine rates were estimated to be 350,000 to 400,000 lb/hr. Because of off/on process control, large oscillations in the flow rates were recorded and could not be resolved to provide meaningful flow data. Therefore, the amount of flashing in each stage is not accurately known. The best estimates would be the design numbers given in the process-flow diagram, Fig. 1. During this first operational phase, the condensate was not cascaded to the next stage, but was either reinjected or used for spray-pond makeup.

Table 1. Geothermal well data.

Well	Production casing size, in.	Perforated interval depth, ft	Total hole depth, ft	Temperature, °C	Depth of temperature measurement, ft
Woolsey No. 1	8-5/8	1866-2375	2400	238	2372
Magmamax No. 1	8-5/8	1797-2264	2805	260	2310
Magmamax No. 2	9-5/8	3784-4360	4368	316	3450
Magmamax No. 3	9-5/8	2618-3078	4000	288	2670

Table 2. Typical temperatures and pressures during GLEF operation.

Location in GLEF	Temperature, °F	Pressure, psig
Wellhead Magmamax No. 1	~ 410	300
Production line, upstream first-stage separator	380	205-245
First-stage separator	360	110-115
First-stage scrubber	343	118-120
Second-stage separator	270	40-55
Second-stage scrubber	270	37-49
Fourth-stage separator	240	10-11
Fourth-stage scrubber	225	8-9
Wellhead Magmamax No. 3	195-200	

Brine Composition

The composition of Magmamax No. 1 brine, uncorrected, for an unknown amount of flashing (but estimated to be 10%) in the wellhead casing is shown in Table 3. Also listed in Table 3 is the normalized composition for 10 elements reported in wet chemical analysis of scale deposited in the GLEF.

Table 4, below, shows the sample numbers and the corresponding locations in the GLEF from which the samples were obtained, June 16, 1976.

The three brine samples collected from the liquid output of the first-, second-, and fourth-stage separators are quite similar in composition for the limited number of species analyzed. Brine out of the fourth-stage separator (VII-B0-L30) is lower in density

and in solids content because recombination of condensate occurred in the fourth-stage separator at the time the sample was collected. Examination of the samples shows no unusual or unexpected amount or distribution of principal scale-forming species in the brine. Tables 5-8 report analyses of brine and steam samples. The suspended solids content is that obtained after cooling to room temperature.

Analyses of the steam samples indicate that the scrubbers are performing effectively, although the first-stage scrubber (V8) may need some operational adjustment to bring the total quantity of solids in the scrubbed steam down to a lower level. However, results such as were obtained for samples V7-S0-L26 and V6-L0-L33 are unusual. The former

Table 3. Magmamax No. 1 brine composition (uncorrected for flashing) and normalized composition for ten elements generally found in scales. Sample collected from LLL test separator on August 10, 1976.

Element	Weight, ppm	Normalized wt%
Li	141	
Na	42,000	
Si	202	0.93
K	8,600	
Fe	256	1.18
Cu	1	.005
Rb	64	
Ba	118	0.54
Mg	80	0.37
Zn	361	1.66
Sr	388	
Al	<1	<0.005
Cl	121,000	
Ca	20,000	91.8
Mn	690	3.17
Pb	78	0.36
pH	5.2	
EH (MV vs H ₂)	237	
Density (g/cm ³ at 25°C)	1.15	
Total solids (g/kg, brine)	208	

Table 4. Sample designation according to location.

Sample number	Location	Sample number	Location
V4-B0-L24	First-stage separator, brine out	V7-S0-L26	Second-stage separator, steam out
V7-B0-L28	Second-stage separator, brine out	V9-S0-L29	Second-stage scrubber, steam out
V11-B0-L30	Fourth-stage separator, brine out	V12-L0-L31	Fourth-stage scrubber, wash water out
V4-S0-L23	First-stage separator, steam out	V12-L0-L32	Fourth-stage scrubber, steam out
V8-S0-L25	First-stage scrubber, steam out	V6-L0-L33	Vent gas separator, condensate out

Table 5. Analysis of brine out, first-stage separator, sample V4-B0-L24.

Date taken:	6/16/76		
Time:	1500		
Method:	Condenser coil		
pH:	6.0		
Density:	1.17 g/cm ³ at 25°C		
Suspended solids:	634 mg/kg		
Dissolved solids:	252 g/kg		
Element	Suspended solids, wt%	Liquid, mg/liter	Reconstructed ^a brine, mg/kg
Si	27.9	33	199
Fe	10.3	280	264
Cu	0.02	2	1.7
Ba	5.0	125	157
Cl		164,000	140,000
Mn	0.04	1,000	788
Pb	0.02	76	64

^aSuspended plus dissolved solids.

Table 6. Analysis of brine out, second-stage separator, sample V7-BO-L28.

Date taken:	6/16/76		
Time:	1535		
Method:	Condenser coil		
pH:	5.9		
Density:	1.18 g/cm ³ at 25°C		
Suspended solids:	657 mg/kg		
Dissolved solids:	252 g/kg		
Element	Suspended solids, wt%	Liquid, mg/liter	Reconstructed ^a brine, mg/kg
Si	26.5	24	194
Fe	8.6	273	288
Cu	0.05	2	2.0
Ba	5.6	133	149
Cl		168,000	142,000
Mn	0.04	950	805
Pb	0.08	87	75

^aSuspended plus dissolved solids.

sample is of the steam leaving the second-stage separator, before it is scrubbed. The analysis shows that the steam is already quite pure. Sample V6-LO-L33 is simply condensed steam from the first-stage scrubber and should have the same solids content as sample V8-SO-L25. In fact, it is greater by tenfold, which suggests brine intrusion in the vent gas separator at some point in the operation.

The noncondensable gas mass fraction is estimated to be from 1 to 1.5% of the brine. By volume, the noncondensable gas consists of 98% CO₂, 1 to 1.5% CH₄, up to 0.35% H₂, up to a few hundred ppm of NH₃, and a variable amount of H₂S, ranging from 1500 to 2500 ppm.

The CO₂ content of the brine is considerably higher than that which has been reported from other wells, namely, 5000 ppm in the No.-1-State-

Table 7. Analysis of brine out, fourth-stage separator, sample V11-BO-L30.

Date Taken:	6/16/76		
Time:	1500		
Method:	Condenser coil		
pH:	6.2		
Density:	1.14 g/cm ³ at 25°C		
Suspended solids:	611 mg/kg		
Dissolved solids:	223 g/kg		
Element	Suspended solids, wt%	Liquid mg/liter	Reconstructed ^a brine, mg/kg
Si	22.5	23	158
Fe	12.9	189	244
Cu	0.06	2	2
Ba	4.5	109	122
Cl		128,000	112,000
Mn	0.28	790	690
Pb	0.05	64	56

^aSuspended plus dissolved solids.

Table 8. Analysis of steam and scrubber wash water.

Sample number	Date	Time	Total solids, mg/liter	Chloride mg/liter	pH
V4-SO-L23	6/16/76	1450	251	79	6.2
V8-SO-L25	6/16/76	1515	107	<10	6.1
V7-SO-L26	6/16/76	1526	33	<10	8.9
V9-SO-L29	6/16/76	1550	31	<10	9.1
V12-LO-L31	6/16/76	1640	397	177	
V12-SO-L32	6/16/76	1650	46	<10	8.4
V6-LO-L33	6/16/76	1800	1300	890	

of-California Well,² 500 ppm in No. 2 IID,² 4000 ppm in Sinclair No. 4,³ and 7150 ppm in No. 1 IID.⁴ The high CO₂ content is the main reason for utilizing a binary-fluid energy-conversion cycle for these geothermal brines. With these large volumes of CO₂, it would be uneconomical to maintain the required low-exhaust pressures in a steam turbine.

The sulfur content in the Magmamax No. 1 brine (based on H₂S) brackets the values^{2,4} reported in brines from other wells in the Imperial Valley. Presently, at the GLEF, a 130-ft high stack is used to disperse the H₂S to meet acceptable ground-level concentrations.

