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**REVIEW AND EVALUATION OF LITERATURE ON
TESTING OF CHEMICAL ADDITIVES FOR SCALE
CONTROL IN GEOTHERMAL FLUIDS**

Final Report

By
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JANUARY 1981

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EXECUTIVE SUMMARY

BACKGROUND

The U.S. National Energy Plan foresees a significant contribution to energy needs from geothermal energy -- heat extracted from the earth in the form of hot and pressurized fluids.¹ If federally-sponsored efforts to accelerate commercialization of this energy source are successful, geothermal resources could produce 3.5-9.0 quadrillion BTU/year by the turn of the century.² This accelerated development of geothermal energy requires surmounting a number of technical and economic problems, most of which are attributable to the unusual thermal and chemical nature of the geothermal resource fluids.

One of the problems that has serious implications for the technical and economic feasibility of geothermal utilization systems is scaling resulting from the deposition of solids from the fluids. Solids deposition in production and injection wells and on the exposed surfaces of fluid-transport and energy-conversion equipment can lead to fouling of equipment and to significant reductions in fluid production rates, through-plant flow rates, heat transfer efficiencies, and injection rates. Energy costs for pumping, especially for maintaining injection rates, will increase and the useful life of production and injection wells will be negatively affected. Periodic shutdown of wells and surface facilities may be required for scale removal services. Therefore, high-impact reductions in operating and maintenance costs, plant downtime, and production declines can be achieved by reducing the amount or rate of scale formation and/or rendering the scale easier to remove during cleaning operations.

Geothermal fluids at sites of major potential or actual energy development typically have high salinity and suspended solids levels and contain a number of other dissolved constituents and noncondensable gases. There are different chemical types and physical forms of scale deposits which can occur in flowing geothermal brines. Any particular deposit will usually contain at least a few different chemical species. The nature and quantity of scale deposition vary with certain brine parameters, especially temperature, composition, and flow rate. The principal factors which can affect geothermal scaling include:³

- brine composition and composition changes (including pH)
- temperature and temperature changes
- pressure changes (including partial pressure changes for CO₂, H₂S, and NH₃)

¹These fluids may be naturally-occurring heated subsurface fluids or liquids pumped through hot rock formations to recover heat.

²National Energy Plan II, Report to Congress, U.S. Department of Energy, May 1979.

³Adapted from A Study of Brine Treatment, Lawrence Berkeley Laboratory, EPRI ER-476, November 1977.

- velocity and turbulence
- residence time in each part of the utilization system
- surface effects and surface-to-volume ratio effects
- fluid phase
- geometry of plant components
- salt carryover in steam phase
- corrosion of materials

Techniques to reduce or prevent scaling may focus on one or more of the three phases in the scaling phenomenon: (1) precipitation from the brine of the scale-producing constituent, (2) flocculation of the precipitate, and (3) deposition/adherence of the solids on exposed surfaces. The use of brine treatment additives represents a primary approach to scale control and includes a number of different potential chemical mechanisms, e.g., uptake of one or more precipitate-forming species, flocculation inhibition, and deliberate flocculation.

Primary concern with geothermal scaling centers around three types of scales: silica (SiO_2), carbonates, and sulfides. The presence of these scales depends on a number of key factors and they can, therefore, be characteristic of particular geothermal sites and/or the type of utilization system and the brine location within the system. Generally, siliceous scales are typical of relatively low-temperature brines, carbonate scales of moderate-temperature brines, and sulfide scales of high-temperature brines. Although these scales may be associated with specific geothermal sites (e.g., carbonate scale in moderate-temperature East Mesa brine and silica scale at Salton Sea), it must be remembered that different types and/or quantities of scale solids may be produced within a geothermal facility due to process-induced changes in brine temperature, flow rate, and composition. For example, at the Salton Sea plant, sulfide-rich scales are formed at high wellhead temperatures while predominantly amorphous silica scale occurs in the lower-temperature effluent brine which has been flashed.

The single most commonly practiced technique for chemical scale control in geothermal applications is brine acidification, but this has the disadvantages of increasing the corrosiveness of the brine and generally requiring large quantities of acid. There is, therefore, growing interest in non-acid additives for scale control.

TASK DESCRIPTION

Reports of site-specific tests with chemical additives for geothermal scale control can be found in the existing literature, but they generally cannot be readily compared with each other for the purposes of evaluating

the progress to date and identifying testing and information needs. This is due to a number of factors arising from the following problem areas:

- Variability of geothermal fluids
- State-of-knowledge concerning chemical scale control
- Quality and reliability of additive testing and test reporting

The purpose of this document is to review and evaluate a selected group of reported tests of chemical additives in actual geothermal fluids to, as far as possible, summarize the status of chemical scale-control testing and identify information and testing needs. This task, by necessity, elucidates some of the major problems mentioned above that are inherent in the interpretation and comparative evaluation of the test reports.

The task distinguishes between scale control in the cooling system of a flash plant and elsewhere in the utilization system due to the essentially different operating environments involved. The major limitations in scope and content of the task are as follows.

- Only tests conducted with actual, not simulated, geothermal fluids are considered
- Brine acidification is not included due to relatively widespread experience with this technique and non-acid chemicals whose primary function is to effect scale control by pH adjustment are also excluded
- The cost of additives and the economics of their use are topics beyond the scope of this study
- The document is not intended to serve as a treatise on geochemistry, scale formation, and scale control techniques

In order to identify test scenarios for which there are incomplete or no results reported, there is a need to use or establish a limited number of generic geothermal operating environments. These categories need not relate to specific geothermal resources because the characteristics of a resource fluid do not necessarily coincide with the process fluid characteristics throughout the various types of utilization systems that may be employed at any particular resource site. For this task, only the basic parameters of temperature and total dissolved solids (TDS) concentration are used as a rough guide to operating environments for each type of scale deposit. "Temperature" refers not only to "resource" temperature, but also to the temperature of the geothermal fluid at any point in the energy conversion process. For the purposes of the categorization, the TDS concentration is assumed to be a relative indicator of the fluid salinity and the concentration of the scaling species; as with temperature, this parameter can refer to any process location of the brine. The brine parameters have been assigned a high, medium, or low ranking (see Table 1).

As more testing and more sites are included, additional parameters and/or redefinition of cut-off values may need to be considered.

RESULTS OF LITERATURE REVIEW AND EVALUATION ON ADDITIVES FOR "NON-COOLING" GEOTHERMAL FLUIDS

Silica Scale Inhibitors

The majority of the results and discussion presented in this document concern Lawrence Livermore Laboratory's (LLL) scale control program at Salton Sea where they used a specially-constructed flashing test facility for evaluating chemical additives. The emphasis was on silica scale because this is the predominant scale formed in Salton Sea brines. The typical test conditions prevailing during this lengthy test program are given in Table 4, which also shows the relative locations along the direction of brine flow of the critical features of the test system. These brine characteristics could vary markedly for a number of reasons. For example, variations in brine flow rate, sometimes uncontrollable, at the LLL facility could cause the composition values to change by as much as 25%, as well as altering the scaling tendency of the brine.

LLL relied mostly on the use of "off-line" quantitative analysis of the silica retained in control and treated brine samples taken from the low-temperature outlet of the second stage flash unit and incubated at 90°C. Although this technique for determining additive effectiveness facilitates a fairly rapid and uncomplicated screening of potential antiscalants, it has two potential drawbacks: (1) the analysis of silica contained in these stagnant samples of brine neglects to take into account the effects of flow and turbulence conditions and (2) being carried out at 90°C, it may not be directly relevant to scaling in higher-temperature parts of the system upstream of the effluent brine. The measurement of scale actually deposited on test specimens located in the brine flow is a more convincing method for evaluating additive effectiveness, but it is a more time-consuming and complicated procedure. LLL conducted precipitation inhibition tests with about 90 additives and on-line scaling tests with 15 additives.

The compiled results of the precipitation inhibition tests are presented in Table ES1 and the results of the scaling tests in Table ES2. It should be noted that the eleven chemical groups used here are not necessarily mutually exclusive in all cases due to the complex structure of many of the additives and an inability to confidently identify the active group(s) for each additive chemical. This is especially so for the proprietary chemicals which are of unknown chemical formulae. Some of the additives could be legitimately placed in more than one category, although this was not done for this task. For example, Ethoquad 18/25 incorporates both oxyethylene and nitrogen-containing groups, but it has been identified as a polyoxyethylene here. The chemical groups are listed in Table ES1 in order of generally decreasing molecular complexity, which can often be a general indicator of decreasing effectiveness for precipitation-inhibiting additives; proprietary additives again present an unknown factor in this respect. The data in Tables ES1 and ES2 must, therefore, be interpreted with caution.

TABLE ES1

RESULTS OF 90°C SILICA RETENTION TESTS¹
 (Showing Number of Additives At Each
 Effectiveness Level)

ADDITIVE GROUP	% IMPROVED RETENTION ²											TOTAL NO. OF ADDITIVES
	0-9	10-19	20-29	30-39	40-49	50-59	60-69	70-79	80-89	90-99	100+	
Polyoxyethylenes	1	1		3	3	2	2	2	1	3	2	20
Cellulose derivatives	4			1	2	1	1		1	1		11
Other polymers	3		1			2					1	7
Quaternary ammonium compounds	3						1	1	1			6
Imines					2		1	1	1			5
Surfactants	1		1			1						3
Organic acids		1			2						1	4
Other organics	1						1					2
Silanes	2	3	1									6
Proprietary chemicals	16	2	2			1	1					22
Inorganics	1						1	1				3
TOTAL NUMBER OF ADDITIVES	32	7	5	4	9	7	8	5	4	4	4	89

¹General Conditions: ~500 ppm SiO₂, 20 - 30 ppm additive, 90°C, pH 4 - 6, reaction time 1 hour (some 48 hours).

²Percentage improved retention is the additional amount of silica that the additive causes to remain in the brine (i.e., prevent from precipitating out) compared to untreated brine.

SOURCE: EER, Inc.

TABLE ES2

GENERAL PERFORMANCE OF CHEMICAL GROUPS
IN SILICA SCALING TESTS

[Showing "Average" Effectiveness of Group by
Positive (Increasing) Effect or Negative (Decreasing)
Effect on Scale Thickness]

TEMPERATURE CHEMICAL GROUP	210°C	125°C	90°C
Polyoxyethylenes	-	+	-
Cellulose Derivatives	-	-	Not Tested
Imines	Not Tested	-	-
Organic Acids	+	Not Tested	-
Proprietary Chemicals	+	+	Not Tested
Polyoxyethylene+ Quaternary Ammonium Compound	+	+	-
Sludge	+	+	Not Tested

Polyoxyethylenes: Ethoquad 18/25

Cellulose Derivatives: Natrosol 250LR

Imines: Corcat P-18

Organic Acids: PAE·HCl

Proprietary Chemicals: SC-210, Geomate 256, Drewsperse 747, Thermosol
APS, CL-165, Betz 419, Mirapol A-15, Natco S-404, Cortron R-16

Polyoxyethylene + Quaternary Ammonium Compound: Ethoquad 18/25. +
Duomac T

SOURCE: Compiled from References 1-8.

As can be seen from Table ES1, three of the eleven chemical groups comprise the bulk of the additives (about 60%): polyoxyethylenes, cellulose derivatives, and proprietary chemicals. Of the additive groups tested, the polyoxyethylenes could be considered to exhibit the most evident inhibition activity. The proprietary additives tested were, almost without exception, notably ineffective. It is probably not justified to draw conclusions about the remaining groups because of the very limited number of tests run on them. It can be seen that 36% of the additives produced a less than 10% improvement in brine silica retention and about 64% of the additives increased retention by less than 50%. In contrast, 5 additives improved retention by over 100%: three polyoxyethylenes, one unclassified polymer, and PAE·HCl. The performance figures for these 5 additives are given in Table ES3. Only two of the 5 additives (both polyoxyethylenes) were tested more than once. Ethomeen C/25 was only half as effective in a second test (66% improvement versus 132%), but it was tested at about one-third of the concentration (18 ppm versus 50 ppm). Carbowax 14,000 gave 89% improvement at 40 ppm versus 102% improvement at 20 ppm, i.e., it was more effective at half the concentration. However, sufficient backup testing has not been conducted to be able to judge whether any of these five apparently very effective additives deserve their indicated performance.

Table ES2 summarizes the results of 82 tests with 15 additives (of which 9 are proprietary), with test times varying from 40-120 hours. Over half of the tests were conducted with proprietary additives. The measurement of the thickness of scale deposited on test coupons is subject to a large margin of error, so caution must be exercised in drawing conclusions from these scaling results for this reason, too. However, a number of tentative observations about these results and the most successful additives can be made.

- Only 37% of the tests resulted in a measurable decrease in scale thickness
- As brine temperature increases, success in scale reduction is less frequent, possibly indicating the critical role of temperature in the scaling and/or inhibition processes
- Only two additives, PAE·HCl and Natrosol 250LR, gave measurable scale reduction under all conditions tested (PAE·HCl is a polyorganic acid and Natrosol 250LR is a cellulose derivative)
- Corcat P-18, an imine, demonstrated good scale inhibition at 90°C and 125°C
- Ethoquad 18/25, a nitrogen-containing polyoxyethylene, performed well at the high and low temperatures, but rather poorly at 125°C.

The scaling results highlight the generally unsatisfactory (detrimental, in fact) effect of the tested proprietary chemicals at medium and high

TABLE ES3
ADDITIVES IMPROVING 90°C SILICA
RETENTION BY AT LEAST 100%

ADDITIVE	CHEMICAL GROUP	ADDITIVE CONCENTRATION (ppm)	% IMPROVED RETENTION
Ethomeen C/25	Polyoxyethylenes	50 18	132 66
Carbowax 14,000	Polyoxyethylenes	20 40	102 89
Tween 20	Polyoxyethylenes	50	135
Vinsol AR-150	Other Polymers	50	144
PAE•HCl	Organic Acids	20	117

SOURCE: Compiled from References 1-8.

temperatures. This is consistent with their relatively low effectiveness in the low-temperature retention tests.

An important aspect of the Salton Sea silica control tests is that only three additives which were tested for precipitation inhibition were also tested for 90°C scale reduction. This means that only a limited assessment can be made of the correspondence between the precipitation and scaling test results. The analysis shows that for two of the three additives, (Corcat P-18 and Ethoquad 18/25), the agreement is reasonable, whereas the results for one (PAE·HCl) are inconsistent. On the whole, not enough data are available to generalize about whether the two test methods can be expected to be supportive or contradictory, and, if the latter, which is the more realistic test.

Silica Flocculants

None of the additives included in the testing reviewed in the previous section on silica inhibitors were intended to be flocculants in this application. However, a number of additives screened at Salton Sea by LLL were found to have good silica flocculating properties, even though they were apparently neither chosen as flocculating agents nor necessarily expected to exhibit such capabilities. Table ES4 lists the additives LLL regarded as potentially useful flocculants which enhanced the rate of precipitation and the filterability of silica from 90-95°C incubated brine samples.

Review of a brief account of tests with slaked lime (CaO) as a flocculant for silica in 90°C discharge brine at Wairakei and Broadlands in New Zealand suggests the usefulness of this removal process. The results of the application of this technique to U.S. brines, and the Salton Sea resource in particular, cannot be predicted from the information reviewed.

Summary of LLL Scale Control Tests

About 60% of the additives containing the oxyethylene moiety increased the retention of silica in 90°C brine by at least 50%. Unfortunately, the medium- and high-temperature effectiveness of these compounds is generally limited by their decreased solubility at elevated temperatures and possibly by the physical susceptibility of their stabilizing properties to the turbulence effects of flowing brine. One polyoxyethylene derivative, however, does not share the same solubility limits of the pure polyoxyethylenes. This compound, Ethoquad 18/25 (methyl polyoxyethylene octadecylammonium chloride), appears to be a good scale inhibitor at 210°C.

Polyethylene imines, polyethyloxazalines, and quaternary ammonium compounds (with and without polyoxyethylene) are all nitrogen-containing compounds shown to have activity as silica precipitation inhibitors. It should be mentioned that Ethoquad 18/25 can also be considered a polyoxyethylene-containing quaternary ammonium compound.

Hydroxyethyl celluloses also possess antiscalant activity, but they cannot be prepared as low-viscosity, high-concentration aqueous solutions.