Scale Production in the GLEF

Because of numerous plant upsets, scale deposited on the walls of the GLEF piping and equipment during the first 300 hr of operation represents scale produced over a wide range of operating conditions. These scales may or may not represent the amount or type of scaling that would occur in the GLEF during a prolonged, steady period of operation. Clearly these scales do not represent what would be deposited when Woolsey No. 1 is brought in for eventual two-well operation. Nevertheless, the mineralogical and chemical analyses of these scales add greatly to our

understanding and ability to interpret the interaction of scaling with brine chemistry, changes in brine temperature and pressure, and with other conditions imposed by a multi-stage flash process.

Frequent interruptions in the GLEF operation resulted in alternating bands of light- and dark-colored layers in the scale as illustrated in Figs. 4 and 5. In most of the brine-piping, scale thickness ranged from 1 to 3 mm (Fig. 6). In the separators, there were at least two scaling regions. Above the normal operating liquid level, scaling on the walls of the separators was 1 to 2 mm thick compared to approximately 5 to 10 mm in the lower half, which



Fig. 4. Scale from fourth-stage separator, GLEF. Sample M1-VII-3, June 23, 1976. Thickness of sample, 9 mm.



Fig. 5. Scale from reinjection pipe flange connection to output of reinjection pump, GLEF. Sample M1-P2-DS-1, June 17, 1976. Thickness of sample, 12 mm. This sample represents scale buildup after approximately 4 mm was scraped from the wall earlier in the operation. Total thickness of undisturbed deposits was 16 mm.

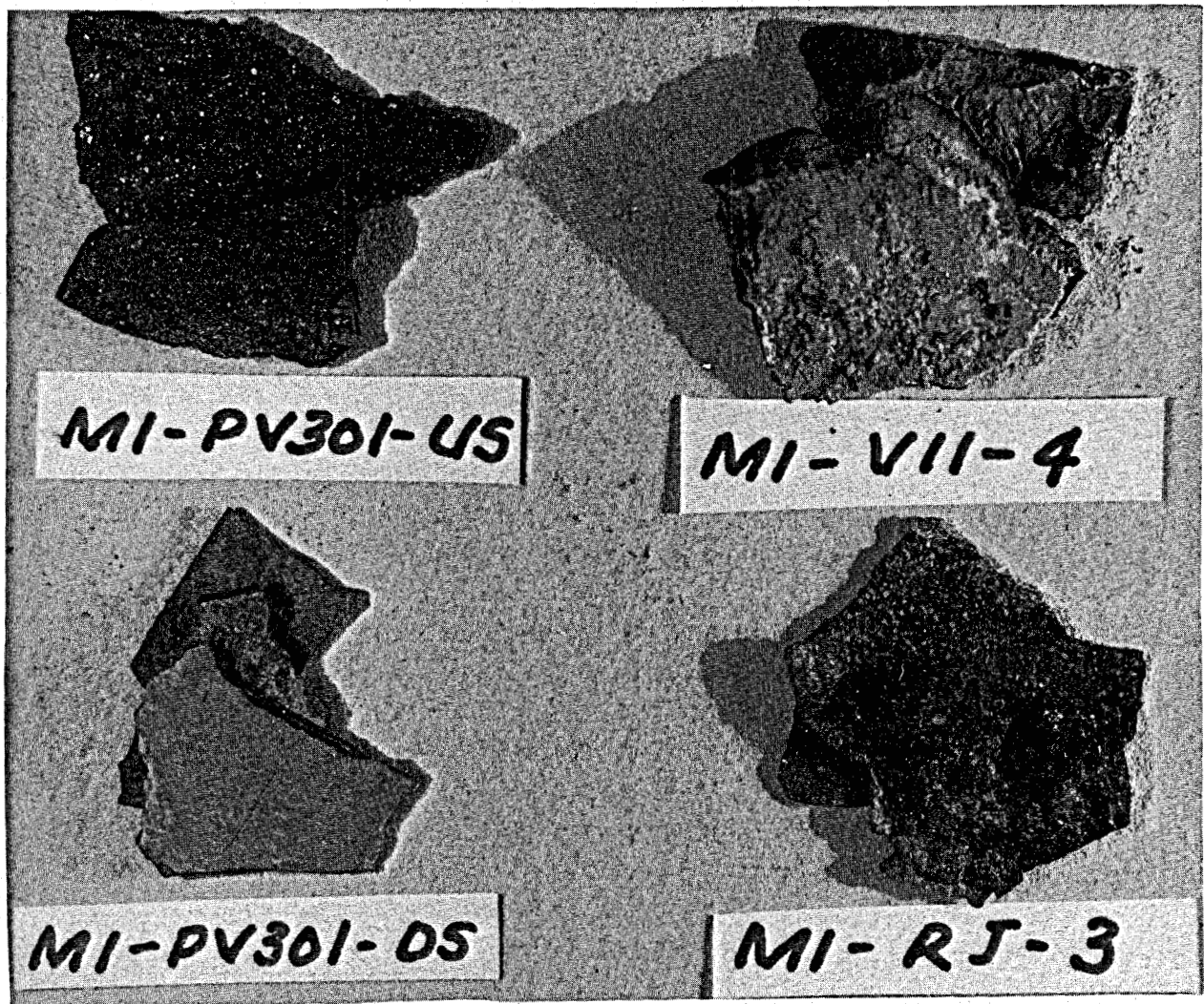


Fig. 6. Scale samples from various points in the GLEF. M1-PV301-US: block valve upstream of first-stage control valve (same block valve also initially located downstream), M1-PV301-DS: 6- to 16-in. expansion pipe downstream of PV-301, the first-stage control valve, M1-VII-4: upper portion, fourth-stage separator, and M1-RJ-3: reinjection wellhead pipe.

was exposed to the liquid (Figs. 7 and 8). This variation is not surprising in that the upper half of the separator is exposed to relatively clean steam with entrained brine plus an undetermined amount of splashing that takes place internally. The

fact that continuous drainage can occur helps to reduce the buildup of scale in the upper half of the separator. Figures 9, 10, and 11 are photographs of the insides of the first-, second-, and fourth-stage separators, respectively.

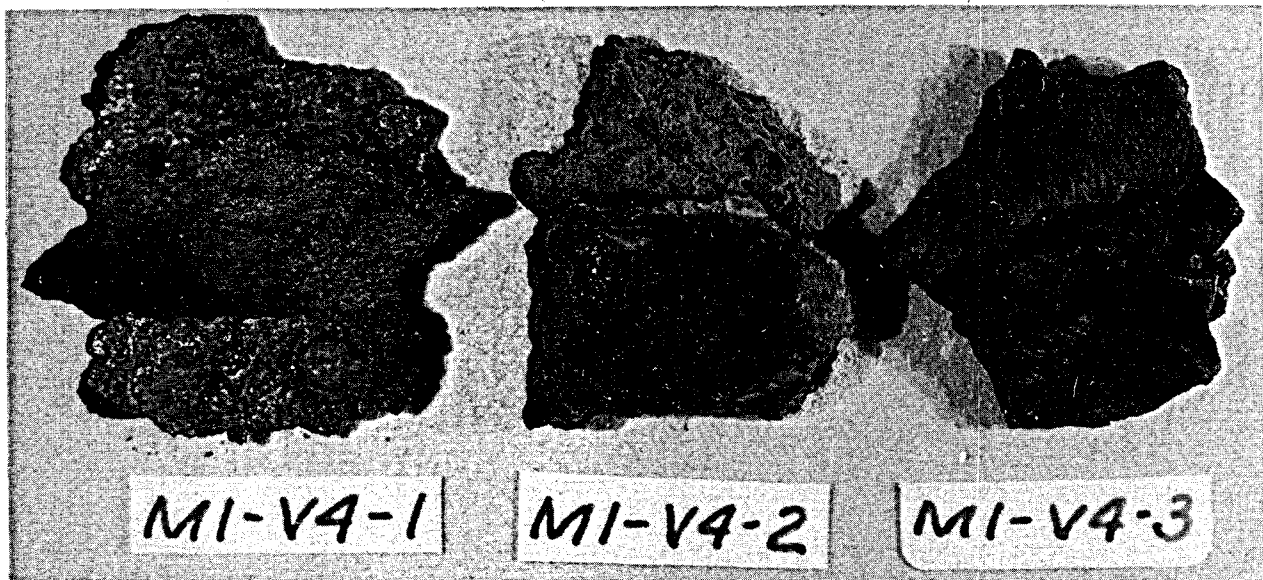


Fig. 7. Scale samples from first-stage separator, GLEF. M1-V4-1: upper half, M1-V4-2: lower half, and M1-V4-3: internal wear plate of input brine stream.

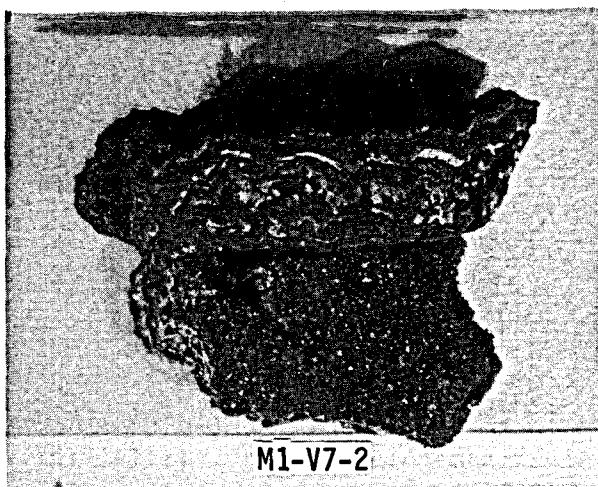


Fig. 8. Scale samples from bottom of second-stage separator, GLEF.

Brine-scaling in the steam scrubbers was minimal as expected, although there was a layer of corrosion products which was apparent not only on scrubber surfaces, but on other steel surfaces as well. These corrosion products become an integral part of the brine scale. Figures 12-A and 12-B show the extent of corrosion on the underside of the lower tray in the second-stage scrubber.

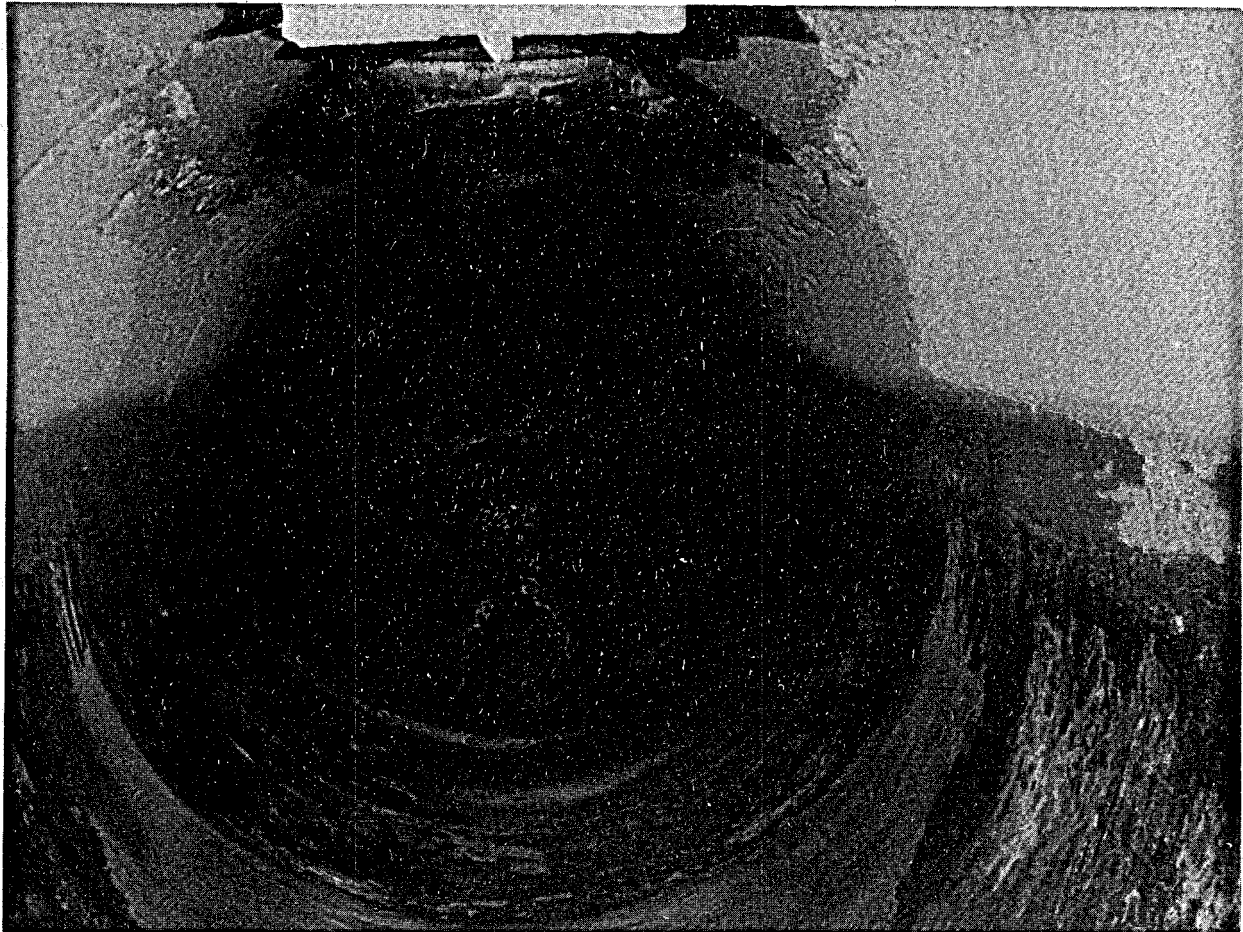


Fig. 9. Interior of first-stage separator after approximately 300 hr operation, GLEF. Intake brine stream enters at top and impinges on wear plate at head of separator. Opening at bottom is solids trap. Heavy scaling in lower half of separator is clearly shown.

The heaviest scaling occurred in the brine effluent piping of the fourth-stage separator and in points beyond. Brine from the fourth stage flows to the reinjection pump which was heavily scaled (Fig. 13). Just downstream of the reinjection pump, 12 to 16 mm of scale was observed on the walls of the 10-in. discharge pipe (Fig. 14). At approximately 100 m further downstream in the surface-reinjection piping, heavy scaling was still evident in the

butterfly valves, which were used to isolate short bypass spool sections (Fig. 15). The piping near the reinjection well was not heavily scaled, however. Apparently either the amount and/or the adherence of scale-forming constituents decreases as the spent brine passes through approximately a kilometer of surface-reinjection piping. This does not imply that the brine is depleted of suspended solids. As it reaches the reinjection well the spent brine does



Fig. 10. Interior of second-stage separator after approximately 300 hr operation, GLEF. Intake brine steam enters at bottom and impinges on wear plate at head of separator. This separator contains a 316L stainless steel cladding.

indeed contain a considerable amount of suspended solids. From filtered samples collected in the line near the reinjection well, an average of 0.48 g of suspended solids per kilogram of brine injection was found. X-ray diffraction analysis indicated that the solids were amorphous material. Silicon and iron were principal cations with calcium, chromium, manganese, zinc, and lead also present, each varying from 1 to 3 wt%. The characteristics

of these suspended solids are being studied in greater detail by Hill and Owen.⁵

Scale Samples from the GLEF

Scale samples were collected from various locations in the GLEF (see Table 9.).