TABLE ES4
SUCCESSFUL FLOCCULANTS TESTED FOR SILICA
CONTROL AT SALTON SEA

Trade Name	Chemical Name	Manufacturer
A-1100	γ -aminopropyl-triethoxysilane	Union Carbide
Z-6070	Methyltrimethoxysilane	Union Carbide
CYAF-5103	Proprietary organic polyelectrolyte	American Cyanamid
P-400	Polyoxypropylene glycol	Dow Chemical
E-400	Polyoxyethylene glycol	Dow Chemical
?	Mixed polyethylene imines	Union Carbide

SOURCE: Effects of Organic Additives on the Formation of Solids from Hypersaline Geothermal Brine, J. E. Harrar, et. al., Preprint UCRL-80970, March 1978 (paper prepared for Geothermal Resources Council Meeting, Hilo, HI, July 25, 1978).

This is an example of a number of technical factors which may constrain the potential usefulness of otherwise effective additives.

At the end of their testing program on organic scale inhibitors for silica, LLL identified the following additives as leading candidates:

- Corcat P-18 (polyethylene imine)
- PAE·HCl (polyaminoethylene hydrochloride)
- Ethoquad 18/25 (polyoxyethylene octadecylammonium chloride)
- Mirapol A-15 (polydiaternary ammonium chloride)

Corcat P-18 was advanced as the most promising single compound. LLL maintains that, for silica control in Salton Sea brine at least, the most successful additives will probably be various mixtures of these compounds with other chemicals. Combination of the best organic inhibitor(s) with pH adjustment of the brine has been proposed as the best chemical approach to silica scale control. Such combinations include:

- Corcat P-18 + HCl + Dequest 2060
- Ethoquad 18/25 + HCl + Dequest 2060
- Mirapol A-15 + HCl + Dequest 2060
- PAE·HCl + Dequest 2060

The Dequest 2060 acts as a phosphonate crystalline deposit inhibitor and is a very effective CaCO_3 inhibitor, as described in this report. It has been conjectured that the precipitation of small amounts of CaCO_3 may enhance the nucleation of silica. Brine acidification with HCl confers high-temperature antiscalant activity and enhances the effect of the silica precipitation inhibitor at lower temperatures. (HCl concentrations of at least 100 ppm do not greatly increase the corrosivity of Salton Sea brine.)

Other tested compounds LLL felt exhibited promise include:

- Arquad 18/50, which is similar in structure to Ethoquad 18/25 and almost as potent
- Hyamine 1622

Both are quaternary ammonium compounds without polyoxyethylene.

Overall, the most promising group of compounds arising from LLL's tests are the cationic nitrogen-containing compounds (including quaternary ammonium compounds, polyethylene imines, and polyethyloxazalines). The presence of polyoxyethylene in these compounds improves, but is not necessary for, their activity toward silica.

Six compounds were identified in the literature as potentially useful flocculating agents for silica at Salton Sea (see Table ES4) although they were not necessarily chosen for their flocculant properties. No quantitative testing information accompanied this identification, so very little of a specific nature can be said about these additives.

Carbonate Scale Inhibitors

Test reports for a number of additives for the reduction of carbonate scaling at East Mesa were reviewed. Dequest 2060 (a phosphonate threshold-type inhibitor) was fairly extensively tested in unflushed brine from two wells in test loops that provided loop sections of progressively decreasing temperature and pressure. (The brine characteristics and spool conditions are presented in Table 13.) The use of Dequest 2060 completely eliminated CaCO_3 scale from the test loop and upstream and downstream sections at all tested concentrations from 1.0–10.0 $\mu\text{l/l}$. The results are summarized in Table ES5 and they indicate that a calcium phosphonate pseudo-scale forms at additive concentrations somewhere between 2.5 and 7.5 $\mu\text{l/l}$. The presence of this additive-induced scale nevertheless represents a significant overall reduction in scale thickness. Table ES6 shows that additive effectiveness increase as the test loop temperature and pressure concurrently drop, although this may also be linked to greater residence time of the brine in the system and/or greater time for the additive to act. The tests indicate that as little as 1.0 $\mu\text{l/l}$ of the additive produced a system free of carbonate scale.

Four other chemicals tested in East Mesa brine are Dearborn 8010, Calgon CL-77W, Drewplex 502, and Calgon SL-500. The first three are threshold-type additives (which inhibit crystal growth in supersaturated solution) while Calgon SL-500 is a chelating agent. The brine characteristics presented in the reviewed report are discussed in section 7.2.1.2, but it is not evident which of the wells supplied the test brine(s). The test flow rates and method and location of additive introduction are also not reported. The test results, contained in Table ES7, showed Dearborn 8010 as the best CaCO_3 antiscalant, but all of the additives were very effective in retaining calcium in the brine. Follow-up scaling experiments found that 7–10 ppm was the optimum concentration range for Dearborn 8010. All four of these additives appear to warrant further attention on the basis of these results.

Carbonate Flocculants

No flocculants for carbonate in geothermal fluids were identified in the reviewed literature.

Sulfide Scale Inhibitors and Flocculants

No information has been found in the course of this task on tests of non-acid additives for directly reducing sulfide scale, which tends to form at high temperature. The general opinion appears to be that silica scaling promotes, and may even be necessary for, sulfide scaling. Therefore, control

TABLE ES5

EFFECT OF DEQUEST 2060 CONCENTRATION
ON CARBONATE AND ADDITIVE-INDUCED SCALES

Additive Concentration (μ l/l)	Scale Present		Overall Scale Reduction
	CaCO ₃	Pseudo-Scale	
1.0	No	No	Yes
2.0	No	No	Yes
2.5	No	No	Yes
7.5	No	Yes	Yes
10.0	No	Yes	Yes

SOURCE: Adapted from Scale Inhibition in Geothermal Operations - Experiments with Dequest 2060 Phosphonate in Republic's East Mesa Field, R. J. Vetter and D. A. Campbell, Vetter Research No. 79-5-27, May 27, 1979.

TABLE ES6

RESULTS OF DEQUEST 2060 TESTS
AT EAST MESA AT 10 μ l/l ADDITIVE¹

Temperature (°C)	Pressure (psig)	% Reduction of Scale ²
151	64	75
143	32	90
121	14	100
118	14	100

¹Well #16-29 with average production rate of 375,000 lb/hr. brine.

²CaCO₃ scale was completely eliminated from system; the scale that was present was formed by the additive itself.

SOURCE: Adapted from Scale Inhibition in Geothermal Operations - Experiments with Dequest 2060 Phosphonate in Republic's East Mesa Field, R. J. Vetter and D. A. Campbell, Vetter Research Report No. 79-5-27, May 27, 1979.

TABLE ES7
RESULTS OF CaCO_3 and BaSO_4 SCALE
INHIBITION TESTS AT EAST MESA

	Additive Concentration (ppm)	Average % Recovery ¹ of Calcium	Average % Recovery ¹ of Barium
Dearborn 8010	25-30	140	104
Calgon CL-77W	25-30	82	65
Drewplex 502	25-30	105	87
Calgon SL-500	70-80	128	65

¹ Average Percentage Recovery is the percentage amount of cation in the brine that is removed by the additive; recovery in excess of 100% indicates that additional cation is taken out of the existing scale in the system.

SOURCE: Experience in Scale Control with East Mesa Geothermal Brine, T. E. Lindemuth, et. al., paper prepared for 1977 SPE-AIME International Symposium on Oilfield and Geothermal Chemistry, La Jolla, CA, June 1977.

of the associated silica scale is expected to represent a prime approach for control of sulfide scale. Lawrence Livermore Laboratory has stated that they have not found any organic additive that clearly reduces the predominantly sulfide scale formed at 200°C at Salton Sea.

RESULTS OF LITERATURE REVIEW AND EVALUATION ON ADDITIVES FOR GEOTHERMAL COOLING WATER

Virtually all of the testing on chemical modification of geothermal cooling water has focussed on addressing materials corrosion in the cooling system due to the severity of this problem. The only reviewed additive testing carried out specifically for geothermal cooling water is a short-term investigation at DOE's Raft River geothermal project. The objective at this site was to induce, rather than inhibit, the precipitation of silica in geothermal water for use as cooling tower make-up.

Three alternative treatment chemicals were evaluated at Raft River with reference to the initially designed system employing dolomite lime (58 weight % Ca(OH)_2 + 37 weight % MgO), which was never used. The three tested treatments were:

- (1) $\text{Mg(HCO}_3)_2$ (magnesium bicarbonate)
- (2) MgCl_2 (magnesium chloride)
- (3) MgSO_4 (magnesium sulfate)

The conditions and procedures for these tests are not fully disclosed in the reviewed literature and quantitative results are presented only for MgCl_2 , the most effective of the three chemicals tested. It can be seen from a summary of these results in Table ES8 that silica deposition can be prevented only with very high dispersant concentrations (>50 ppm). However, reduction of calcium and sulfate concentrations reduces the amount of additive required for silica control, though no data were supplied in support of this. The MgCl_2 -based treatment was recommended for make-up water at the Raft River site.

IDENTIFICATION OF TESTING AND INFORMATION NEEDS

The identification of fairly specific gaps in scale-control additives testing at this stage cannot always be confidently supported by a reliable set of data. There are basically two categories of gaps in testing that need to be considered:

- further testing which could be done at a particular geothermal site/system to complete all practicable and relevant testing possible at that site
- geothermal sites/systems where no or negligible testing has been conducted and where existing or planned testing is not applicable.

TABLE ES8

CONDITIONS AND RESULTS FOR TESTS WITH MgCl_2 TREATMENT
SYSTEM FOR SILICA IN GEOTHERMAL COOLING WATER AT RAFT RIVER

(Data for 5 and 8 Cycles of Concentration)¹

	Five Cycles	Eight Cycles
Make-up flow rate	386 gpm (24.3 l/s)	352 gpm (22.2 l/s)
Blowdown flow rate	62 gpm (3.9 l/s)	30 gpm (1.9 l/s)
Cl^- concentration	6,000 ppm	9,000 ppm
Dispersant concentration	50 ppm	65 ppm
Dispersant addition	.02 gpm (.001 l/s)	.02 gpm (.001 l/s)

¹ Reduction of silica level to 10-15 ppm will provide make-up for ten cycles of concentration

SOURCE: Compiled from Short-Term Cooling Tower Tests, D. Suciu and R. Miller, EGG-FM-5087, January 1980.

These gaps can relate to generic operating environments and/or additives.

Table ES9 relates the testing reviewed under this task to the basic parameters of brine temperature and concentration of total dissolved solids. Conditions apparently not represented by testing are not necessarily areas of genuine testing need for two reasons:

- (1) literature reviewed has been limited by the scope of this task, and
- (2) scale problems may not be present in some of these situations.

There are two major needs indicated by this literature review and evaluation. The first is that a more comprehensive and detailed follow-up study to adequately assess the status of geothermal scale-control additives testing would contribute to organizing, focussing, and publicizing geothermal scale control research and to stimulating the interest of chemical companies as potential suppliers of antiscalants. Consideration should be given in this study to:

- encompassing a wider literature review, perhaps including chemically-similar fluids where appropriate
- incorporation of recent unpublished testing or testing plans when available
- compilation and evaluation of available information on the chemistry of scaling in geothermal fluids, especially as it relates to flow and other critical conditions expected in geothermal facilities
- compilation of site-specific scaling information (qualitative and/or quantitative)
- identification and evaluation of viable chemical mechanisms for scale control (i.e., flocculation, stabilization, reaction, etc.)
- more clearly defining generic geothermal operating environments and relating these to actual or expected scaling problems at specific sites and/or utilization systems
- identification of the types of additives which the analysis of geothermal scaling indicates may be active antiscalants
- identification of optimum methods for the dissemination of additives testing information to geothermal developers/operators and other interested parties.

A second need is the development of the most efficient strategy for identifying useful additives with minimum testing effort. This strategy

TABLE ES9

APPLICATION OF REVIEWED TESTING TO
GENERIC GEOTHERMAL OPERATING ENVIRONMENTS

TEMPERATURE TOTAL DISSOLVED SOLIDS	SILICA SCALE			CARBONATE SCALE			SULFIDE SCALE ¹		
	HIGH	MEDIUM	LOW	HIGH	MEDIUM	LOW	HIGH	MEDIUM	LOW
HIGH	Salton Sea ² ← Scaling Tests (Flashed Brine) →		Salton Sea ² Precipitation-Inhibition and Flocculation Tests (Flashed Brine)						
MEDIUM					?				
LOW		Raft River ³ Flocculation Tests (Flashed Cooling Water)	Wairakei and Broadlands ³ Flocculation Tests (Cooled Discharge Brine) ⁵		East Mesa ⁴ Scaling Tests (Unflashed Brine)				

¹ No relevant testing for sulfide scale control was identified for review. Since sulfide deposits appear to be primarily associated with silica scale, the control of silica scale is believed to be an effective approach to sulfide control.

² Salton Sea corresponds to Radian Corporation's Class 1 geothermal fluid.

³ Raft River, Wairakei, and Broadlands correspond to Radian Corporation's Class 4 geothermal fluid.

⁴ The East Mesa geothermal resource represents a wide variation in brine characteristics; some wells there produce brine with medium-level TDS concentrations (up to 26,000 ppm). It is possible that some of the reviewed testing applies to medium TDS brine, but this cannot be accurately determined from the test literature due to incomplete reporting. The East Mesa resource is included in both Classes 3 and 4 of Radian Corporation's classification of geothermal fluids.

⁵ It is not reported whether this is flashed or unflashed brine.

may constitute a "generic" on-going investigation or may address scale control on a site-by-site basis as and when scale problems arise. Priorities should be set with regard to:

- types of scale addressed
- types of utilization system considered and the locations of problem scaling within these systems
- mechanisms of chemical scale-control selected for study
- types of additives screened and tested further
- geothermal sites chosen for additives research.

In addition, some sort of standardized testing procedures and/or additive performance standards may need to be established to aid in comparative evaluation of different tests. The identification and implementation of this testing strategy will require input from the type of study recommended above.

The following list identifies more specific information needs and possible areas for further work suggested by evaluation of the reviewed literature. A number of these problems may already have been addressed in literature not incorporated in the source information for this project and the list should, therefore, be considered tentative with regard to geothermal scale-control testing to date. The list does not indicate any priority ranking. (Since a number of these items apply specifically or generally to LLL's Salton Sea, it should be mentioned that LLL has terminated its scale control program at this site and dismantled its test facility.)

- (1) Determination of the validity of LLL's 90°C precipitation-inhibition tests as a screen for potentially useful scale-preventing additives. Not only will this aid in future testing, but it will help determine the usefulness of the large amount of testing that has already been conducted at Salton Sea.
- (2) Emphasis on on-line scaling tests as opposed to 90°C precipitation-inhibition tests at Salton Sea, particularly if the 90°C test is judged to be an invalid or unreliable screen. This may be applicable to testing programs at other sites, too.
- (3) Determination, with a greater degree of confidence than before, of the relative proportions of monomeric versus polymeric silica at critical temperatures and process-flow locations in the Salton Sea utilization system, and perhaps at other relevant sites.
- (4) Evaluation of brine acidification in conjunction with the use of scale-control additives and, in particular, those acid/additive combinations LLL recommended for testing for Salton Sea silica.

- (5) Relative evaluation of scale inhibition and flocculation of scale-causing brine constituents as approaches to scale control. Given these two basic choices and the various inhibition options, identification (as far as possible) of what chemical approaches to scale control are appropriate for what types of scale, at what sites, and at what locations in the processes. Identification of the properties of chemical additives necessary for the various methods of scale control and the types of additives they suggest.
- (6) Testing to determine the technical advantages and disadvantages of continuous versus intermittent additive introduction.
- (7) Testing to determine optimum process-flow injection points for additives for specific systems.
- (8) More testing to study the effects of additive concentration on effectiveness. This may have to be done on an additive-specific basis, and then only for likely candidates.
- (9) Compilation of physical and chemical data on geothermal cooling water at relevant sites with regard to identifying the specific scale-control problems of cooling systems.
- (10) Analysis of the cost-effectiveness of using the most promising additives.

1. INTRODUCTION

The U.S. National Energy Plan foresees a significant contribution to energy needs from geothermal energy--heat extracted from the earth in the form of hot and pressurized fluids. If federally-sponsored efforts to accelerate commercialization of this energy source are successful, geothermal resources could produce 3.5-9.0 quadrillion BTU/year by the turn of the century.¹ A large proportion of the technical problems constraining geothermal development can be directly attributed to the unusually demanding conditions presented by geothermal fluids. The high-temperature, highly-corrosive, and scale-forming nature of these fluids quite often imposes an environment for which there is little adequate technology or operating experience directly transferable from other industries. A major chemistry-related problem is scaling resulting from the deposition of solids contained or formed in geothermal brines. The control of geothermal scaling is critical to the successful economic use of much of the country's geothermal resource base.