The results of mineralogical and chemical analyses of these samples are listed in Tables 10-12-B. Temperatures and pressures at the locations in the GLEF where these scale

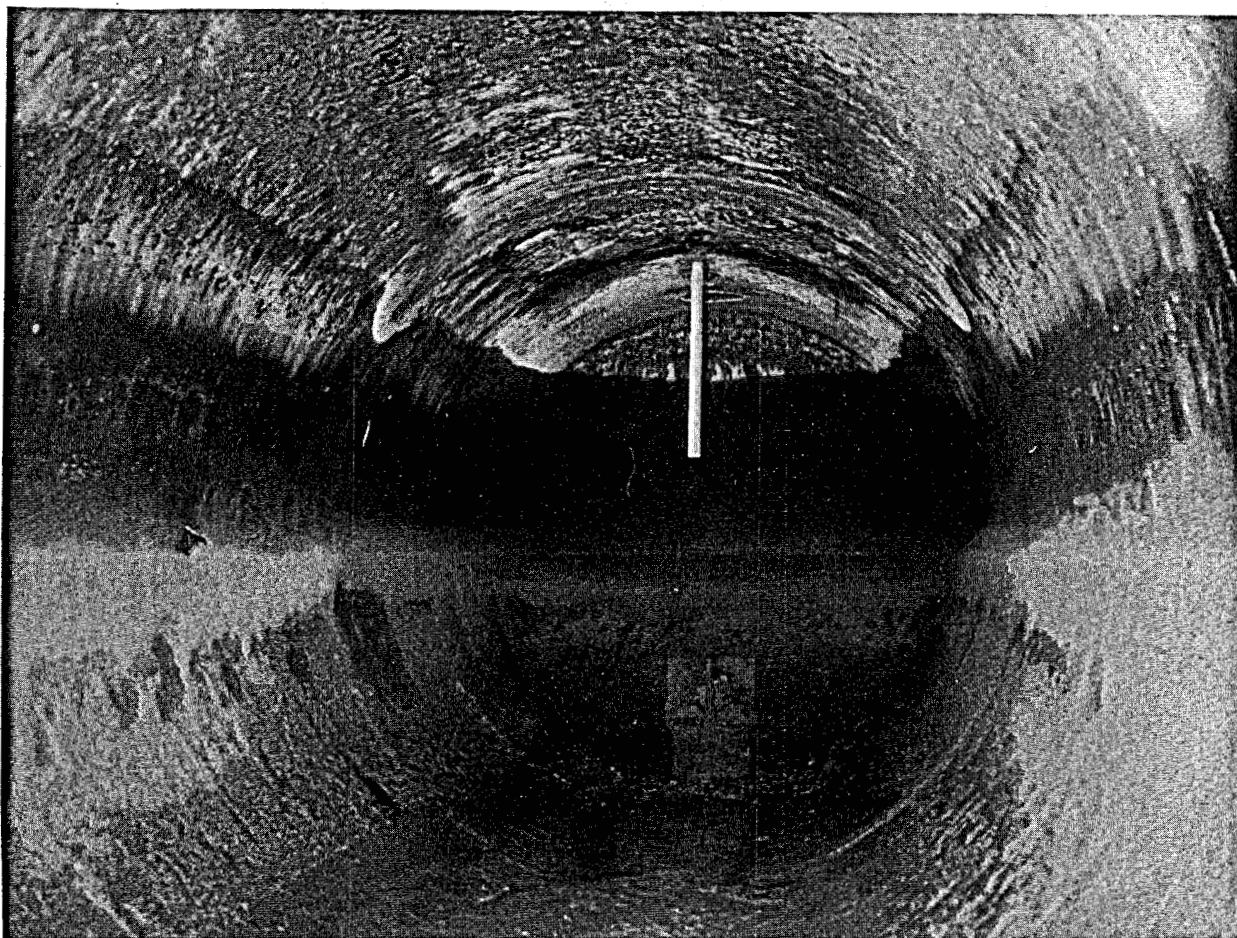


Fig. 11. Interior of fourth-stage separator after approximately 300 hr operation, GLEF. Vortex baffle is shown at bottom where brine exhausts. Intake pipe is at camera end. Liquid level sensing probe protrudes from top.

samples were collected can be estimated from the data given in Table 2. It should be emphasized again that the operating conditions at every location were highly variable.

Scale Mineralogy and Chemical Composition

Samples M1-PV301-US-2 and M1-V301-DS-1

In the mixed-phase brine immediately downstream of the first-stage control valve, where large temperature and pressure drops occur, the scale deposited on the pipe walls is predominately a galena-crystalline phase. The galena is interspersed in an iron-rich amorphous silica matrix. This scale can be chipped off the pipe wall in small flakes with moderate effort. Thickness is approximately 2 mm, coloring is

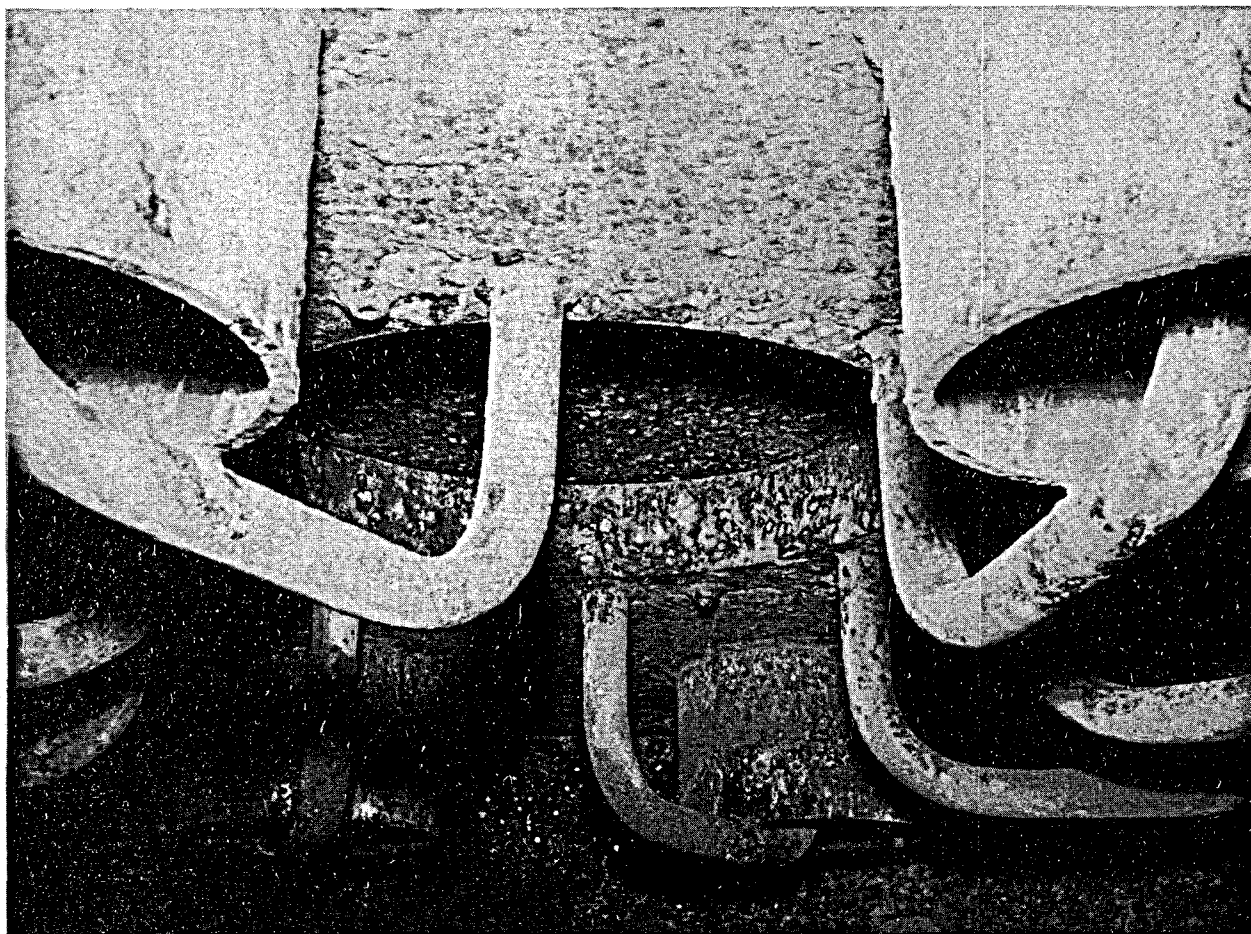


Fig. 12. Scaling on underside of lower tray of second-stage steam scrubber, GLEF, after approximately 300 hr operation.

grey to black, and the scale is quite hard and brittle. The underlayer consists of magnetite/hematite, steel corrosion products. The block valve where sample M1-PV301-US-2 was collected was also in service approximately 50% of the time at a location downstream of the first-stage control valve. The lead-rich scale may have been deposited then, leaving uncertain whether this particular scale sample resembles the amount and the type of scaling at points upstream of the control valve.

Galena is by far the predominate sulfide mineral found in the Magmamax-No.-1 scales, whereas scales from Sinclair-No.-4 well and No.-1-IID well were predominately copper sulfides, bornite, and digenite enclosed also in an iron-rich amorphous silica matrix.^{3,4}

Samples M1-V4-2, M1-V7-2, and M1-LV711-DS-1

Scales found in the lower half of the first- and second-stage separators were primarily an iron-rich amorphous

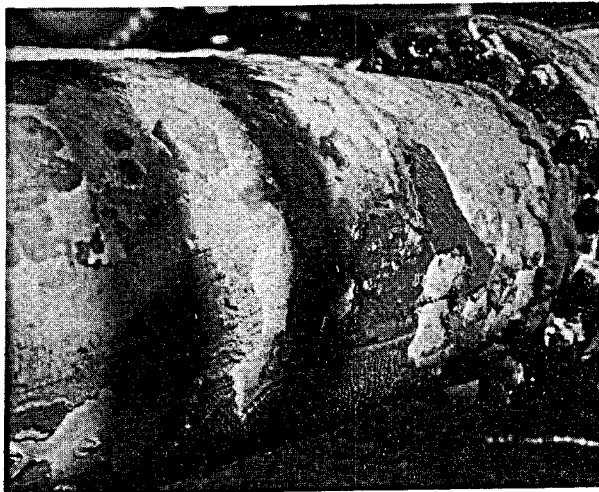


Fig. 13. Scale deposits on reinjection pump intake housing, GLEF. Approximately 300 hr operation.

silica with galena present as the principal crystalline phase, but to a much lesser extent than scales deposited just downstream of the first-stage control valve. The relatively high Na (halite) content results from interruptions in operation and subsequent cooling of the residual brine to ambient temperatures. The high iron content may be in part mixed corrosion products. These scales are light brown to black in color, softer than the galena-rich scales, and when lightly ground resemble fine-grained dirt.

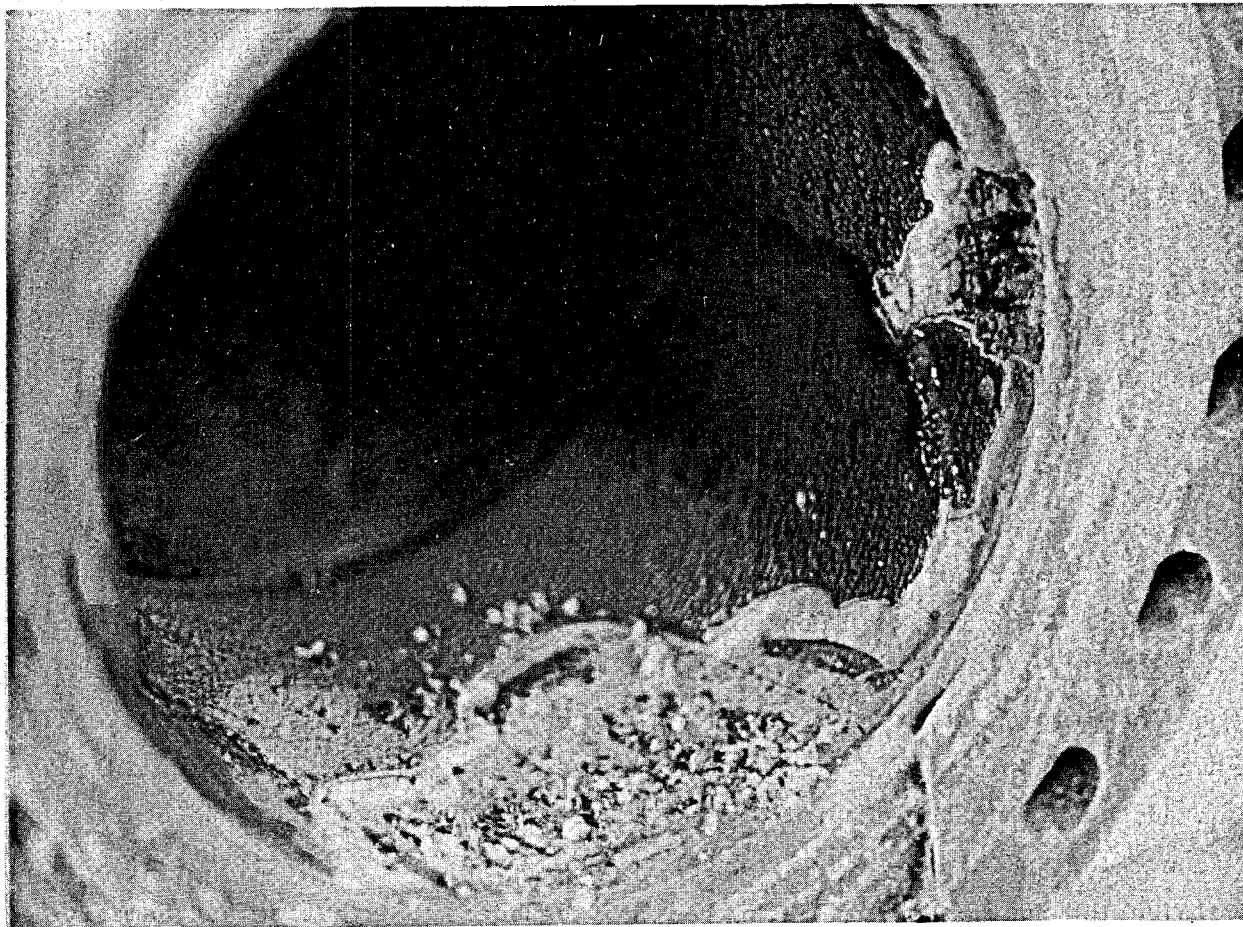


Fig. 14. Scale from reinjection pipe flange (10-in. diameter) connected to reinjection pump output, GLEF, after approximately 300 hr operation.

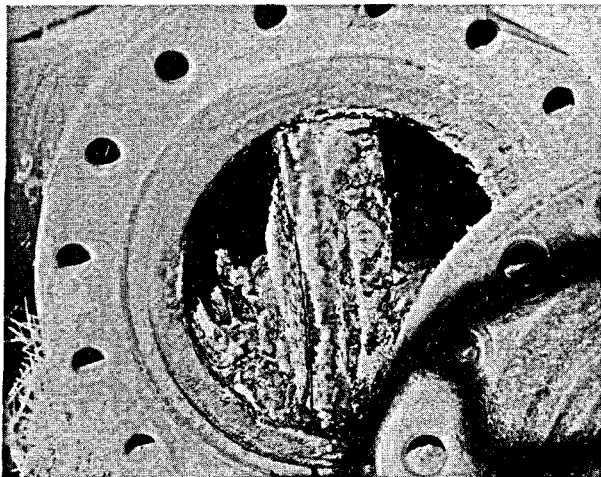


Fig. 15. Scale in butterfly valve (10-in. diameter) isolating short bypass pipe spools in reinjection line at about 100 m downstream of the reinjection pump, GLEF, after approximately 300 hr operation.