1.1 Background

Energy conversion systems for utilizing geothermal fluids have experienced severe problems directly and indirectly associated with the scaling of process equipment and the downhole environment. Scale buildup can cause significant decreases in through-plant flow rates, heat transfer efficiencies, and injection rates; they can be severe enough to require periodic plant shutdown for scale removal and to cause plugging of injection wells and subsurface formations. Plant and well operating and

¹National Energy Plan II, Report to Congress, U.S. Department of Energy, May 1979.

maintenance costs will increase and plant availability will be curtailed as a result of this problem. In addition, injection pumping costs escalate due to the greater pressures required to maintain injection rates when downhole scale builds up. Production and injection well cleanout techniques may also be needed to extend well life. Therefore, significant reductions in operating and maintenance costs, plant downtime, and production declines could be achieved by reducing the amount or rate of scale deposition and/or rendering the scale easier to remove during cleaning operations.

Geothermal fluids at sites of major potential or actual energy development typically have high salinity and suspended solids levels and contain a number of other dissolved constituents and noncondensable gases. As would be expected, there are different chemical types and physical forms of scale deposits which can occur in flowing geothermal brines. Any particular deposit will usually contain at least a few different chemical species. The nature and quantity of scale deposition vary with certain brine parameters, especially temperature, composition, and flow rate. The principal factors which can affect geothermal scaling include:¹

- brine composition and composition changes (including pH)
- temperature and temperature changes
- pressure changes (including partial pressure changes for CO_2 , H_2S , and NH_3)
- velocity and turbulence
- residence time in each part of the utilization system
- surface effects and surface-to-volume ratio effects

¹Adapted from A Study of Brine Treatment, Lawrence Berkeley Laboratory, EPRI ER-476, November 1977.

- fluid phase
- geometry of plant components
- salt carryover in steam phase
- corrosion of materials

There are generally three distinct steps in the scaling phenomenon:

(1) precipitation from the brine of the scale-producing constituent;
 (2) flocculation of the precipitate; and (3) deposition/adherence of the solids on exposed surfaces. Techniques intended to prevent or reduce scaling may focus on one or more of these aspects of the scaling process. Potential scale-control methods being utilized or evaluated can be conveniently categorized as either brine treatment additives (such as organic chemicals, hydrochloric acid, and seeding sludge) or non-chemical methods (such as control of energy conversion process variables, altered flow rates, and mechanical scale removal).

Primary concern with geothermal scaling centers around three types of scales: silica (SiO_2), carbonates, and sulfides. The presence of these scales depends on a number of key factors and they can, therefore, be characteristic of particular geothermal sites and/or the type of utilization system and the brine location within the system. Generally, siliceous scales are typical of relatively low-temperature brines, carbonate scales of moderate-temperature brines, and sulfide scales of high-temperature brines. Although these scales may be associated with specific geothermal sites (e.g., carbonate scale in moderate-temperature East Mesa brine and silica scale at Salton Sea), it must be remembered that different types and/or quantities of scale solids may be produced within a geothermal facility due to process-induced changes in brine temperature, flow rate, and composition. For example, at the Salton Sea plant, sulfide-rich scales are formed at high wellhead

temperatures while predominantly amorphous silica scale occurs in the lower-temperature effluent brine which has been flashed.

The single most commonly practiced technique for chemical scale control in geothermal applications is brine acidification, but this has the disadvantages of increasing the corrosiveness of the brine and generally requiring large quantities of acid. There is, therefore, growing interest in non-acid additives for scale control.

1.2 Purpose of Task

The testing of scale-control additives in the U.S. has, by necessity, been on a site-specific basis. The procedures followed and additives tested do not constitute a single, organized program designed to identify generic types of effective treatment chemicals or to elucidate and demonstrate fundamental chemical scale-control principles. Reports of test results can be found throughout the relevant literature, but they lack a consistent format and must be individually assessed. This creates problems in gaining an overview of the progress to date in scale prevention.

There is no single source which provides a comparative evaluation of the testing conducted on chemical additives for scale control in actual geothermal fluids. Such information is needed in order to determine the types of additives that are being considered for these applications, the specific additives that have been or are being tested, and the geothermal conditions under which the tests have been conducted. This will permit identification of significant gaps in additives testing and will ensure that knowledgeable decisions are made concerning further work that may be required in this field. This document is intended to address these information needs and identify possible areas for further work.

2. TASK OBJECTIVES

The objectives of this task are, through review and evaluation of literature pertaining to the testing of chemical additives for scale control in actual geothermal fluids, to:

- (1) consolidate the reviewed testing information in a single source document;
- (2) identify test scenarios for which there are incomplete or no results reported;
- (3) ensure that field testing that essentially duplicates tests already conducted or that has little practical application to identified geothermal resources or utilization systems not be conducted; and
- (4) identify areas for further study related to the testing and use of scale-control additives.

3. DEFINITION AND SCOPE OF TASK

As designed, the task distinguishes between chemical additives for scale control in geothermal fluids used for purposes other than cooling and geothermal liquids which remain after flashing and are used as a source of on-site cooling water. The rationale for this differentiation is that cooling systems present a fundamentally different operating environment to the fluid than does the main utilization system (e.g., lower temperatures, brine aeration in cooling towers, greater concentration of dissolved solids, etc.). These differences will be discussed in more detail in Section 8 of this report.

The specific requirements of the task are to:

- (1) identify and review selected literature on testing of chemical additives for control of silicate, carbonate, and sulfide scales in geothermal fluids;
- (2) identify and discuss aspects of geothermal fluid characteristics, utilization, and additives testing that have a direct bearing on test evaluation and intercomparison;
- (3) evaluate the test results as reported;
- (4) identify and define, as far as possible, areas in the testing where there is a lack of adequately reported data relating to important test conditions and types of additives; and
- (5) identify additional areas for, and expected benefits of, further testing.

There is a number of important qualifications built into this task which defines its scope. First, consideration was given only to tests conducted with actual geothermal fluids and not with laboratory-synthesized or

chemically-similar fluids; computer-simulated systems were also excluded from consideration. Second, brine acidification was not included within the scope of this task due to widespread experience with this technique, nor were other chemicals whose primary function is to effect scale control by pH adjustment. Third, the costs of additives and the economics of their use, whether in general terms or on a site-specific basis, are topics beyond the scope of this project.

It must be emphasized that this task is a literature evaluation rather than an evaluation of the testing and, in addition, that it is not intended to serve as a treatise on geochemistry, scale formation, and scale control techniques. However, certain aspects of all of these topics are discussed where necessary for interpreting and comparing the reported test conditions and results.

The present effort has been limited to a small number of selected references in order to illustrate the evaluation technique and minimize task time and costs. Sources used were primarily those supplied by DGE, with some additional reports identified and acquired by the contractor, notably through an on-line bibliographic search of DOE's RECON database system. It is expected that the effort will be enlarged to derive a comprehensive evaluation in the near future.

4. EVALUATION METHODOLOGY

The overall methodology pursued to fulfill the defined objectives of the task involves the following steps:

- (1) identify and review literature relating to chemical additives testing for scale control in actual geothermal fluids;
- (2) identify brine, utilization system, and testing procedure parameters that can affect additive performance and which are necessary for test evaluation and intercomparison;
- (3) extract the relevant test information on an additive-specific basis;
- (4) classify additives by chemical class or mode of scale-control action;
- (5) select a limited number of "generic" geothermal operating environments or sets of test conditions on the basis of the parameters identified in step (2) above;
- (6) format the reviewed testing information in terms of the categories set out in steps (4) and (5);
- (7) evaluate these data for the purposes of assessing additive effectiveness and identifying areas where insufficient testing has been conducted; and
- (8) identify areas where further testing or testing-related information is needed to establish a comprehensive and useful baseline database for additives testing and projection of the benefits of this further work.

Figure 1 is a flowchart of the essential elements of the task methodology. This methodology will prove useful as testing results from varying geothermal sites are evaluated. Selection of generic geothermal operating environments will not be an exercise that has to be repeated every time new test data are assimilated, although other parameters may need to be added or slight modifications of parameter threshold values may be required at some stage.

FIGURE 1

TASK METHODOLOGY

5. TASK EXECUTION AND TEST REPORTING

There are basically three major categories of problems this task, or any similar task, must deal with to meet its objectives:

- (1) Variability of geothermal fluids - The physical, chemical, and scaling characteristics of geothermal fluids can vary markedly from resource to resource, from well to well within any specific site, and even over relatively short periods of time for a single well. In addition, process-induced changes in the values of these characteristics can add a complicating factor to the "natural" variability.
- (2) State-of-knowledge concerning chemical scale control - There is an incomplete understanding of chemical mechanisms of scale control and of the parameters and critical values thereof that affect the scale-inhibiting activity of additives.
- (3) Quality and reliability of additive testing and test reporting - The majority of the literature available on this subject is rather incomplete in the reporting. Information basic to a comparative evaluation between tests, such as test procedures or test conditions, are not always discussed adequately. In addition, variations between tests, both at a given site as well as between different sites, complicate the analysis. The incompleteness of reported information combined with test variabilities raise concern regarding the quality and reliability of the reported information.

Every on-site test presents its own special set of test conditions and problems. This factor, particularly when combined with incomplete reporting,

makes test interpretation and intercomparison difficult. A major obstacle, therefore, to fulfilling the task objectives involves establishing some basis on which to realistically compare the results of different additive tests.

The validity of a direct comparison of these results is constrained by the large number of variables which can have a significant effect on the outcome of the experiments, as well as the degree to which their values are reported in the documentation. These variables include not only temperature, composition, flow rate, and pressure of the brine, but also the test concentration of the additive, "reaction" time, scaling tendency/rate of the brine, and technique utilized for measuring additive effectiveness.

A major component in the successful completion of this task lies in the need to develop a limited set of field test conditions or "generic" geothermal operating environments that will enable reduction of the test data to manageable proportions. This simplification, however, may result in a loss of detail which in some cases will significantly limit the use of the information.

The raw data extracted from the acquired literature were recorded on large tables to facilitate an orderly evaluation and intercomparison of test results through a standardized reporting format. These tables were intended to primarily serve the contractor's data analysis needs. Since they represent a considerable amount of work and contain a large quantity of relevant detailed information, they are included in Appendix 3 of this report.

A major observation of note with regard to the literature reviewed is that a single organization, using specially-constructed test facilities at one particular geothermal site, has been responsible for conducting most of the additive testing that has been reviewed. This has the theoretical advantage of promising a high degree of expertise and consistency in approach and procedures for additive testing, but also has the potential for masking any systematic problems in the testing and for concentrating attention on only one specific, although important, resource that is hypersaline and high-temperature.

6. SELECTION OF GENERIC GEOTHERMAL OPERATING ENVIRONMENTS

As discussed, general categories need to be established for the range of expected geothermal conditions on the basis of a few selected critical parameters. These categories, or generic geothermal operating environments, need not necessarily relate to specific geothermal resources. In fact, it is preferable that they do not do so because the characteristics of a "resource" fluid itself do not necessarily coincide with the process fluid characteristics throughout the various types of utilization systems that may be employed at that resource.

For the purposes of this task, only the basic parameters of temperature and total dissolved solids (TDS) concentration are used as a rough guide to operating environments for each type of scale deposit. "Temperature" refers not only to "resource" temperature, but also to the temperature of the geothermal fluid at any point in the energy conversion process. For the purposes of the categorization, the TDS concentration is assumed to be a relative indicator of the fluid salinity and the concentration of the scaling species; as with temperature, this parameter can refer to any process location of the brine.

The brine parameters chosen for this study have been assigned a high, medium, or low ranking based on the test literature reviewed and other general work related to geothermal brine characterization. The cut-off values for temperature and TDS are set out in Table 1. These categories are adequate for the limited amount of additives testing reviewed, but as more testing and more sites are included, additional parameters may need to be considered along with some redefinition of cut-off values. This is not a problem that needs to be completely resolved at this stage, but the

TABLE 1
VALUES OF BRINE PARAMETERS FOR
INITIAL BRINE CLASSIFICATION¹

	High	Medium	Low
Temperature (°C)	>150	100-150	<100
Total Dissolved Solids (ppm)	>150,000	5,000-150,000	<5,000

¹These parameters are not limited to "resource" fluid, but can apply to brine in any process location.

basic information presented here will aid in a fuller definition of the categorized conditions in the future.

It is logical to examine the usefulness of any relevant existing geothermal classification system for the needs of this study. The only such classification of interest here is the work of the Radian Corporation who, as part of a DOE study to develop materials selection guidelines,¹ evaluated and classified geothermal sites where corrosion testing has been carried out. The resulting classification into six types of resource brines is, however, oriented toward brine characteristics that play key roles in materials corrosion; it was not intended to necessarily include consideration of scale-producing aspects of the fluids. For this classification, Radian relied on the concentration of "total key species" (TKS),² concentration of chloride (salinity), plant inlet fluid temperature, and fluid pH. The values of these characteristics for the six brine classes are presented in Table 2. Table 3 identifies the specific geothermal sites Radian included in each of the classes.

The Radian classification, however, cannot be used for this task since there is no direct and reasonably proportional relationship between the corrosive properties and scaling tendencies of geothermal fluids. Scaling is a function of a somewhat different set of variables than corrosion is, especially in terms of the concentration of the particular scale-producing constituents. There are two basic aspects of using the Radian classification that could prove troublesome. First, a characterized brine for

¹Materials Selection Guidelines for Geothermal Energy Systems, Second Edition, Radian Corporation, 1979.

²The concentration of total key species equals the sum of the concentrations of chloride, bicarbonate, carbonate, sulfate, hydrogen sulfide, and ammonia:

$$[TKS] = [Cl^-] + [HCO_3^-] + [CO_3^{2-}] + [SO_4^{2-}] + [H_2S] + [NH_3]$$

TABLE 2
CLASSIFICATION OF GEOTHERMAL FLUIDS

Characteristics Brine Class	Total Key Species ¹ (ppm)	Cl ⁻ (% of TKS)	Inlet Temp. ⁵ (°C)	pH	
				Unflashed	Flashed
Class 1	>100,000	99	>205	--	5-6
Class 2	1,000-10,000	<1	120-75	<<4.9	<4.9
Class 3 ²	10,000-20,000	45-99	150-90	5-6	≥ 6
Class 4 ³	1,000-10,000	45-99	120-205	≥ 5	≥ 7
Class 5 (steam)	2,800 ⁴	<1 ppm	--	--	--
Class 6 (low-temperature)	<5,000	3-72	49-105	≥ 7	--

GENERALLY
DECREASING
CORROSIVITY

¹Total Key Species (ppm) = Cl⁻ + HCO₃⁻ + CO₃²⁻ + SO₄²⁻ + H₂S + NH₃.

²One East Mesa well conforms to this category, but all the other wells at this site have ~1,000-2,000 ppm TKS; therefore, East Mesa is included in both Classes 3 and 4.

³Baca (Valles Caldera) has only 520 ppm TKS.

⁴Mostly CO₂ and H₂S.

⁵Inlet temperature is first-stage separator temperature for "flash" plant, wellhead temperature for binary plant, and wellhead temperature or temperature of first use for low-temperature resources.

SOURCE: Compiled from Materials Selection Guidelines for Geothermal Energy Systems, Second Edition, Radian Corporation, 1979.

TABLE 3

GEOHERMAL SITES CONSIDERED
FOR CLASSIFICATION OF GEOHERMAL FLUIDS

Class 1:	<u>Salton Sea, CA*</u>
Class 2:	Matsukawa, Japan
Class 3:	Cerro Prieto, Mexico; <u>East Mesa, CA*</u>
Class 4:	Wairakei, New Zealand; Ahuachapan, El Salvador; <u>Baca, NM*</u> ; <u>Brady, NV*</u> ; Broadlands, New Zealand; <u>Heber, CA*</u> ; Hachobaru, Japan; Otake, Japan; <u>Raft River, ID*</u> ; <u>East Mesa, CA*</u>
Class 5 (steam):	<u>Geysers, CA*</u>
Class 6:	Iceland, (15 sites); <u>Madison Aquifer, SD*</u> (3 sites)*; <u>Klamath Falls, OR*</u>

*U.S. sites

SOURCE: Compiled from Materials Selection Guidelines for Geothermal Energy Systems, Second Edition, Radian Corporation, 1979.

which there are no corrosion data would require prediction of its corrosivity in order to determine which brine class it belongs to and, therefore, whether existing scale-control tests are applicable (irrespective of whether the existing tests are with the classified or unclassified brine). Second, two brines of roughly equivalent corrosivity may well exhibit different scaling rates and/or types of scale and, therefore, a testing gap may go unidentified.