Samples M1-V11-2, M1-V11-3, and M1-LV714-DS-1

In the fourth-stage separator and in locations further downstream, low-temperature-scaling species predominate. For the most part the scales are softer and layered. The dark scale consists of halite intermixed with an iron-rich amorphous silica. Trace amounts of galena may be present. The thick, lighter layers consist of amorphous silica and halite. Large volumes of ponded brine from the facility's emergency brine pond was pumped into the fourth-stage separator on at least two instances because the separator was a convenient point of entry to the reinjection pump. How this affected scaling in the fourth stage and beyond has not been established.

Samples M1-P2-DS-2 and M1-RJ-2

Downstream of the reinjection pump and approximately 100 m beyond in the piping, the scale was similar to that deposited in the fourth-stage separator. The dark layer, however, consisted of kutnahorite, $[Ca (Mn, Mg) CO_3]$ in an iron-rich amorphous silica matrix. It should be noted that at times the condensate from the first-, second-, and third-stage heat exchanges was combined with the brine at the input to the reinjection pump. Analysis of the condensate shows amounts as much as 1440 ppm as $CaCO_3$ of CO_3 and/or HCO_3 , which very likely contributed to the presence of the carbonate phase in the dark-layered scale. Calcite/aragonite was detected also in scales at locations where steam condensate may have contacted the brine. Barite is present also as a result of the reaction of $SO_4^{=}$ in irrigation water used to prime the well and barium in the brine.

Samples M1-V8-2 and M1-V9-2

The scale collected from the steam scrubbers showed a high iron content consistent with visual observation of surface corrosion in the scrubbers. There were no brine-type scales of any significance in the scrubbers. Magnetite and hematite have been detected in scales at other locations in the facility, generally

as the scale underlayer adjacent to steel surfaces. It is believed that corrosion is, in part, due to exposure of wet surfaces to air during facility shutdowns and inspections.

Sample M1-RJ-3

This sample from the reinjection wellhead piping contains a very high lead content. This is unusual since beyond the second-stage separator the lead content in the scale is low. We believe that a galena-rich

scale was deposited on the reinjection piping at the wellhead when the reinjection well, Magmamax No. 3, was producing approximately two months before the GLEF operation. This is consistent with sample M1-MX3-1, which consisted of scale removed from the pressure-sensing tubing in the reinjection well casing. This tubing was installed after Magmamax No. 3 was producing and before GLEF began its operation. This scale contained very little lead.

Table 9. Scale samples and locations.

Sample number	Sampling date	GLEF location
M1-PV301-DS-1	6/22	6 to 16 in. expansion pipe downstream of PV301, first-stage control valve.
M1-V4-2	6/23	Bottom, first-stage separator
M1-V7-2	6/23	Bottom, second-stage separator
M1-V11-3	6/23	Middle, fourth-stage separator
M1-P2-DS-2	6/17	Connecting pipe flange to reinjection pump output
M1-PV-301-US-2	6/22	Block valve upstream of first-stage control valve
M1-V8-2	6/22	First-stage scrubber, bottom tray
M1-LV714-DS-1	6/22	Downstream, fourth-stage control valve
M1-V9-2	6/22	Second-stage scrubber, bottom tray
M1-RJ-3	6/30	Reinjection wellhead pipe
M1-V11-2	6/22	Bottom, fourth-stage separator
M1-RJ-2	6/22	Reinjection line, second bypass spool
M1-LV711-DS-1	6/22	Downstream, second-stage control valve
M1-MX3-1	6/23	Downhole pressure-sensing tubing, Magmamax No. 3

Table 10. X-ray diffraction analysis of scale deposited in GLEF, May-June 1976 operation.

Sample number	Date	Location	XRD analysis, crystalline phases ^a
M1-PV301-DS-0 (see Fig. 6)	6/3/76	Elbow, downstream of first-stage control valve	<ol style="list-style-type: none"> 1. Very strong galena phase 2. Underlayer in contact with steel surface, predominately hematite, with possible trace of akaganeite (β-FeOOH)
M1-PV301-DS-1 (see Fig. 6)	6/22/76	Expansion pipe, downstream of first-stage control valve	Strong galena phase; no other material observed
M1-V7-2 (see Fig. 8)	6/23/76	Bottom, second-stage separator	Predominately halite with some galena
M1-V11-3 (see Fig. 4)	6/23/76	Middle, fourth-stage separator	<ol style="list-style-type: none"> 1. Black underlayer, halite with lesser amounts of galena 2. Redish layer, halite with trace of galena 3. White thick layer, halite 4. Redish-brown layer, halite 5. Top light brown layer, halite
M1-P2-DS-2 (see Fig. 5)	6/17/76	Connecting pipe flange to reinjection pump output	<ol style="list-style-type: none"> 1. Green material, halite, possibly barite 2. White material, galena trace 3. Light brown layer halite, some sylvite (KCl) 4. Dark brown, kutnahorite [Ca(Mn,Mg)CO₃]
M1-V14-1/2	6/2/76	Inspection port, third-stage separator	Halite, sphalerite (Zn, Fe)S

Table 10. (Continued)

Sample number	Date	Location	XRD analysis, crystalline phases ^a
M1-P9-2	6/3/76	Intake housing, condensate pump	Solids due to brine intrusion into pump well during operation 1. Galena, wustite (FeO)
M1-P9-US-1	5/19/76	Intake screen, condensate pump	Halite, hematite

^a The crystalline material is almost always interspersed in an iron-rich amorphous silica matrix and, in many samples, is present in only trace quantities.

Table 11. Weight percent of elements in GLEF scale by atomic absorption and/or wet chemical analysis, May-June 1976.

Element	M1-PV301		M1-V7-2	M1-V11	M1-V11	M1-P2	M1-P2
	-DS-1	M1-V4-2		-3A	-3A	-DS-2B	-DS-2B
				"dark"	"light"	"dark"	"light"
Si	7.38	14.17	14.93	16.04	20.30	17.79	15.28
Fe	10.36	22.50	9.94	9.39	1.24	8.87	0.73
Mn	0.77	1.38	1.68	1.84	0.27	2.68	0.12
Ca	0.09	0.27	0.99	0.30	0.44	1.02	0.40
Pb	43.90	6.70	5.10	0.45	0.16	0.54	0.07
Na	0.56	2.89	4.09	2.77	2.54	1.36	2.60
K	0.32	0.80	0.65	0.75	0.49	0.47	0.53
Al	0.26	0.27	0.22	0.018	0.018	0.015	0.017
Zn	0.05	0.76	0.82	0.38	0.09	0.55	0.04
Cu	1.56	0.10	0.15	0.13	0.081	0.11	0.097
Ba	<0.005	<0.005	0.26	0.04	0.67	0.17	0.24
S	5.11	1.33	0.56	0.044	0.06	0.10	0.043
Sb	1.21	0.10	0.06	0.02	<0.005	0.04	<0.005
Mg	0.054	0.24	0.095	0.017	0.012	0.009	0.008

Table 12-A. Weight percent of elements in GLEF scale by spectrochemical analysis, May-June 1976.

Element	Sample Number						
	M1-PV301-US-2	M1-V4-2	M1-LV711-DS-1	M1-V7-2	M1-LV714-DS-1	M1-V11-2	M1-V11-3
Pb	40	3	2	3	3	1	0.2
Fe	4	>10	1	>4	1	6	>3
Si	2	>8	0.3	>3	20	>10	>10
Ag	1	0.03	0.05	0.03	1	0.02	0.008
K	<0.5		1		nd<0.5	1	
Ca	0.3	0.6	1	0.6	0.2	3	0.3
Mn	0.3	0.1	0.2	0.3	0.2	0.2	0.8
Sb	0.3	0.01	0.03	0.02	2	0.03	0.03
As	0.2	0.03	0.1	0.1	0.1	0.1	0.03
Na	0.2	1	>20	1	0.3	2	1
Al	0.1	0.1	0.06	0.1	0.2	0.06	0.02
Cu	0.1	0.06	0.3	0.08	2	0.2	0.07
Zn	0.06	0.2	0.08	0.4	0.2	0.2	0.2
Mg	0.03	0.4	0.06	0.1	0.02	0.02	0.01
B	0.01	0.03	0.02	0.02	0.06	0.1	0.09
Sr	0.01	0.01	0.03	0.04	0.006	0.1	0.04
Ga	0.006	0.01	0.001	0.02	0.03	0.01	0.02
Ba	0.006	0.01	0.03	0.06	0.02	1	0.03
Ni	0.006		0.001		0.003	0.002	
Mo	0.003	0.005	nd<0.003	0.003	nd<0.003	0.003	0.001
Be	0.002	0.003	0.0003	0.004	0.02	0.002	0.002
Co	0.002		0.001		0.001	nd<0.0001	
Ti	<0.0003	0.007	0.001	0.02	0.001	0.01	nd<0.0003
Cr	nd<0.0001		0.001		0.003	0.003	

Table 12-B. (Continued).

Element	Sample Number					
	M1-P2-DS-2	M1-RJ-2	M1-RJ-3	M1-MX3-1	M1-V8-2	M1-V9-2
	Approximate wt%					
Pb	0.2	0.3	40	0.05	0.4	0.4
Fe	>3	>4	2	>10	30	30
Si	>10	>10	20	>10	1	4
Ag	0.003	0.005	1	0.005	0.003	0.005
K		1	<0.5	<0.5	<0.5	<0.5
Ca	2	3	0.1	3	0.1	0.3
Mn	0.1	0.8	0.08	3	0.3	0.8
Sb	nd<0.003	0.01	0.2	0.02	nd<0.003	nd<0.003
As	0.03	0.02	0.1	0.03	0.1	0.1
Na	0.7	6	0.1	0.6	0.01	0.3
Al	0.06	0.03	0.1	0.003	0.01	0.1
Cu	0.06	0.06	0.1	0.001	0.04	0.1
Zn	0.3	0.2	0.1	0.2	0.2	1
Mg	0.01	0.01	0.3	0.1	0.04	0.1
B	0.1	0.08	0.01	0.04	0.06	0.1
Sr	0.03	0.1	0.002	0.01	0.01	0.003
Ga	0.02	0.02	0.006	0.03	0.006	0.01
Ba	0.1	0.3	nd<0.006	nd<0.003	0.006	nd<0.006
Ni		nd<0.001	0.003	nd<0.001	0.01	0.008
Mo	0.003	0.005	nd<0.003	0.003	nd<0.003	0.01
Be	0.003	0.0003	0.0003	0.0003	0.0004	0.002
Co		nd<0.0001	0.001	nd<0.0001	0.01	0.004
Ti	nd<0.0003	<0.0003	0.002	<0.0003	<0.0003	0.02
Cr		0.0001	nd<0.0001	0.02	0.01	0.004

Table 13 lists the weight percentage, normalized to 100, of 10 major scale constituents found by wet chemical analysis in several scale samples and in the brine. The degree of fractionation of these elements from the brine is clearly indicated. The scale samples are highly enriched in lead, iron, and silicon and are depleted in calcium with respect to their composition in the brine. Silicon enrichment increases from upstream to downstream conditions while lead decreases. Iron

content in the scale appears to be fairly constant in all positions, except for the light-colored portion of the scale in samples M1-V11-3A and M1-P2-DS-2A. Since samples M1-V11-3 A/B and M1-P2-DS-2 A/B are separated in position by only the reinjection pump, it is not surprising that the two lighter-colored scales are very similar in composition, as are the two darker-colored portions of these two scales. Sodium and potassium were excluded from this table because it is believed their presence in the

Table 13. Normalized weight percent of 10 chemical constituents of scale deposited in the GLEF, May-June 1976.

Sample number	Element									
	Si	Fe	Mn	Ca	Pb	Al	Zn	Cu	Ba	Mg
Magmamax-1 brine	0.93	1.18	3.17	91.8	0.36	<0.005	1.66	0.005	0.54	0.37
M1-PV301- DS-1	11.45	16.08	1.20	0.14	68.14	0.40	0.08	2.42	<0.01	0.08
M1-V4-2	30.54	48.50	2.97	0.58	14.44	0.58	1.64	0.22	<0.01	0.52
M1-V7-2	43.67	29.08	4.91	2.90	14.92	0.64	2.40	0.44	0.76	0.28
M1-V11-3B dark	56.07	32.83	6.43	1.05	1.57	0.06	1.33	0.45	0.14	0.06
M1-V11-3A light	87.20	5.33	1.16	1.89	0.69	0.08	0.39	0.35	2.88	0.05
M1-P2-DS-2B dark	56.02	27.93	8.44	3.21	1.70	0.05	1.73	0.35	0.54	0.03
M1-P2-DS-2A light	89.87	4.29	0.71	2.35	0.41	0.10	0.24	0.57	1.41	0.05

scale is due to conditions not usually encountered during normal, continuous operation.

It is of interest to calculate the maximum amount of scale that could be deposited at some position in the GLEF, provided we can assume that all the scale has identical composition to that of the scale sample. The maximum amount of scale per unit weight of brine is

$$M_s \leq \frac{X_{\text{brine}}^i}{X_{\text{scale}}^i},$$

where M_s = mass of scale per unit mass of brine

X_{brine}^i = wt fraction of species, i , in brine

X_{scale}^i = wt fraction of species, i , in scale.

The most enriched species in the scale is i .

For example, from Table 13, the i -species is Pb for sample M1-PV-301-DS-1, giving $M_s \leq 0.00018$; Fe for sample M1-V4-2, giving $M_s \leq 0.0011$; and Si for the remainder of the samples, giving $M_s \leq 0.0010-0.0014$. Copper and aluminum were not used because of their low concentration in the brine. Obviously, lead in the absence of sufficient sulfide, or undersaturated silica, or any other species does not, and will not precipitate completely to form a unique

scale. The scale mass which adheres to GLEF equipment and piping is but a small fraction of the suspended solids and a minute fraction of what is available in the brine.

The bulk of these suspended solids is reinjected. The actual mass distribution of specific species in the deposited scales and in the solid precipitates with respect to their position in the GLEF is difficult to determine even under uniform scaling conditions. With a prolonged and steady period of operation we will be in a better position to state the rate of scale production, the scale composition, quantitatively, and the temperature and pressure relationships associated with the principal scaling phases.

Effect of Scaling on GLEF Operation

Over this relatively short period of operation, there were incidents of valve malfunctions and drainage problems in some of the components. Although it is difficult to isolate the exact causes of these problems, there is little doubt that some were related to scaling and solids deposition. There were cases of pump-intake screens being obstructed by a combination of debris and corrosion products and, later, siliceous solids. The screens were eventually removed since the soft

siliceous solids do no harm to the pumps. Downstream of the first-stage control valve, rapid erosion of pipe elbows occurred until a piping modification was made. Relocation of the control valve to a point downstream of the elbow and a piping increase from 6 to 16 in. immediately downstream of the control valve have eliminated this problem for the present. Details of the materials problems are discussed by Goldberg.⁷

Solids were reinjected into the formation at Magmamax No. 3. The effects on formation permeability and/or well integrity are undetermined but not dismissed.

Scale Surveillance through Use of Radiographs

Radiography is a completely external means of scale surveillance. Internal methods such as probes, depth gauges, etc., would in themselves promote local scaling and not give a true scaling rate on GLEF piping and components.