There are three fundamental differences between the classification used in this study and that of Radian. First, Radian's work is based on empirical data for materials corrosion testing at a limited number of geothermal sites while the brine categories for this report are based strictly on selected brine characteristics and not on any operational data. Second, Radian's brine classes overlap to varying degrees depending on the parameters used, while the clear intention in this task is to define mutually-exclusive, sequential value-ranges for the selected brine characteristics. Third, Radian's classes do not recognize the various combinations of brine characteristics that may exist throughout the utilization system at specific sites.

7. LITERATURE REVIEW AND EVALUATION RESULTS: ADDITIVES FOR NON-COOLING GEOTHERMAL FLUIDS

7.1 Silica Scale

7.1.1 Inhibitors

Test Conditions. For all intents and purposes, all of the reviewed testing has been conducted with $>150^{\circ}\text{C}$ resource brines, although some testing has been carried out with brines in lower-temperature (125°C and 90°C) parts of the utilization system. The vast majority of the over 100 additives tested have been intended for silica scale control at the high-temperature ($200\text{--}225^{\circ}\text{C}$) Salton Sea geothermal field. This has involved injecting the additives into once-flashed brine at $200\text{--}220^{\circ}\text{C}$, flowing at approximately 7 gallons/min., and with the following pre-flash characteristics:

- 105,000–139,000 ppm characteristics:
- 425–530 ppm SiO_2
- 3.7–6.1 pH
- approximately 220,000 ppm total dissolved solids
- $1.135\text{--}1.167\text{ g/cm}^3$ density @ 25°C

Extrapolation of the results of the lengthy testing program of Lawrence Livermore Laboratory (LLL) with Salton Sea brine to other brines or brine/process conditions is very speculative due to the highly site-specific nature of geothermal fluids and the particular test facilities and procedures used at Salton Sea.

A brief description of LLL's scale-control test facility and procedures is presented here in order to acquaint the reader with the conditions and limitations of the additive test results. Figure 2 is a schematic of the

FIGURE 2

LAWRENCE LIVERMORE LABORATORY'S SCALE
CONTROL TEST SYSTEM AT SALTON SEA
(Magmamax No. 1 Well or Woolsey No. 1 Well)

SOURCE: On-Line Tests of Organic Additives for the Inhibition of the Precipitation of Silica From Hypersaline Geothermal Brine, J. E. Harrar, *et. al.*, UCID-18091, April 3, 1979.

test system showing the locations of the flash units, additive injection, scaling specimens, and brine sampling. At the facility, a portion of the liquid exiting from the first stage flashing unit is split and fed into two nominally-identical separate test channels, each of which is set up as follows. The additive is always injected into 200-220°C brine flowing at approximately 7 gallons/min. Test spools and coupons are located downstream of the first separator. The 105-125°C brine effluent from the second separator can be sampled after passing a second set of test spools and coupons. The brine can be routed through a delay stage and flowed through tubing specimens at 90-100°C and a flow rate of 0.5 liters/min.

This arrangement permits a number of test measurements:

- (1) effect of additive on silica scaling in 200-220°C once-flashed brine flowing at approximately 7 gallons/min.;
- (2) effect of additive on silica scaling in 105-125°C twice-flashed brine flowing at approximately 7 gallons/min.;
- (3) effect of additive on retention of silica and suspended solids in stagnant samples of twice-flashed brine incubated at 90°C (the samples are of 105-125°C twice-flashed brine flowing at approximately 7 gallons/min.); and
- (4) effect on additive performance of increased retention time of the brine in the low-temperature end of the system (allowing greater reaction time), based on the scaling rates of 90-100°C twice-flashed brine flowing through tubing specimens at approximately 0.5 liters/min.

Not all of these tests were conducted for every additive evaluated by LLL at the site. The source brine for the tests was usually Magmamax

No. 1 well, or less frequently, Woolsey No. 1 well, the latter of which produces a more aggressive brine.

Of the two techniques used by LLL for their additive testing (on-line scaling tests and "off-line" precipitation inhibition tests), the scaling tests are probably more likely to accurately reflect the actual performance of the additives under normal plant operating conditions. The analysis of dissolved silica in stagnant samples of brine neglects to take into account the full effects of flow and turbulence conditions and, being carried out at 90°C, it may not be directly relevant to scaling in higher-temperature parts of the system upstream of the final effluent brine. The precipitation inhibition and 90-100°C scaling tests are applicable, however, to scaling problems encountered in injection systems and possibly cooling systems. The rationale for using the 90°C precipitation tests is that relatively quick and less complicated preliminary screening of compounds can be conducted that will hopefully identify likely candidates for more extensive follow-up scaling tests.

Table 4 is a compilation of the reported test value-ranges of Salton Sea brine characteristics for the critical process-flow locations. Certain LLL reports omitted some of this information, so the figures may represent the ranges over a number of separate experiments or as few as one observation. Variations in the brine flow rate at the facility can cause the composition to change by as much as 25%, as well as altering the scaling tendency of the brine. In addition, variations can be introduced by other circumstances, (e.g., the specific well supplying the test brine, other users flowing the well, and other unexpected or unexplained factors).

TABLE 4

SALTON SEA BRINE CHARACTERISTICS AS REPORTED
BY LAWRENCE LIVERMORE LABORATORY DURING
ADDITIVE TESTS

TEST PARAMETER \ SYSTEM LOCATION	WELLHEAD	POINT OF ADDITIVE INJECTION	POINT OF BRINE SAMPLING	LOCATION OF SCALING SPECIMENS
Brine Pressure	250-330 psia	Not Reported	15 psig	Not Reported
Brine Temperature	200-225°C	200-220°C	105-125°C (Sample incubated at 90°C)	125°C and 210°C for spool and coupon speci- mens; 90-100°C for tubing specimens
Brine Flow Rate	50-150 gpm	7 gpm	7 gpm	7 gpm (.5 l/min. in tubing specimens)
Brine Composition				
Total Dissolved Solids	Not Reported	220,000 ppm	Concentra- tion of suspended solids after incubation with addi- tive usually reported.	Not Reported
Cl ⁻		105,000- 139,000 ppm		
SiO ₂		425-530 ppm		
pH		3.7-6.1		
Density @ 25°C (g/cm ³)		1.135-1.167

SOURCE: Compiled from References 1-8.

Test Results and Comments. The results of the evaluation of LLL's tests for silica scale control are presented in Tables 5-9 in this section (see Appendix 3 for the raw data extracted from the reviewed literature). Tables 5 and 6 apply only to the 90°C precipitation inhibition tests, i.e., quantitative chemical analysis of silica retained in the brine before and after treatment. Tables 7 and 8 summarize the results of the actual on-line scale deposit tests, i.e., measurement of scale thickness on test specimens before and after brine treatment.

The additives have been classified here into eleven chemical categories. These categories, however, are not necessarily mutually exclusive due to the complex structures of many of the additives and an inability to definitively identify the active group(s) for each additive chemical. The group of proprietary additives, especially, may contain any number of chemicals which should fall into other categories; for example, Ethoquad 18/25 incorporates both oxyethylene and nitrogen-containing groups and must be categorized based on general assumptions. The data in Table 5 must, therefore, be interpreted with caution due to, amongst other things, this overlap between additive groups. As far as can be ascertained from the test literature, none of these additives are flocculants in this application, although flocculant properties were occasionally observed with some additives during the testing. The chemical groups are listed in Table 5 in order of generally decreasing molecular complexity, which can often be a general indicator of decreasing effectiveness for precipitation-inhibiting additives; proprietary additives again present an unknown factor in this respect.

As can be seen from Table 5, three of the eleven chemical groups comprise the bulk of the additives (about 60%): polyoxyethylenes, cellulose

TABLE 5

RESULTS OF 90°C SILICA RETENTION TESTS¹
 (Showing Number of Additives At Each
 Effectiveness Level)

ADDITIVE GROUP	% IMPROVED RETENTION ²											TOTAL NO. OF ADDITIVES
	0-9	10-19	20-29	30-39	40-49	50-59	60-69	70-79	80-89	90-99	100+	
Polyoxyethylenes	1	1		3	3	2	2	2	1	3	2	20
Cellulose derivatives	4			1	2	1	1		1	1		11
Other polymers	3		1			2					1	7
Quaternary ammonium compounds	3						1	1	1			6
Imines					2		1	1	1			5
Surfactants	1		1			1						3
Organic acids		1			2						1	4
Other organics	1						1					2
Silanes	2	3	1									6
Proprietary chemicals	16	2	2			1	1					22
Inorganics	1						1	1				3
TOTAL NUMBER OF ADDITIVES	32	7	5	4	9	7	8	5	4	4	4	89

¹General Conditions: ~500 ppm SiO₂, 20 - 30 ppm additive, 90°C, pH 4 - 6, reaction time 1 hour (some 48 hours).

²Percentage improved retention is the additional amount of silica that the additive causes to remain in the brine (i.e., prevent from precipitating out) compared to untreated brine.

TABLE 6
ADDITIVES IMPROVING 90°C SILICA
RETENTION BY AT LEAST 100%

ADDITIVE	CHEMICAL GROUP	ADDITIVE CONCENTRATION (ppm)	% IMPROVED RETENTION
Ethomeen C/25	Polyoxyethylenes	50 18	132 66
Carbowax 14,000	Polyoxyethylenes	20 40	102 89
Tween 20	Polyoxyethylenes	50	135
Vinsol AR-150	Other Polymers	50	144
PAE•HCl	Organic Acids	20	117

SOURCE: Compiled from References 1-8.

TABLE 7

RESULTS OF 90°C, 125°C, AND 210°C SILICA SCALING TESTS¹

[Showing Number of Tests With Positive (Increasing) Effect
and Negative (Decreasing) Effect on Scale Thickness]²

SPECIMEN MATERIAL \ TEMPERATURE	210°C		125°C		90°C		TOTAL NO. OF TESTS	
	-	+	-	+	-	+	-	+
Mild Steel	4	11	9	4	4		17	15
Teflon	2	12	4	9			6	21
Hastelloy	3	8	4	8			7	16
TOTAL NO. OF TESTS	9	31	17	21	4		30	52

¹Based on 82 tests on 15 additives; 9 of the additives were proprietary and over half of the tests involved proprietary chemicals. Reaction time varied from 40-120 hours.

²For example, there were 11 tests in which an additive increased the scale thickness on mild steel specimens in 210°C brine and 4 tests which recorded a decrease in scale thickness on Hastelloy specimens at 125°C. It should be noted that for any particular set of results, the number of tests may or may not correspond to the number of different additives actually represented by those tests.

SOURCE: Compiled from References 1-8.

TABLE 8

GENERAL PERFORMANCE OF CHEMICAL GROUPS
IN SILICA SCALING TESTS

[Showing "Average" Effectiveness of Group by
Positive (Increasing) Effect or Negative (Decreasing)
Effect on Scale Thickness]

<div style="text-align: center;"> <div style="display: inline-block; transform: rotate(-45deg);">TEMPERATURE</div> <div style="display: inline-block; transform: rotate(45deg);">CHEMICAL GROUP</div> </div>	210°C	125°C	90°C
Polyoxyethylenes	-	+	-
Cellulose Derivatives	-	-	Not Tested
Imines	Not Tested	-	-
Organic Acids	<u>+</u>	Not Tested	-
Proprietary Chemicals	+	+	Not Tested
Polyoxyethylene+ Quaternary Ammonium Compound	+	+	-
Sludge	+	+	Not Tested

Polyoxyethylenes: Ethoquad 18/25

Cellulose Derivatives: Natrosol 250LR

Imines: Corcat P-18

Organic Acids: PAE·HCl

Proprietary Chemicals: SC-210, Geomate 256, Drewspers 747, Thermosol APS, CL-165, Betz 419, Mirapol A-15, Natco S-404, Cortron R-16

Polyoxyethylene + Quaternary Ammonium Compound: Ethoquad 18/25 + Duomac T

SOURCE: Compiled from References 1-8.

TABLE 9

COMPARISON OF 90°C SILICA SCALING AND RETENTION TESTS
FOR THREE ADDITIVES

TEST RESULT ADDITIVE	SCALE REDUCTION	PRECIPITATION INHIBITION
	(% DECREASE IN SCALE THICKNESS)	(% IMPROVEMENT IN RETENTION)
PAE·HCl (organic acid)	9	117
Corcat P-18 (imine)	94	75
Ethoquad 18/25 (polyoxyethylene)	84	96

SOURCE: Compiled from References 1-8.

derivatives, and proprietary chemicals. Of all the additive groups tested, only the polyoxyethylenes could be considered to exhibit reasonably evident inhibition activity. The proprietary additives tested were, almost without exception, notably ineffective. It is probably not justified to draw conclusions about the remaining groups because of the very limited number of tests run on them. It can be seen that 36% of the additives produced a less than 10% improvement in brine silica retention and about 64% of the additives increased retention by less than 50%. In contrast, 5 additives improved retention by over 100%: three polyoxyethylenes, one unclassified polymer, and PAE·HCl. The performance figures for these 5 additives are given in Table 6. Only two of the 5 additives (both polyoxyethylenes) were tested more than once. Ethomeen C/25 was only half as effective in a second test (66% improvement versus 132%), but it was tested at about one-third of the concentration (18 ppm versus 50 ppm). Carbowax 14,000 gave 89% improvement at 40 ppm versus 102% improvement at 20 ppm, i.e., it was more effective at half the concentration. However, sufficient backup testing has not been conducted to be able to judge whether any of these five apparently very effective additives deserve their rating.

It would be difficult to select an across-the-board minimum performance desired of a scale-control additive because of site-specific and additive-specific factors. In addition, it must be remembered that these particular results apply only to 90°C stagnant brine and, at best, are limited directly to the low-temperature end of electricity-generating systems (spent fluid for injection, in particular) and possibly to low-temperature resource brines.

The literature indicates that an additive concentration of 20-40 ppm appears to be optimal for most additives. Increasing the amount of additive

above this range has generally lead to "diminishing return" in effectiveness and has also occasionally created additive-induced scale. It must be remembered, however, that very little testing has been carried out with additives above 40 ppm because this appears to be the approximate economic limit of most additives.

The on-line scaling test results are not amenable to the same data presentation format as the precipitation tests because of the added variables of temperature and specimen-material used, and because the accuracy of scale-thickness measurements tends to be subject to large margins of error. It is sufficient for these reasons to identify only a qualitative change in the thickness of scale deposited. Table 7 shows the results of 82 tests with 15 additives (of which 9 are proprietary chemicals) for silica scale, with test times varying from 40-120 hours. Over half of the tests were conducted with proprietary additives.

A number of tentative general observations can be made about the scaling tests. First, successful tests are in the minority: of the 82 tests, 30 resulted in a decrease in scale thickness, while 52 increased or did not affect the scale thickness. Second, scale reduction is most prominent with mild steel coupons and least noticeable with Teflon coupons. Third, as brine temperature increases, success in scale reduction is less frequent; this may emphasize the critical role of temperature in the scaling and/or inhibition processes.

A few aspects of the performance of the most successful additives in the scaling tests deserve mention. Only two additives, PAE·HCl and Natrosol 250LR, gave measurable scale reduction under all conditions tested (PAE·HCl is a polyorganic acid and Natrosol 250LR is a cellulose derivative). Corcat

P-18, an imine, demonstrated good scale inhibition at 90°C and 125°C, but was ineffective at 220°C. Ethoquad 18/25, a polyoxyethylene, performed well at the high and low temperatures, but rather poorly at 125°C.

These scaling results, as summarized according to additive groups in Table 8, highlight the generally unsatisfactory (detrimental, in fact) effect of the proprietary chemicals at medium and high temperatures. Similar qualitative performance of this group of additives was observed during the low-temperature retention tests. Since most of the scaling tests were with proprietary chemicals, their ineffectiveness skews the overall scaling results: 80% of the tests with proprietary additives actually led to an increase in scale thickness.