A 1.2-MeV, 15-Ci cobalt-60 source was used after it was found that a 0.4-MeV iridium-192 source did not provide sufficient penetration. The principle is quite simple. The source and a film plate are positioned on opposite sides of the subject. The differences in gamma absorptivity of brine fluid, scale, and steel result in sufficient

contrast to produce a radiograph from which projected thicknesses can be measured. A 12- by 16-in. film plate is used and is the limiting factor in subject size. Source strength, exposure time, solid source angle, film and source position, and opacity of the subject are all important factors in the quality of the radiograph. In general, scale deposition on the inside walls of pipes, fittings, and stationary valves can be viewed radiographically with approximately 1-mm resolution.

Figure 16 is a radiograph reproduction of a 10-in. pipe downstream of the reinjection pump. Scale thickness as determined from this radiograph was 7 mm. Table 14 lists the scale thickness at various locations in the GLEF as determined by radiographs taken at the end of the first operational phase. Also listed are the measured values of thickness determined from scale samples or in plant measurements at or near the radiographic site.

These results show that radiography is a reliable method for in-process surveillance of scale buildup in full-size pipes. The ability to monitor scale buildup during plant operation is important in enhancing the operator's ability to assess scale-related problems and, if necessary, in safely curtailing operation.

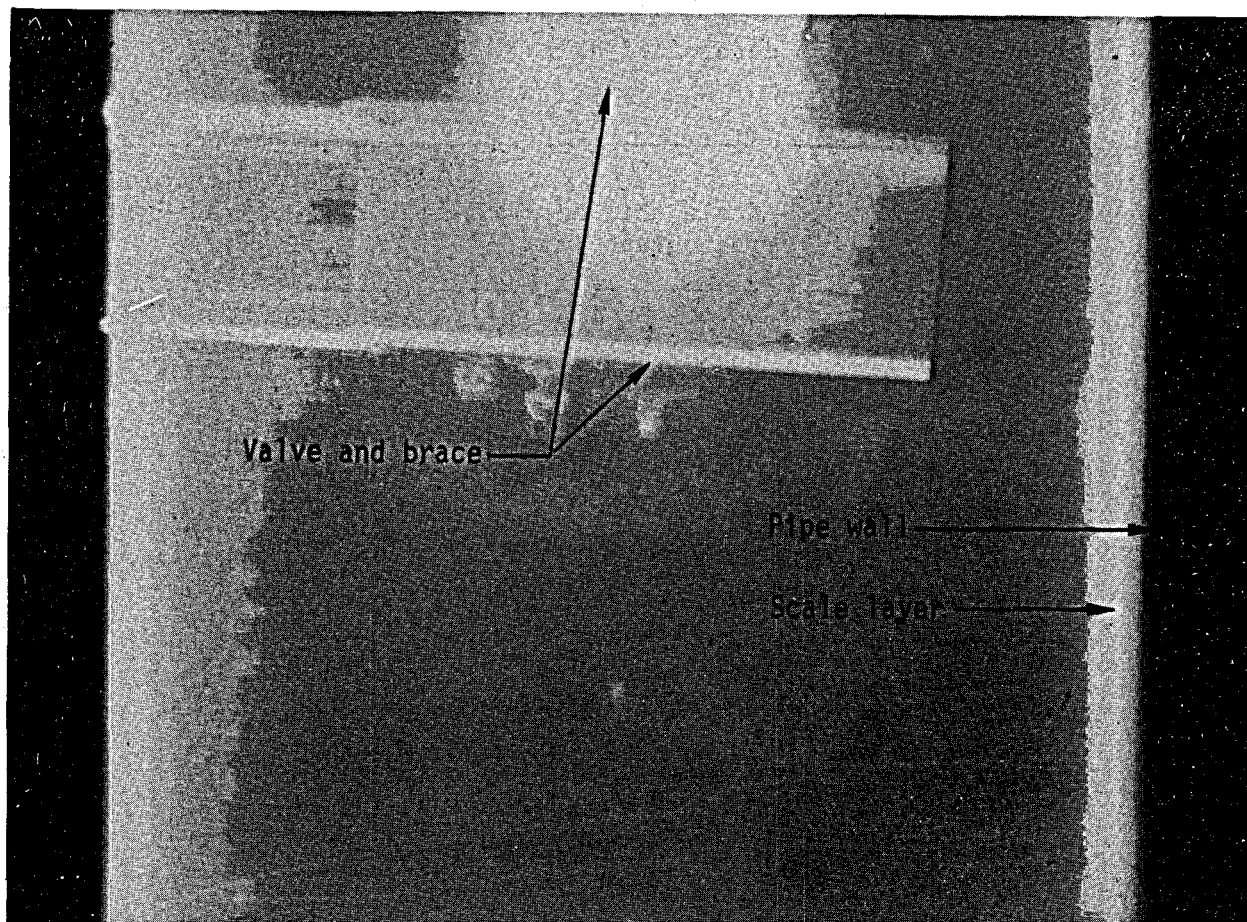


Fig. 16. Reproduction of radiograph of a vertical 10-in. diameter pipe section downstream of a reinjection pump, GLEF. Inner scale layer is observable.

Possibilities for Scale Control by Brine Modification in the GLEF

Scaling in geothermal process equipment and piping is a crucial problem in long-term operation. Formation of suspended solids and adherent scale could drastically reduce process efficiency and eventually curtail operation. The process conditions whereby the brine is flashed successively in lower temperature and pressure steps are extremely favorable in promoting the precipitation of

solid material from the brine. These suspended solids, some of which originate as soon as the brine is flashed in the production casing, are the source of scaling, solids buildup, equipment erosion, and potential damage to the formation when reinjected with the brine.

There is evidence that chemical modification of the brine could alter the nucleation and precipitation of solids and hence may be a means of controlling, if not preventing, the

Table 14. Scale thickness as determined by radiographic technique, GLEF, May-June, 1976.

GLEF location	Scale thickness by radiograph, mm	Actual scale thickness in vicinity of radiographic site, mm
Output brine pipe, first-stage separator	2	1-3
Output brine pipe, second-stage separator	<1	1-3
Downstream piping, second-stage control valve	5	1-3
Output brine pipe fourth-stage separator	15	16-17
Downstream piping, reinjection pump	7	12-16
Downstream piping, fourth-stage control valve	1	<1
Downstream piping, brine level control valve, reinjection pump	10	12-16
Piping just upstream of reinjection wellhead Magmamax No. 3	<1	<1
Piping near production wellhead, Magmamax No. 1	2	not measured
Upstream pipe elbow, first-stage control valve	<1	<1

problems associated with scaling and solids formation during energy extraction from the brine.^{8,9}

Analysis of scales produced by high-temperature and high-saline brines found in the Imperial Valley show principal constituents to be heavy metal sulfides and an iron-rich amorphous silica. The solubility of both phases is temperature-dependent, and, in addition, silica solubility is strongly pH-dependent.⁸ Furthermore, there is evidence that the rate of silica deposition as a scale constituent is dependent on the degree of polymerization of monomeric silica and that the rate of polymerization is also pH-dependent.⁸ Field tests¹⁰ have verified that brine acidification to a pH of 5 or less will prevent solids and scale formation in the brine during cooling. Chemical additions to modify the brine could be applicable in the GLEF process. Precisely which modifying chemical or chemicals would be most effective, how the addition would be accomplished, and what extraneous effects may result

(e.g., aggravated corrosion or reinjection problems) will need to be answered by tests in the field using properly scaled equipment analogous to those used in the GLEF.

Preliminary design of equipment for such tests is in progress. It will consist of a single-flash stage to operate in series with the existing LLL test facility.¹⁰ There will be appropriate valving and controls to enable selection of operating temperatures and pressures. Chemical feed system, instrumentation, sampling ports, corrosion spools, and other test sections will be included. With this system we will be able to conduct controlled brine-modification tests on actual brine under realistic process conditions. The results of these small-scale tests will give us a firm basis on which to evaluate the effectiveness of brine-modification as a means of controlling or preventing solids and scale-formation in a process such as the GLEF, and will also provide valuable material and engineering design data.

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