An important aspect of the Salton Sea silica control tests is that only three additives which were tested for precipitation reduction were also tested for 90°C scale reduction. This means that only a limited assessment can be made of the correspondence between the precipitation and scaling test results. Table 9 shows that for two of the three additives, the agreement is reasonable compared to the totally incongruous results for PAE·HCl. On the whole, not enough data are available to generalize about whether the two test methods can be expected to be supportive or contradictory, and, if the latter, which is the more realistic test.

7.1.2 Flocculants

A number of additives tested at Salton Sea were found to have good silica flocculating properties, even though they were apparently neither chosen as flocculating agents nor necessarily expected to exhibit such capabilities. Table 10 lists the additives regarded as potentially useful flocculants,¹

¹Effects of Organic Additives on the Formation of Solids from Hypersaline Geothermal Brine, J.E. Harrar, et. al., Preprint UCRL-80970, March 1978 (paper prepared for GRC Meeting, Hilo, HI, July 25, 1978).

TABLE 10
SUCCESSFUL FLOCCULANTS TESTED FOR SILICA
CONTROL AT SALTON SEA

Trade Name	Chemical Name	Manufacturer
A-1100	γ -aminopropyl-triethoxysilane	Union Carbide
Z-6070	Methyltrimethoxysilane	Union Carbide
CYAF-5103	Proprietary organic polyelectrolyte	American Cyanamid
P-400	Polyoxypropylene glycol	Dow Chemical
E-400	Polyoxyethylene glycol	Dow Chemical
?	Mixed polyethylene imines	Union Carbide

SOURCE: Effects of Organic Additives on the Formation of Solids from Hypersaline Geothermal Brine, J. E. Harrar, et. al., Preprint UCRL-80970, March 1978 (paper prepared for Geothermal Resources Council Meeting, Hilo, HI, July 25, 1978).

although the quantitative standards used to distinguish these flocculants in unreported. These additives enhanced the rate of precipitation and filterability of silica from 90-95°C incubated brine samples under the usual low-temperature test conditions (see Table 4).

Review of a brief account¹ of tests with slaked lime (CaO) as a flocculant for silica in 90°C discharge brine at Wairakei and Broadlands (New Zealand) suggests the usefulness of this removal process. Table 11 sets out the test conditions and Table 12 the test results. The Wairakei tests utilized CaO on its own for the most part and demonstrated that 350 g/tonne CaO reduced the brine silica content by 76% and 425 g/tonne reduced the silica level by 87%. Nearly total silica removal was achieved with less than 1,000 g/tonne CaO. (The silica forms a hydrated calcium silicate gel.)

Only in the Broadlands treatment was an attempt made to determine the influence of the chlorine (in the form of hypochlorite) on the flocculating process. The inconclusive results indicate that the chlorine did not enhance flocculation and, in fact, may actually have been detrimental. The Broadlands results in general are complicated by the fact that the test times varied from 1-1/4 to 4-3/4 hours, but it is evident that the silica was effectively precipitated out of the brine, though not quite to the extent as at Wairakei. The original report identifies 700 g/tonne CaO as the optimum treatment amount for brine containing about 1,000 g/tonne. Figure 3 is a schematic of the continuously-operating treatment system installed at Broadlands.

¹ Contained in A Study of Brine Treatment, S.L. Phillips, et. al., EPRI ER-476, November 1977.

TABLE 11
TEST CONDITIONS FOR SILICA
FLOCCULATION AT WAIRAKEI
AND BROADLANDS

		WAIRAKEI ¹	BROADLANDS
Cl ⁻ (g/tonne)		2,100	1,873
Total SiO ₂ (g/tonne)	Before Aging	560	980
	After Aging	560 ²	910 ³
Monomeric SiO ₂ (g/tonne)	Before Aging	115	110
	After Aging	390	410
pH @ 20°C		7.9	8.6
Temperature (°C)		90	90

¹Brine was a mixture of brines from various wells.

²Brine was aged 2.5 hours to allow SiO₂ to polymerize.

³Brine was aged 0.5 hours to allow SiO₂ to polymerize.

SOURCE: Compiled from A Study of Brine Treatment, S. L. Phillips,
et. al., EPRI ER-476, November 1977.

TABLE 12

RESULTS OF SILICA FLOCCULATION TESTS AT WAIRAKEI AND BROADLANDS

WAIRAKEI					BROADLANDS			
Flocculating Mixture (g/tonne)			Silica Remaining in Brine (%)		Flocculating Mixture (g/tonne)		Silica Remaining in Brine (%)	
CaO Added	Active Chlorine Added	Polyflok 90 AP ¹ Added	Monomeric SiO ₂ in Brine	Total SiO ₂ in Brine	CaO Added	Active Chlorine Added	Monomeric SiO ₂ in Brine	Total SiO ₂ in Brine
350			43	24	460		68	28
350	10		41	21	460	5	71	29
410			24	16	460	10	61	26
425		1	19	13	460	20	59	25
580			9	6	605		40	18
780			4	3	685		23	10
985			2	1	685	5	32	14
1,000		1	3	2	685	10	29	13
					685	20	29	13
					815		17	8
					1,120		1	1

¹A flocculant.

SOURCE: Compiled from A Study of Brine Treatment, S. L. Phillips, et. al., EPRI ER-476, November 1977.

FIGURE 3

SCHEMATIC OF CONTINUOUS FLOCCULATING TREATMENT
SYSTEM FOR SILICA AT BROADLANDS

SOURCE: A Study of Brine Treatment, S. L. Phillips, et. al., EPRI
ER-476, November 1977.

7.2 Carbonate Scale

7.2.1 Inhibitors

7.2.1.1 Dequest 2060

Test Conditions. Carbonate and sulfate scale tests were conducted in 1978 by Vetter Research at Republic Geothermal, Inc.'s facilities at the moderate-temperature East Mesa field using five additives. The major, and most successful, work was for CaCO_3 control with Dequest 2060. Separate test loops were used for tests at two different wells. Figures 4 and 5 illustrate the two test systems. The most notable features of these systems are that they both flow unflashed wellhead brine through the test loops and that they are designed to provide loop sections (test spools) of decreasing temperature and pressure. Another important factor is that, because of this set-up, the measured characteristics of the wellhead brine are also those of the brine entering the actual testing stage; this is not the case with the Salton Sea system where the brine is flashed once before additive injection and once or twice before measurements of additive effectiveness are made.

The critical test conditions as reported appear in Table 13. The test at well #16-29 was restricted to 24 hours due to an operational problem not associated with the test itself. The composition of untreated brine from this well was not reported as it was for well #56-30. The East Mesa geothermal field can produce brines that vary dramatically in chemical composition. There are wells that produce brine with 1,600 ppm TDS and 500 ppm Cl^- and those that produce brine with as much as 26,000 ppm TDS and 17,000 ppm Cl^- . The characteristics of well #56-30 indicate that it is not the source of a "harsh" brine. The thickness of scale deposited in the test loop for

FIGURE 4
 SCALE CONTROL TEST SYSTEM FOR WELL#16-29
 AT EAST MESA AS OPERATED BY VETTER RESEARCH
 (Additive injected approximately 10 feet downstream of wellhead)

SOURCE: Scale Inhibition in Geothermal Operations - Experiments with Dequest 2060
 Phosphonate in Republic's East Mesa Field, R. J. Vetter and D. A. Campbell,
 Vetter Research Report No. 79-5-27, May 27, 1979.

FIGURE 5
SCALE CONTROL TEST SYSTEM FOR WELL#56-30
AT EAST MESA AS OPERATED BY VETTER RESEARCH

SOURCE: Scale Inhibition in Geothermal Operations - Experiments with Dequest 2060 Phosphonate in Republic's East Mesa Field, R. J. Vetter and D. A. Campbell, Vetter Research Report No. 79-5-27. May 27, 1979.

TABLE 13

TEST CONDITIONS AT EAST MESA FOR
DEQUEST 2060 INHIBITION OF CaCO_3

Location Brine Conditions	Well # 16-29						Well # 56-30					
	Wellhead	Spool 1	Spool 2	Spool 3	Spool 4	Spool 5	Wellhead	Spool 1	Spool 2	Spool 3	Spool 4	Spool 5
Temperature (°C)	160	151	143	121	118	118	158	158	156	--	148	130
Pressure (psig)	220	64	32	23	14	14	145	117	89	75	55	25
Cl^- (ppm)	Not Reported						530-540					
SiO_2 (ppm)	Not Reported						140					
Ca^{2+} (ppM)	Not Reported						4.9-5.0					
pH	Not Reported						7.2-7.9					
Flow rate (ave. lb/hr.)	375,000						722,000					

SOURCE: Compiled from Scale Inhibition in Geothermal Operations - Experiments with Dequest 2060 Phosphonate in Republic's East Mesa Field, R. J. Vetter and D. A. Campbell, Vetter Research Report No. 79-5-27, May 27, 1979.

untreated brine from each well is shown in Tables 14 and 15. The Dequest 2060 was tested at 2.5 and 10 $\mu\text{l/l}$ concentrations with well #16-29 brine and at 1.0, 2.0, and 7.5 $\mu\text{l/l}$ with well #56-30 brine.

Test Results and Comments. The use of Dequest 2060 virtually, if not completely, eliminated all CaCO_3 scale from the test loop at all tested concentrations. In addition, equipment both downstream and upstream of the test loop was also clear of carbonate scale. The additive's performance was comparable in the test loop at the well with a production rate of 375,000 lb/hr. and a first-spool temperature of about 151°C and in the loop at the other well with a much larger production rate of 722,000 lb/hr. and a slightly higher spool entry temperature of approximately 158°C .

Table 16 summarizes Vetter Research's results and shows that Dequest 2060 is very effective in preventing CaCO_3 scale at East Mesa. The tests indicate that as little as 1.0 $\mu\text{l/l}$ of the additive produced a system free of carbonate scale. However, an additive concentration somewhere between 2.5 and 7.5 $\mu\text{l/l}$ begins to produce a calcium phosphonate pseudo-scale. Formation of this additive-produced scale nevertheless represents a significant overall reduction in scale thickness of untreated brine, as shown in Table 17. Although Vetter Research concluded that additive concentrations above 7.5 $\mu\text{l/l}$ caused pseudo-scale, this scale may occur at much lower additive levels.

7.2.1.2 Other Additives

Test Conditions. Tests with four additives other than Dequest 2060 have been reported¹ for CaCO_3 and $\text{Ba}(\text{SO}_4)_2$ (barium sulfate) scale

¹Experience in Scale Control with East Mesa Geothermal Brine, T.E. Lindemuth, et al., paper prepared for 1977 SPE-AIME International Symposium on Oilfield and Geothermal Chemistry, La Jolla, CA, June 1977.

TABLE 14

SCALE THICKNESS IN WELL #16-29 TEST
LOOP FOR UNTREATED BRINE¹

SPOOL NO. (STARTING) UPSTREAM)	SPOOL LENGTH (FEET)	SCALE THICKNESS (INCHES)		AVERAGE SCALE THICKNESS (INCHES)
		TOP	BOTTOM	
1	10	1/64	1/64	0.0625
2	12	1/16	3/8	0.22
3	10	1/16	3/8	0.22
4	12	3/8	1/2	0.44
5	10	1/8	3/16	0.156
	Total 54			Average 0.22

¹ 93-hour test

SOURCE: Scale Inhibition in Geothermal Operations - Experiments with
Dequest 2060 Phosphonate in Republic's East Mesa Field,
R. J. Vetter and D. A. Campbell, Vetter Research Report No.
79-5-27, May 27, 1979.

TABLE 15

SCALE THICKNESS IN WELL #56-30 TEST
LOOP FOR UNTREATED BRINE¹

SPOOL NO. (STARTING UPSTREAM)	SPOOL LENGTH (FEET)	AVERAGE SCALE THICKNESS (INCHES)
1	18	Thin Film
2	18	Thin Film
3	8.75	0.10
4	18	1.25
5	18	1.50
	Total 80.75	Average 0.62

¹ 108-hour test

SOURCE: Scale Inhibition in Geothermal Operations - Experiments with
Dequest 2060 Phosphonate in Republic's East Mesa Field,
R. J. Vetter and D. A. Campbell, Vetter Research Report No.
79-5-27, May 27, 1979.

TABLE 16

EFFECT OF DEQUEST 2060 CONCENTRATION
ON CARBONATE AND ADDITIVE-INDUCED SCALES

Additive Concentration (μ l/l)	Scale Present		Overall Scale Reduction
	CaCO ₃	Pseudo-Scale	
1.0	No	No	Yes
2.0	No	No	Yes
2.5	No	No	Yes
7.5	No	Yes	Yes
10.0	No	Yes	Yes

SOURCE: Adapted from Scale Inhibition in Geothermal Operations - Experiments with Dequest 2060 Phosphonate in Republic's East Mesa Field, R. J. Vetter and D. A. Campbell, Vetter Research No. 79-5-27, May 27, 1979.

TABLE 17
RESULTS OF DEQUEST 2060 TESTS
AT EAST MESA AT 10 μ l/l ADDITIVE¹

Temperature (°C)	Pressure (psig)	% Reduction of Scale ²
151	64	75
143	32	90
121	14	100
118	14	100

¹Well #16-29 with average production rate of 375,000 lb/hr. brine.

²CaCO₃ scale was completely eliminated from system; the scale that was present was formed by the additive itself.

SOURCE: Adapted from Scale Inhibition in Geothermal Operations - Experiments with Dequest 2060 Phosphonate in Republic's East Mesa Field, R. J. Vetter and D. A. Campbell, Vetter Research Report No. 79-5-27, May 27, 1979.

inhibition in East Mesa brine. The four chemicals are Dearborn 8010, Calgon CL-77W, Drewplex 502, and Calgon SL-500; the first three are threshold-type additives (which inhibit crystal growth in supersaturated solution) while Calgon SL-500 is a chelating agent. The characteristics of 150-170°C brines from four East Mesa wells as reported appear in Table 18; unfortunately, which brine or brines were used in the tests is not mentioned. Of the four wells, No. 6-1 clearly produces the most demanding brine conditions. The relevant test flow rates and method and location of additive introduction are also not reported.

These additive screening tests, plus operating experience with Dearborn 8010, were obtained at U.S. Bureau of Reclamation desalination facilities at East Mesa, where investigations into the feasibility of producing high quality water from geothermal brine have been taking place. The results, which apply to scaling in a vertical tube evaporator (TVE) desalting unit, are applicable to energy-producing uses of geothermal fluids.

Test Results and Comments. The test results are contained in Table 19. This initial screening relied on quantitative analysis of Ca^{2+} and Ba^{2+} in the various brine streams. Percentage recoveries in excess of 100% indicate that some metal cation must have been removed from the existing scale in the system. The general effectiveness level of moderate concentrations of the threshold additives could be matched only by very large amounts of the chelating compound (Calgon SL-500). Dearborn 8010 can be identified as the best antiscalant, but all the additives except Calgon CL-77W were very effective in retaining calcium in the brine (>100% retention). Dearborn 8010 was the only additive to also cause retention of all the barium.

TABLE 18
CHARACTERISTICS OF UNFLASHED BRINE
FROM FOUR EAST MESA WELLS

Brine Characteristic	Brine Source	Well No.			
		6-1	6-2	8-1	31-1
Cl ⁻ (mg/l)		16,850	2,142	500	510
SiO ₂ (mg/l)		320	269	389	274
TDS (mg/l)		23,600	5,000	1,600	2,900
pH		5.45	6.12	6.27	6.27
Ba ²⁺		14	.25	.15	.15
Ca ²⁺		1,360	16.4	8.5	8.9
SO ₄ ²⁻		42.8	156	173	183

SOURCE: Compiled from Experience in Scale Control With East Mesa Geothermal Brine, T. E. Lindemuth, et. al., paper prepared for 1977 SPE-AIME International Symposium on Oilfield and Geothermal Chemistry, La Jolla, CA, June 1977.

TABLE 19
RESULTS OF CaCO_3 and BaSO_4 SCALE
INHIBITION TESTS AT EAST MESA

	Additive Concentration (ppm)	Average % Recovery ¹ of Calcium	Average % Recovery ¹ of Barium
Dearborn 8010	25-30	140	104
Calgon CL-77W	25-30	82	65
Drewplex 502	25-30	105	87
Calgon SL-500	70-80	128	65

¹ Average Percentage Recovery is the percentage amount of cation in the brine that is removed by the additive; recovery in excess of 100% indicates that additional cation is taken out of the existing scale in the system.

SOURCE: Experience in Scale Control with East Mesa Geothermal Brine, T. E. Lindemuth, et. al., paper prepared for 1977 SPE-AIME International Symposium on Oilfield and Geothermal Chemistry, La Jolla, CA, June 1977.

Follow-up scaling experiments in this series of tests were conducted to determine the optimum additive level for Dearborn 8010. It was found that dosages less than about 5 ppm allowed enough CaCO_3 scale to plug the VTE tube nozzles. A concentration of 7-10 ppm was chosen as the most acceptable additive range. No subsequent testing with this additive or the other three has been identified in the literature reviewed.

Only Dearborn 8010 was selected for further use, primarily because it was also very effective against barium. The scale-inhibiting performance of Calgon SL-500 and Drewplex 502 on CaCO_3 may have been comparable to Dearborn 8010 had they been tested. Although the results for the tests were not reported in as much detail as the later Vetter Research tests with Dequest 2060, the carbonate-inhibiting performance of Dearborn 8010, Calgon SL-500, and Drewplex 502 appear to warrant attention.

7.2.2 Flocculants

No flocculants for carbonate in geothermal fluids were discussed in the reviewed literature.

7.3 Sulfide Scale

No information has been found in the course of this task on tests of non-acid additives for directly reducing sulfide scale, which tends to form at high temperatures. The general opinion appears to be that silica scaling promotes, and may even be necessary for, sulfide scaling. Therefore, control of the associated silica scale is expected to represent a prime approach for control of sulfide scale. Lawrence Livermore Laboratory has stated that they have not found any organic additive that clearly reduces the predominantly sulfide scale formed at 200°C at Salton Sea.¹

¹On-Line Tests of Organic Additives for the Inhibition of the Precipitation of Silica from Hypersaline Geothermal Brine III. Scaling Measurements and Tests of Other Methods of Brine Modification, J.E. Harrar, et. al., UCID-18238, August 1979.

8. LITERATURE REVIEW AND EVALUATION RESULTS: ADDITIVES
FOR GEOTHERMAL FLASH EFFLUENT USED AS COOLING WATER

As described in the task definition, the intention of this section is to consider only the geothermal brine left after separation/flashing which is used as cooling water in the system. The distinction between scale control in the cooling system and in the rest of the plant arises because of the somewhat different operating environments. The flash effluent will be at a lower temperature than the power-producing sections of the system, particularly after it has been cooled. In addition, the brine becomes aerated while it is being cooled in wet-type cooling systems where direct air-liquid contact cooling is used. The dissolved solids tend to concentrate during cooling due to the evaporative loss of water in the cooling tower.

The primary concern arising from brine aeration in wet or wet-dry cooling towers is the greatly increased corrosiveness of the brine. This increase is predominantly due to the introduction of oxygen, which directly corrodes materials through oxidation and increases the acidity of the liquid by oxidizing sulfide to sulfate. However, aeration of the brine can also create an environment conducive to solids deposition, such as, for example, an increase in CaCO_3 formation by loss of CO_2 and the deposition of insoluble metal sulfates.

The key corrosive species in cooling water will be essentially the same as for the geothermal fluid in the remainder of the system, i.e., H^+ , Cl^- , H_2S , CO_2 species, NH_3 species, and SO_4^{2-} , plus oxygen, which is not normally a natural component of most geothermal fluids. The principal scale-producing constituents will also be the same as elsewhere, particularly SiO_2 and CO_3^{2-} , plus oxygen-induced formation of sulfates. As mentioned, evaporative loss of water in the cooling tower will effectively concentrate dissolved solids in the liquid, contributing to the scaling potential.

Figures 6 and 7 show the process flows for a flash/separation plant utilizing a portion of the flash effluent to condense steam. If a surface contact condenser is used, some or all of the cooling water may be recirculated if desired. The surface contact condenser system will be more sensitive to scale deposition than the direct contact condenser system due to the arrangement of the heat transfer process.

Virtually all of the testing on chemical modification of geothermal cooling water has concentrated on addressing materials corrosion in the cooling system due to the severity of this problem. For the most part, the testing reviewed for scale control in the main system can be applied, on a basic level, to cooling water treatment to the extent that the scale formation parameters are similar. Of course, this does not consider the greater corrosivity and other effects of aeration that may influence the type and rate of scaling and the behavior of chemical additives in the cooling water. If the cooling system environment is expected to pose a significantly different set of conditions from the standpoint of scale control, there is probably little realistic prediction, in the absence of empirical data, that can be made about inhibitor effectiveness other than extending the general conclusions of the non-cooling testing.

All of the LLL silica control experiments at Salton Sea injected the additives into the liquid leaving the flash stage. The majority of these tests studied the precipitation of silica in 90°C brine samples after flashing a second time and, therefore, the results probably provide a reasonable starting point for identifying candidate additive groups for initial screening. It seems unlikely that any additives that were notably unsuccessful in the LLL tests will perform otherwise in cooling system tests.

Additive groups that should receive particular attention for cooling water treatment for silica inhibition are the polyoxyethylene-containing compounds

FIGURE 6

SCHEMATIC OF SEPARATION/FLASH SYSTEM USING FLASH EFFLUENT
AS COOLING WATER IN SURFACE CONTACT CONDENSER

SOURCE: EER, Inc.

FIGURE 7

SCHEMATIC OF SEPARATION/FLASH SYSTEM USING FLASH EFFLUENT
AS COOLING WATER IN DIRECT CONTACT CONDENSER

SOURCE: EER, Inc.

and organic nitrogen-containing compounds identified earlier. Compounds containing both nitrogen and oxyethylene moieties should also be included. In addition, studies to examine the compatibility of scale-control additives with corrosion-control agents must be carried out. PAE·HCl, which was identified as a good antiscalant in the non-cooling tests, is unlikely to be useful in cooling systems due to its acid content. Inhibition of CaCO₃ scale in cooling systems may be a useful test application for Dequest 2060.

Short-term investigations at the Raft River geothermal project have been reported¹ for silica control of geothermal water cooled for use as make-up for the cooling towers. The objective at this site, however, is removal of silica by inducing precipitation, not scale prevention by inhibition. The Raft River utilization system is not a flash system and it uses medium-temperature, relatively low-TDS brine, so the tests there may be of only limited applicability to high-temperature, high-salinity flash systems. Three alternative treatment chemicals were evaluated with reference to the initially designed, but unused, treatment system employing dolomite lime. The original and three tested treatments were based on:

- (1) dolomite lime (58 weight % Ca(OH)₂ + 37 weight % MgO)
- (2) Mg(HCO₃)₂ (magnesium bicarbonate)
- (3) MgCl₂ (magnesium chloride)
- (4) MgSO₄ (magnesium sulfate)

The conditions and procedures for these tests have not been fully reported. Briefly, though, geothermal fluid from three different wells (1, 2, and 5) were mixed in a 300-gallon tank in 2:1:1 proportions and then cooled to 60°C. The mixture was flash mixed during addition of the treatment chemical and then Ca(OH)₂ (calcium hydroxide) was added to remove the silica and Na₂CO₃ (sodium carbonate) to remove calcium. The mixture was stirred slowly for twenty

¹Short-Term Pilot Cooling Tower Tests, D. Suciu and R. Miller, EGG-FM-5087, January 1980.

minutes after which the flocculent was allowed to settle for about one hour. After filtering, the water could be used as cooling tower make-up. The quantitative results presented in the report reviewed were very limited ones for only MgCl_2 , the most effective of the three chemicals tested. It can be seen from a summary of these results in Table 20 that silica deposition can be prevented only with very high dispersant concentrations (>50 ppm). However, reduction of calcium and sulfate concentrations reduces the amount of additive required for silica control, though no data were supplied in support of this. The MgCl_2 -based treatment was recommended for make-up water at the Raft River site.

TABLE 20

CONDITIONS AND RESULTS FOR TESTS WITH MgCl_2 TREATMENT
SYSTEM FOR SILICA IN GEOTHERMAL COOLING WATER AT RAFT RIVER

(Data for 5 and 8 Cycles of Concentration)¹

	Five Cycles	Eight Cycles
Make-up flow rate	386 gpm (24.3 l/s)	352 gpm (22.2 l/s)
Blowdown flow rate	62 gpm (3.9 l/s)	30 gpm (1.9 l/s)
Cl^- concentration	6,000 ppm	9,000 ppm
Dispersant concentration	50 ppm	65 ppm
Dispersant addition	.02 gpm (.001 l/s)	.02 gpm (.001 l/s)

¹ Reduction of silica level to 10-15 ppm will provide make-up for ten cycles of concentration

SOURCE: Compiled from Short-Term Cooling Tower Tests, D. Suciu and R. Miller, EGG-FM-5087, January 1980.

9. CONCLUDING REMARKS

The concluding remarks to this report are concerned with four major subject areas:

- Test procedures
- Scale formation and prevention
- Promising additives
- Cooling water treatment

All of these topics have been discussed earlier; this section summarizes what has been said already plus additional unexplored matters.

9.1 Test Procedures

Serious questions can be raised not only about the validity of testing reported in the reviewed literature but also about its reliability. The validity aspect refers to the extent to which the test procedures employed realistically duplicate "normal" operation at the site of testing and at "similar" sites where no testing has taken place. A major problem with the Salton Sea tests is the use of silica precipitation-inhibition analysis of stagnant samples of brine incubated at 90°C as a technique for preliminary additive screening, which presupposes that: (1) no additive effective at reducing high-temperature scale would prove ineffective in the low-temperature test; (2) the most promising chemical mechanism for silica scale control is stabilization of colloidal silica; and (3) the absence of flow and turbulence effects during the incubation test will not significantly affect the qualitative outcome of the screen, i.e., whether the additive has a noticeably positive or negative effect.

Statement (1) is assumed to be the case by LLL on the basis of their "hope...that the 90°C incubation test is valid insofar as the results are

related to the scaling rates at that temperature, and that the diminished effect of inhibition at higher temperatures will not be greater than the decrease in scaling rates".¹ Statement (2) does not reflect an opinion of LLL that there could not be other chemical methods of scale control but rather their conclusion from an assessment of precipitation and scaling theory and experience that this is the testing route most likely to identify the most effective antiscalant(s) for hypersaline brine. Statement (3) is justified by assuming "that a substance that decreases the rate of precipitation of silica in solution also will have the potential for decreasing the rate of growth of silica on the surface of forming scale".² In addition, this test method is operationally simpler than on-line scaling tests when carried out in the field.

These three statements are reasonable to the extent that certain assumptions of this nature must be made in order to initiate some sort of preliminary on-site screening of additives. However, it may have been advisable to conduct more on-line scaling tests in the low-temperature end of the system to confirm the validity of the first assumption. As mentioned earlier, not enough results have been generated to determine whether the stagnant environment and quantitative analysis technique of the precipitation tests can be expected to accurately and reliably reveal the potential effectiveness of chemical additives.

There has been a general lack of follow-up testing at the Salton Sea site to confirm initial results. This may be due to one or more of the following:

¹Preliminary Results of Tests of Proprietary Chemical Additives, Seeding, and Other Approaches for the Reduction of Scale in Hypersaline Geothermal Systems, J.E. Harrar, et. al., UCID-19051, February 1, 1979, p. 22.

²Ibid., p. 21.

- Restricted time available for testing, which may have to be conducted at appropriate times during and/or between the main development/operation activities at the site
- A desire to screen as many additives and potential additives as possible
- Availability of chemical additives to test, especially proprietary and experimental chemicals (e.g., not all the manufacturers of treatment chemicals approached by LLL offered their products for testing)
- Limited funding
- Operational problems at the facility and/or technical problems with the testing

Another observation is that there has not been sufficient experimentation on the effect of additive concentration on performance. This can be attributed in part to some or all of the above five constraints but also to the judgment by LLL that 40 ppm concentration represented the approximate upper limit to the economic use of most likely candidate additives on the basis of their costs and certain expected technical requirements of their in-plant utilization.

No information was found during the course of this project on the effect of continuous versus intermittent additive injection. All of LLL's silica control testing and the Dequest 2060 tests at East Mesa employed continuous pumping of the additive solution into the flowing brine. No reports reviewed indicate the use of any method other than continuous introduction. None of the reports contain a discussion of this aspect of the testing, probably because it was not considered to be an important factor. This notion seems to be supported by the fact that LLL did not explicitly consider intermittent injection in spite of the fact that it potentially represents a direct cost saving through reduced consumption of the additive.

Most of the foregoing remarks relate specifically to the LLL testing program conducted at Salton Sea, except where stated otherwise. The specially-constructed test facility there presents an opportunity to test additives without interrupting operation of the wells or plant and theoretically should serve as a small-scale model of the critical scaling aspects of the power plant. However, the latter expectation has not been completely fulfilled. It was discovered, after a large amount of testing had been reported, that the two separate but nominally-identical test channels (see Figure 2) were not always acceptably identical in operation and that they both contained brine which was often different in some regards from the wellhead brine. This was in spite of both channels being fed from the same source. The fact that the two channels seemed to be associated with slightly different brine and scaling characteristics suggested that a degree of caution must be exercised in comparing test results from the channels.

Both the Salton Sea and Republic Geothermal's East Mesa power plants will be flash plants, but while LLL conducted their screening with flashed brine, the Dequest 2060 tests were performed on unflashed brine. Whether this indicates that Republic Geothermal intends to regularly treat the geothermal fluid before flashing when power comes on line is unclear, but it should be mentioned that the East Mesa tests were planned to have direct relevance to the problems of downhole carbonate scaling as well as scaling in above-ground process equipment.

The East Mesa Dequest 2060 tests did not present the same actual and potential problems as LLL's multi-additive testing program at Salton Sea. In particular, Vetter Research relied exclusively on on-line scaling tests with pipe spools as opposed to LLL's primary concentration on off-line precipitation inhibition tests. In addition, there is not as much room for

varying interpretations of the Dequest 2060 results as the Salton Sea tests due to the single additive tested at East Mesa and its relatively high degree of success. Therefore, the identification of Dequest 2060 as a highly effective carbonate inhibitor compared to LLL's less definitive results for silica control should not be necessarily construed as a reflection of the validity of the respective test procedures employed. Overall, however, the experimental set-up and test monitoring for the East Mesa carbonate scale tests were better suited to the prevailing circumstances and, in some regards, the reporting was also better organized.

The Salton Sea and New Zealand silica flocculating tests were not reported in sufficient detail to permit useful comments, even though they identified active geothermal flocculating agents.

9.2 Scale Formation and Prevention

A discussion of precipitation and scale formation in geothermal fluids is beyond the scope of this document, but there are a few pertinent remarks to make concerning the scaling process. The factors affecting geothermal scaling and the incomplete understanding of the influence of their various interrelationships have already been mentioned. Investigation of chemical controls for silica have been primarily oriented toward stabilizing the silica in colloidal form in the brine, thereby preventing its aggregation and deposition. Candidate additives preselected for screening have tended to be large polymeric molecules expected to be suitable for adsorbing onto relatively large silica particles and stabilizing them. This approach to scale control was formulated on the implicit assumption that silica in the brine at the more important scaling locations in the plant is present in particulate form.

Experiments conducted by LLL after their testing program was underway unexpectedly indicated that most of the silica (at least 70%) is in monomeric form at all temperature ranges (see Table 21). This suggests that the scale may be formed mainly from monomeric silica. If this is the case, additives that inhibit precipitation only by adsorption will not be able to function, and either additives possessing a different mode of scale-control action or means to increase the proportion of particulate silica must be demonstrated. Sufficient analysis has not been carried out to accurately assess the relative proportions of monomeric silica at different temperatures and process-flow locations.

Another aspect of scale control that has not been adequately investigated is the effect of the process-flow location of additive introduction. Limited tests at Salton Sea indicate that additive effectiveness may increase the earlier the additive is introduced into the system. The principal factor at work here may be the increased residence time in the system which allows greater time for the added chemical to "react" with the silica. Table 21 shows that the percentage of non-monomeric silica is slightly greater in the 210°C brine than in the 125°C brine, but significantly greater in the 85°C brine. The decrease in additive effectiveness is consistent with the observed decrease in percentage of non-monomeric silica from 15% in 210°C brine to 10% in 125°C brine, but is apparently inconsistent for the lower-temperature end of the system where the proportion of non-monomeric silica increases to 29% at 85°C. However, neither this trend in additive effectiveness nor in the relative proportions of non-monomeric silica were confirmed. Therefore, an interplay of temperature, proportion of silica in monomeric form, reaction time, and one or more other factors is suggested.

TABLE 21

CONCENTRATION OF MONOMERIC SILICA IN
UNTREATED SALTON SEA BRINE IN TEST SYSTEM

Sample Location	Temperature (°C)	% of Monomeric Silica
First-stage separator output	210	85
Second-stage separator output	125	90
Delay stage output	85	71

SOURCE: On-Line Tests of Organic Additives for the Inhibition of the Precipitation of Silica from Hypersaline Geothermal Brine II. Tests of Nitrogen-Containing Compounds, Silanes, and Additional Ethoxylated Compounds, J. E. Harrar, et. al., UCID-18195, June 1, 1979.

The primary objective of LLL's scale-control experiments was not to prevent scaling by flocculation and removal of silica from the brine, but to preserve the silica in colloidal form and prevent its precipitation and aggregation. This is because flocculation and ancillary techniques to remove the flocculent do not represent the most practicable method to control silica scales in geothermal fluid before it is used in the primary energy extracting process. The emphasis in non-geothermal applications is on silica flocculation rather than stabilization. However, there can be a close relationship between the physical/chemical requirements for flocculation and steric stabilization. In fact, many compounds can exhibit both properties with nothing more than a change in concentration. Most of the additives tested at Salton Sea were not intended to act as flocculants, although flocculating activity was occasionally observed under certain circumstances.

Different scale-producing constituents of geothermal fluid can form by different chemical/physical routes and under different operating conditions. Therefore, the mechanism of control for one type of scale may be totally unsuitable for another type. For example, the fundamental difference between the control of SiO_2 and carbonate scales is that the silica exists in that molecular (or polymeric) form in the brine while carbonate scales are formed by the combination of separate species in solution. This theoretically means that there can be more chemical control options for carbonate scales (control of one or more of the precursor species involved or the insoluble product itself) than for silica. Silica control has been pursued mainly via steric colloidal stabilization while inhibition of CaCO_3 scale has relied on the uptake of calcium ions (Ca^{2+}) to prevent their reaction with carbonate

species. This highlights the importance of understanding geothermal chemistry, especially on a site-specific basis, as it relates to various types of deposits from the brine.

9.3 Promising Additives

As far as stabilizing silica in Salton Sea geothermal brine is concerned, a few chemicals have demonstrated or indicated significant precipitation and/or scale inhibiting powers. However, the silica control results can serve only as an extremely rough guide to additive effectiveness by group. Assumptions, sometimes questionable, of essentially equivalent test procedures and conditions are implicit in the presentation of the data in one table. It would probably not be advisable to completely exclude any group from further consideration on the basis of these results alone. In particular, proprietary additives should not be discounted on the basis of their generally poor performance because of their unknown chemical structures, i.e., they do not represent a single chemical type or class of additives. Although no outstanding additive groups are revealed, the large polymeric additives containing oxyethylene and/or nitrogen have shown promise and certainly have been preferentially selected by the main testing organization for screening. Selection of certain additives for screening may, however, reflect their relative availabilities and other factors in addition to any performance expectations.

About 60% of the additives containing the oxyethylene moiety increased the retention of silica in 90°C brine by at least 50%. Unfortunately, the medium- and high-temperature effectiveness of these compounds is generally limited by their decreased solubility at elevated temperatures and possibly by the physical susceptibility of their stabilizing properties to the

turbulence effects of flowing brines. One polyoxyethylene derivative, however, does not share the same solubility limits of the pure polyoxyethylenes. This compound, Ethoquad 18/25 (methyl polyoxyethylene octadecylammonium chloride), appears to be a good scale inhibitor at 210°C.

Polyethylene imines, polyethyloxazalines, and quaternary ammonium compounds (with and without polyoxyethylene) are all nitrogen-containing compounds shown to have activity as silica precipitation inhibitors. It should be mentioned that Ethoquad 18/25 can also be considered a polyoxyethylene-containing quaternary ammonium compound.

Hydroxyethyl celluloses also possess antiscalant activity, but they cannot be prepared as low-viscosity, high-concentration aqueous solutions. This is an example of a number of technical factors which may constrain the potential usefulness of otherwise effective additives.

At the end of their testing program on organic scale inhibitors for silica, LLL identified the following additives as leading candidates:

- Corcat P-18 (polyethylene imine)
- PAE·HCl (polyaminoethylene hydrochloride)
- Ethoquad 18/25 (polyoxyethylene octadecylammonium chloride)
- Mirapol A-15 (polydiquaternary ammonium chloride)

Corcat P-18 was advanced as the most promising single compound. LLL maintains that, for silica control in Salton Sea brine at least, the most successful additives will probably be various mixtures of these compounds with other chemicals. Combination of the best organic inhibitor(s) with pH adjustment of the brine has been proposed as the best chemical approach to silica scale control. Such combinations include:

- Corcat P-18 + HCl + Dequest 2060
- Ethoquad 18/25 + HCl + Dequest 2060

- Mirapol A-15 + HCl + Dequest 2060
- PAE·HCl + Dequest 2060

The Dequest 2060 acts as a phosphonate crystalline deposit inhibitor and is a very effective CaCO_3 inhibitor, as described in this report. It has been conjectured that the precipitation of small amounts of CaCO_3 may enhance the nucleation of silica. Brine acidification with HCl confers high-temperature antiscalant activity and enhances the effect of the silica precipitation inhibitor at lower temperatures. (HCl concentrations of at least 100 ppm do not greatly increase the corrosivity of Salton Sea brine.)

Other tested compounds LLL felt exhibited promise include:

- Arquad 18/50, which is similar in structure to Ethoquad 18/25 and almost as potent
- Hyamine 1622

Both are quaternary ammonium compounds without polyoxyethylene.

Overall, the most promising group of compounds arising from LLL's tests are the cationic nitrogen-containing compounds (including quaternary ammonium compounds, polyethylene imines, and polyethyloxazalines). The presence of polyoxyethylene in these compounds improves, but is not necessary for, their activity toward silica.

The effectiveness of Dequest 2060 against CaCO_3 scale at East Mesa does not need to be reiterated here. It is sufficient to note that this additive is very effective and will probably have application to carbonate problems at other geothermal sites. Dearborn 8010, Calgon SL-500, and Drewplex 502 have exhibited good control of Ca^{2+} in East Mesa brine and Dearborn 8010 has performed well in on-line scaling tests and operational experience in a geothermal desalination plant.

Six compounds were identified in the literature¹ as potentially useful flocculating agents for silica at Salton Sea (see Table 10), although they were not necessarily chosen for their flocculant properties. No quantitative testing information accompanied this identification, so very little of a specific nature can be said about these additives.

The only intentional flocculating treatment for silica in the reviewed literature is the CaO tests in New Zealand. Silica could be effectively removed from 90°C effluent brine at two sites with this technique (depending on additive concentration), but the usefulness of the application of this process to U.S. brines, and the Salton Sea field in particular, is unknown.

9.4 Cooling Water Treatment

This subject has already been discussed in section 8. The lack of widely reported testing of alternative chemical scale-control treatments to enable spent geothermal brine to be used as cooling water is somewhat surprising in view of the growing drive to utilize on-site geothermal cooling water. In fact, the future of development at certain geothermal sites is in question due to the scarcity of accessible non-geothermal waters for power-plant cooling needs. The Raft River tests reviewed here form part of a cooling water treatment investigation that is primarily directed towards corrosion problems and that it is being carried out at a moderate-temperature, low-salinity, binary system. It must also be noted that the Raft River resource does not produce a harsh geothermal fluid.

Flocculation and removal of silica, as opposed to maintaining the silica in the brine in a non-scaling form, is probably a more practical treatment option for cooling systems than for other sections of the plant. In addition

¹Effects of Organic Additives on the Formation of Solids from Hypersaline Geothermal Brine, J.E. Harrar, et. al., UCRL-80970, March 1978.

to the directly relevant Raft River tests, the previously reviewed use of CaO to precipitate SiO_2 from low-temperature effluent brine at Wairakei and Broadlands may be of interest here. However, the brine characteristics and details of the experiments would have to be studied more closely to determine whether the slaked lime process is suitable for any U.S. sites.

10. IDENTIFICATION OF TESTING AND INFORMATION NEEDS

The testing reviewed under this task, although difficult to interpret and extrapolate, does not demonstrate the full impact of the identified evaluation problems that will be experienced as testing with an increasing number of additives and under increasingly diverse conditions is conducted. Similarly, the identification of fairly specific gaps in scale-control additives testing at this stage cannot always be confidently supported by a reliable set of data. There are basically two categories of gaps in testing that need to be considered:

- further testing which could be done at a particular geothermal site/system to complete all practicable and relevant testing possible at that site
- geothermal sites/systems where no or negligible testing has been conducted and where existing or planned testing is not applicable.

These gaps can relate to generic operating environments and/or additives. The ability to identify these gaps can be hampered by incomplete reporting of test results in the literature. This can make it difficult to determine under what conditions the tests were conducted and to judge the applicability of the test results to untested scenarios.

Table 22 relates the testing reviewed under this task to the basic parameters of brine temperature and concentration of total dissolved solids. Conditions apparently not represented by testing are not necessarily areas of genuine testing need for two reasons:

- 1) literature reviewed has been limited by the scope of this task, and
- 2) scale problems may not be present in some of these situations.

TABLE 22

APPLICATION OF REVIEWED TESTING TO
GENERIC GEOTHERMAL OPERATING ENVIRONMENTS

TEMPERATURE TOTAL DISSOLVED SOLIDS	SILICA SCALE			CARBONATE SCALE			SULFIDE SCALE ¹		
	HIGH	MEDIUM	LOW	HIGH	MEDIUM	LOW	HIGH	MEDIUM	LOW
HIGH	Salton Sea ² ← Scaling Tests (Flashed Brine) →		Salton Sea ² Precipitation-Inhibition and Flocculation Tests (Flashed Brine)						
MEDIUM					?				
LOW		Raft River ³ Flocculation Tests (Flashed Cooling Water)	Wairakei and Broadlands ³ Flocculation Tests (Cooled Discharge Brine) ⁵		East Mesa ⁴ Scaling Tests (Unflashed Brine)				

¹No relevant testing for sulfide scale control was identified for review. Since sulfide deposits appear to be primarily associated with silica scale, the control of silica scale is believed to be an effective approach to sulfide control.

²Salton Sea corresponds to Radian Corporation's Class 1 geothermal fluid.

³Raft River, Wairakei, and Broadlands correspond to Radian Corporation's Class 4 geothermal fluid.

⁴The East Mesa geothermal resource represents a wide variation in brine characteristics; some wells there produce brine with medium-level TDS concentrations (up to 26,000 ppm). It is possible that some of the reviewed testing applies to medium TDS brine, but this cannot be accurately determined from the test literature due to incomplete reporting. The East Mesa resource is included in both Classes 3 and 4 of Radian Corporation's classification of geothermal fluids.

⁵It is not reported whether this is flashed or unflashed brine.

SOURCE: EER, Inc.

There are two major needs indicated by this literature review and evaluation. The first is that a more comprehensive and detailed follow-up study to adequately assess the status of geothermal scale-control additives testing would contribute greatly to organizing, focussing, and publicizing geothermal scale control research and to stimulating the interest of chemical companies as potential suppliers of antiscalants. Consideration should be given in this study to:

- encompassing a wider literature review, perhaps including chemically-similar fluids where appropriate
- incorporation of recent unpublished testing or testing plans when available
- compilation and evaluation of available information on the chemistry of scaling in geothermal fluids
- compilation of site-specific scaling information (qualitative or quantitative)
- identification and evaluation of viable chemical mechanisms for scale control (i.e., flocculation, stabilization, reaction, etc.)
- more clearly defining generic geothermal operating environments and relating these to actual or expected scaling problems at specific sites and/or utilization systems
- identification of the types of additives which the analysis of geothermal scaling indicates may be active antiscalants
- identification of optimum methods for the dissemination of additives testing information to geothermal developers/operators and other interested parties.

A second need is the development of the most efficient strategy for identifying useful additives with minimum testing effort. This strategy may constitute a "generic" on-going investigation or may address scale control on a site-by-site basis as and when scale problems arise. Priorities should be set with regard to:

- types of scale addressed
- types of utilization system considered and the locations of problem scaling withing these systems
- mechanisms of chemical scale-control selected for study
- types of additives screened and tested further
- geothermal sites chosen for additives research.

In addition, some sort of standardized testing procedures and/or additive performance standards may need to be established to aid in comparative evaluation of different tests. The identification and implementation of this testing strategy will require input from the secondary study recommended above.

The following list identifies more specific information needs and possible areas for further work suggested by evaluation of the reviewed literature. A number of these problems may already have been addressed in literature not incorporated in the source information for this project and the list should, therefore, be considered tentative with regard to geothermal scale-control testing to date. The list does not indicate any priority ranking. (Since a number of these items apply specifically or generally to LLL's Salton Sea tests, it should be mentioned that LLL has terminated its scale control program at this site and dismantled its test facility.)

- (1) Determination of the validity of LLL's 90°C precipitation-inhibition tests as a screen for potentially useful scale-preventing additives. Not only will this aid in future testing, but it will help determine the usefulness of the large amount of testing that has already been conducted at Salton Sea.

- (2) Emphasis on on-line scaling tests as opposed to 90°C precipitation-inhibition tests at Salton Sea, particularly if the 90°C test is judged to be an invalid or unreliable screen. This may be applicable to testing programs at other sites, too.
- (3) Determination, with a greater degree of confidence than before, of the relative proportions of monomeric versus polymeric silica at critical temperatures and process-flow locations in the Salton Sea utilization system, and perhaps at other relevant sites.
- (4) Evaluation of brine acidification in conjunction with the use of scale-control additives and, in particular, those acid/additive combinations LLL recommended for testing for Salton Sea silica.
- (5) Relative evaluation of scale inhibition and flocculation of scale-causing brine constituents as approaches to scale control. Given these two basic choices and the various inhibition options, identification (as far as possible) of what chemical approaches to scale control are appropriate for what types of scale, at what sites, and at what locations in the processes. Identification of the properties of chemical additives necessary for the various methods of scale control and the types of additives they suggest.
- (6) Testing to determine the technical advantages and disadvantages of continuous versus intermittent additive introduction.
- (7) Testing to determine optimum process-flow injection points for additives for specific systems.

- (8) More testing to study the effects of additive concentration on effectiveness. This may have to be done on an additive-specific basis, and then only for likely candidates.
- (9) Compilation of physical and chemical data on geothermal cooling water at relevant sites with regard to identifying the specific scale-control problems of cooling systems.
- (10) Analysis of the cost-effectiveness of using the most promising additives.

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APPENDIX 1

LIST OF ADDITIVES IN REVIEWED LITERATURE,
ALPHABETICALLY AND WITH MANUFACTURER

ADDITIVE	MANUFACTURER
A-1100	Union Carbide
A-1160	Union Carbide
AlCl ₃	
Alkaphos Q.S.	Alkaril Chemicals
Alkateric 2CIB	Alkaril Chemicals
Arquad 18/50	Armak
B-2014-25	Dow Corning
B-2080-182	Dow Corning
Belclene 200	Ciba-Geigy
Betz 419	Betz Labs
Calgon CL-77W	Calgon
Calgon SL-500	Calgon
Carbowax 350	Union Carbide
Carbowax 1,000	Union Carbide
Carbowax 6,000	Union Carbide
Carbowax 14,000	Union Carbide
Cellosize QP-09-L	Union Carbide
CL-165	Calgon
CMHEC-420H	Hercules
Conco NI-125	Continental Chemical
Corcat P-18	Cordova
Corcat P-100	Cordova
Corcat P-145	Cordova Chemical
Corcat P-200	Cordova Chemical
Cortron R-16	Champion Chemicals
Crotein BTA	Croda, Inc.
CYAF-5103	American Cyanamid
Darex 41s	Dearborn - W. R. Grace
Dearborn 8010	Dearborn
Dequest 2060	Monsanto
Drewplex 502	
Drewsperser 747	Drew Chemical
Duomac T	Armak
Duoquad T-50	Armak
E-400	Dow Chemical
Emcol CC-36	Witco Chemical
Ethomeen 18/60	Armak Chemical
Ethomeen C/25	Akzora - Armak Chemical
Ethoquad 18/25	Armak Chemicals (company)
Ethoquad HT-60MS	Armak Chemical
Ethoquad 18/25 + Dequest 2060	
Ethoquad 18/25 + Duomac T	
Ethoquad 18/25 + HCl	
Fluorad FC430	3M
Geomate 256	Dearborn Chemical
Geomate 259	Dearborn Chemical
Goodrite K732	Goodrich
Glyoxal	J. T. Baker
Hipochem ADN	High Point Chemical
Hyamine 1622	Rohm & Haas
Jeffox FF-200	Jefferson Chemical
KH ₂ PO ₄	J. T. Baker

ADDITIVE	MANUFACTURER
<p> Lipal 200C Marasperse N-3 Mirapol A-15 Mirapol A-15 + Cycloryl NA Natrosol 180LR Natrosol 250HR Natrosol 250LR Natrosol 420H P-100, Chloracetic Derivative P-100, Glycidol Derivative P-100, Quaternized P-400 PAE•HCl Pluronic F38 Polymer JR-125 Polyox WSRN-10 Polyox WSRN-80 Polysperse Plus Pyronate 40 Q-C-50 Quat 188 RC-412 RC-413 Resorcinol S-404 SC-210 Schercoquat DAB-90 Starpol 100 Surfactant AR-150 Surfynol 465 Surfynol 485 Tetronic 1504 Thermosol APS Triton X-100 Tween-20 Tylose MHB Variquat K-1215 Varstat 66 Vinsol AR-150 Visco 3744 XD-8779.00 XD-8918.00 XD-30469.00 XFS-43075 XZ-8-5061 Z-6020 Z-6070 Z-6071 Zonyl FSB Zonyl FSN Zonyl's (series) </p>	<p> PVO International American Can Miranol Chemical Co. Hercules Hercules Hercules Hercules Cordova Cordova Cordova Dow Chemical Dynapol BASF - Wyandotte Union Carbide Union Carbide Union Carbide Betz Labs Witco Chemical Tomah Products Dow Chemical American C-E Natco Southwest Specialty Chemicals Scher Chemicals A. E. Staley Hercules Air Products Air Products BASF - Wyandotte Far-Best Corp. Rohm & Haas ICI - U.S. (America) American Heochst Sherex Chemical Sherex Chemical Hercules Nalco Chemical Dow Chemical Dow Chemical Dow Chemical Dow Chemical Dow-Corning Dow-Corning Union Carbide Dow Corning DuPont DuPont DuPont </p>

APPENDIX 2

LIST OF TESTED ADDITIVES IN REVIEWED LITERATURE,
BY CHEMICAL GROUP

Note: The chemical groups used here are not necessarily mutually exclusive in all cases due to the complex structure of many of the additives and an inability to confidently identify the active group(s) for every additive chemical; this is especially so for the proprietary chemicals which are of unknown chemical formulae.

CHEMICAL GROUP	COMMENT
<u>POLYOXYETHYLENES</u>	
Carbowax 350	
Carbowax 1,000	
Carbowax 6,000	
Carbowax 14,000	
Conco NI-125	
Ethomeen 18/25	
Ethomeen 18/60	Also Amine
Ethomeen C/25	Also Amine
Ethoquad 18/25	Also Quaternary Ammonium
Ethoquad HT-60MS	Also Quaternary Ammonium
Hipochem ADN	Also Quaternary Ammonium
Lipal 200C	
Polyox WSRN-10	
Polyox WSRN-80	
Q-C-50	Also Quaternary Ammonium
Surfactant AR-150	
Surfynol 485	
Tween 20	
Variquat K-1215	Also Quaternary Ammonium
Varstat 66	Also Quaternary Ammonium
<u>CELLULOSE DERIVATIVES</u>	
Cellosize QP-09-L	
CMHEC-420H	
Marasperse N-3	
Natrosol 180LR	
Natrosol 250HR	
Natrosol 250LR	
Natrosol 420HR	
Polymer JR-125	
Starpol 100	
Tylose MHB	
XD-8918.00	
<u>OTHER POLYMERS</u>	
Jeffox FF-200	copolymer
Pluronic F38	copolymer
Resorcinol	polymeric alcohol
Surfynol 465	polymeric alcohol
Tetronic 1504	copolymer
Triton X-100	polymeric alcohol
Vinsol AR-150	polyethylene glycol ester
<u>QUATERNARY AMMONIUM COMPOUNDS</u>	
Arquad 18/50	
Duomac T	
Duoquad T-50	
Emcol CC-36	
Hyamine 1622	
Quat 188	

CHEMICAL GROUP	COMMENT
<u>IMINES</u>	
Corcat P-18	Polyethylene Imine
Corcat P-100	"
Corcat P-145	"
Corcat P-200	"
P-100 and derivatives	"
<u>SURFACTANTS</u>	
Pyronate 40	
Zonyl FSB	
Zonyl FSN	
<u>ORGANIC ACIDS</u>	
Belclene 200	polycarboxylic acid
Dequest 2060	phosphoric acid derivative
Goodrite K732	polyacrylic acid
PAE•HCl	poly HCl salt
<u>OTHER ORGANICS</u>	
Fluorad FC 430	ester
Glyoxal	aldehyde
<u>SILANES</u>	
A-1160	
B-2014-25	
B-2080-182	
XZ-8-5061	
Z-6020	
Z-6071	
<u>PROPRIETARY CHEMICALS</u>	
Alkaphos Q.S.	
Alkateric 2CIB	
Betz 419	
Calgon CL-165	
Cortron R-16	
Crotein BTA	
Darex 41s	
Drewspers 747	
Geomate 256	
Geomate 259	
Mirapol A-15	
Polysperse Plus	
RC-412	
RC-413	
S-404	
SC-210	
Schercoquat DAB-90	

CHEMICAL GROUP	COMMENT
<p data-bbox="224 389 751 421"><u>PROPRIETARY CHEMICALS</u> (Concluded)</p> <p data-bbox="253 438 464 470">Thermosol APS</p> <p data-bbox="253 470 418 502">Visco 3744</p> <p data-bbox="253 502 418 534">XD-8779.00</p> <p data-bbox="253 534 435 566">XD-30469.00</p> <p data-bbox="253 566 402 597">XFS-43075</p> <p data-bbox="224 634 386 666"><u>INORGANICS</u></p> <p data-bbox="253 683 337 715">AlCl_3</p> <p data-bbox="253 715 545 746">Ammonium molybdate</p> <p data-bbox="253 746 354 778">KH_2PO_4</p>	

APPENDIX 3

DATA TABLES FROM TEST LITERATURE REVIEW
(Folded Tables Contained in Accompanying Envelope)

TABLE 1

[illegible]

ADDITIVE

BRINE TEST CONDITIONS

TABLE 2

ADDITIVE TEST CONDITIONS

TEST RESULTS

TEST CONCLUSIONS AND RECOMMENDATIONS

ADDITIVE TEST CONDITIONS																	TEST RESULTS				TEST CONCLUSIONS AND RECOMMENDATIONS	
Trade Name	Manufacturer	Chemical Name/Formule	Chemical Class	Comments	Temperature	Pressure	Composition	Flow Rate	Comments	Concentration	Method and Location of Introduction	Comments	Quantitative Results		Additive Effectiveness	Comments						
													X Silica Retained									
													40 ppm	20 ppm								
													86	88								
Natrozol 250LR	Hercules		Hydroxyethyl celluloses	Mean molecular wt. (M _w) = 85,000. Molar substitution* = 2.5. nonionic. Up to now in LLL's testing, this has been most effective inhibitor.	~200°C Samples incubated at 90°C.	~260 psia for separated brine.	Ranges: 3.4-3.7 Mol/l Cl ⁻ , pH 5.8-6.0, density @ 25°C, 1.135-1.145 g/cm ³ , SiO ₂ conc. 450-500 mg/kg.	7.0 gpm (~1 lb/sec.) in test channel.	Used LLL's test system at Imperial Valley (Wileland brine), Magnamax No. 1 well. (1) Used effluent brine flashed to atmospheric pressure. Brine for these apts. does not precipitate silica as rapidly as at full flow of Magnamax No. 1 well. At full flow, the dissolved solids (and silica) concs. are higher and this accelerates rate of precipitation.	40 + 20 ppm	Additive injected after first flash at rate of 0.02-0.04 gpm. Introduction approximately 8 feet upstream of first test specimen. Additive solution ~0.5-1.0% strength. Sample is 125°C brine exiting from 2nd stage separator.	Brine samples collected from 125°C sampling ports. As collected, brine flashed to 105°C. 1 hr. and 30 min. tests: only results for 1 hr. test reported because 30-min. data always consistent with longer test. Additive concs. could be controlled within ± 10% of nominal values.	—	69			Best additives were Carbowax 14,000 and Natrosol 250LR, with Polymer JR-125 approaching these. Two best were actually more effective at 20 ppm rather than 40 ppm. Dequest 2060, a phosphonate, showed intermediate activity toward silica, but it is also useful in inhibiting precipitation of FeSO ₄ . AlCl ₃ showed slight inhibition, but neither KH ₂ PO ₄ nor any of the proprietary additives had significant effect (<50% SiO ₂ retained). Effectiveness of 10-20 ppm Carbowax 14,000 estimated to be equivalent to brine acidification to ~pH 4.8. A brief test with Carbowax 14,000, the most promising inhibitor, showed that, although it significantly retarded scaling at 90°C, there was no improvement at 125°C or higher, and at 125°C there may even have been a slight increase in scaling rate. This test was done by inference from accumulated scale on equipment rather than by chemical analysis methods used elsewhere.					
Natrozol 250HR	Hercules			M _w = 1,000,000, MS = 2.5, nonionic										—				69				
Cellosize QP-09-L	Union Carbide			M _w = 85,000, MS = 1.8, nonionic										70				69				
Natrozol 180LR	Hercules			M _w = 85,000, MS = 1.8, nonionic										72				74				
Natrozol 420H	Hercules		Ethylene oxide polymers	M _w = 1,000,000, MS = 4.2, nonionic									—	65								
CMEC-420H	Hercules			M _w = 85,000, MS = 4.2, with carboxymethyl substitution										76				68				
Polymer JR-125	Union Carbide			M _w = 100,000 (est.), amine-substituted for cationic character										85				68				
Polyox WSRM-80	Union Carbide	HO(CH ₂ CH ₂ O) _n H		M _w = 200,000										50				50				
Polyox WSRM-10	Union Carbide	"	Other cellulose compounds	M _w = 100,000										78	79			The ethylene oxide moiety was confirmed as a source of activity for 90°C inhibition, and the polyethylene glycols in the molecular wt. range of ~10,000-100,000 are the most effective. See note in this column in Table 3 on impracticability of using hydroxyethyl celluloses as antiscalants.				
Carbowax 14,000	Union Carbide	"		M _w = 14,000										89	95							
Carbowax 6,000	Union Carbide	"		M _w = 6,000										—	84							
Carbowax 1,000	Union Carbide	"		M _w = 1,000										—	56							
Carbowax 350	Union Carbide	CH ₃ O(CH ₂ CH ₂ O) _n H	Proprietary mixtures	M _w = 350										62	—			(Also reported is effect of additives on conc. of suspended solids in brine.)				
ID-8918.00	Dow Chemical	Hydroxypropyl methylcellulose		M _w = 15,000										49	50							
Tylose MMS	American Hoechst	Methyl hydroxyethyl cellulose		M _w = high										—	50							
Nacasperse W-3	American Can	Modified sodium lignosulfonate		M _w = ?										50	—							
Starpol 100	A. E. Staley	Acrylamidomethyl-substituted starch	Other organic compounds	M _w = ?										—	46							
Geomate 259	Dearborn			Geothermal antiscalant										45	—							
XFS-43075	Dow Chemical			Antiscalant										46	—							
Polysperse Plus	Bets			Geothermal antiscalant										—	48							
Visco 3744	Witco		Inorganics	Low MW acrylate and nonionic surfactant										—	48							
Ethomeen C/25	Arnak	Polyoxyethylene (15) cocoamine ^(a)		M _w = 860										18 ppm	5 ppm							
Ethomeen 18/60	Arnak	Polyoxyethylene (50) octadecylamine		M _w = 2,400										78	—							
Surfactant AR-150	Hercules	Polyoxyethylene glycol ester of rosin		M _w = ?										92	—							
Surfynol 485	Air Products	Polyoxyethylene (30) acetylenic glycol	Inorganics	M _w ~ 1,500										69	—							
Tween 20	ICI American	Polyoxyethylene (20) sorbitan monolaurate		M _w ~ 2,000										64	—							
Zonyl FSW	DuPont	Fluorinated nonionic surfactant		M _w = ?										63	—							
Zonyl FSB	DuPont	Fluorinated amphoteric surfactant		M _w = ?										56	—							
Conce WI-125	Continental Chemical	Polyoxyethylene (200) nonyl phenol	Inorganics	M _w ~ 9,000										57	—							
Pluronic F38	SASF-Wyandotte	Polyoxyethylene polyoxypropylene copolymer		M _w ~ 5,000										73	—							
Dequest 2060	Monsanto	Diethylenetriamine pentamethylene phosphonic acid		M _w = 525										74	—							
—	—	KH ₂ PO ₄		M _w = 136										—	71							
—	—	AlCl ₃		M _w = 133										54	—							
—	—													57	—							
													Conc. Silica retained (mg/kg)									
													0	30 min.	1 hr.	2 hr.						
													474	281	215	215						
													469	431	412	—						
													469	431	421	347						
													460	442	436	—						
													475	436	423	—						
													SiO ₂ Conc. (mg/kg)									
													Time	Untreated Brine	Treated Brine							
													0	526	513							
													15 min.	262	467							
													30 min.	211	414							
													1 hr.	201	328							
													2 hr.	192	—							
													4 hr.	102	—							
													8 hr.	163	—							
													24 hr.	147	—							
</																						

Trade Name	Manufacturer	Chemical Name/Formula	Chemical Class	Comments	Temperature	Pressure	Composition	Flow Rate	Comments	Concentration	Method and Location of Introduction	Comments	Quantitative Results	Additive Effectiveness	Comments
Ethoquad 18/25	Arnak Chemicals	Methyl-polyoxyethylene (15) octadecylammonium chloride	Quaternary Ammonium Compounds	Reference describes and discusses the structures and expected activities of the substances chosen.	210°C injection temperature; sample incubated at 90°C	Not reported.	Ranges: 3.5-3.9 Mol/l Cl ⁻ , pH 5.8-6.1, density @ 25°C of 1.146-1.159 g/cm ³ , 443-486 mg/kg SiO ₂ conc.	7 gpm in test channel, 50 gpm overall.	Used LLL's Scale Control Test System at Imperial Valley (Miland brine), Magmax No. 1 well brine. Brine somewhat more saline than expts. in Reference 2 (Table 2).	20 ppm	Injected into separated 210°C brine, collected at atmospheric flash temp. of 105°C, and incubated at 90°C. Injection in usual location between 1st and 2nd stage separators.	30 min. and 1 hr. tests; only results for 1 hr. test reported because shorter test results always consistent with 1 hr. test.	<u>SiO₂ retained</u> No Additive 48 96,92 85 85 81 75 53 46 52 89 73 95 70 51 62 54 51 33,47 ^(b) 58 ^(b) 55 ^(b) 88 80 60 46 46 45 49 50		Leading candidate so far in LLL's program is Ethoquad 18/25. This compound has other advantages as an antiscalant: at ambient temp. it is a liquid which could be injected neat; and it also may have some activity as a corrosion inhibitor, which should further reduce the scaling of corroding surfaces. Ethoquad 18/25 is more powerful inhibitor than the pure polyoxyethylene polymers, and it apparently has no high-temperature solubility limitations.
Hyamine 1622	Rohm & Haas	Di-isobutyl-phenoxyethoxyethyl-dimethyl-benzyl-ammonium chloride		↓	↓	↓	↓	↓		↓					
Q-C-50	Tomah Products	Methyl-polyoxyethylene (50) cocoammonium chloride		↓	↓	↓	↓	↓		↓					
Variquat K-1215	Sherex Chemical	Methyl-polyoxyethylene (15) cocoammonium chloride		↓	↓	↓	↓	↓		↓					
Varstat 66	Sherex Chemical	Methyl-polyoxyethylene (15) talloammonium ethyl sulfate		↓	↓	↓	↓	↓		↓					
Hipochem ADW	High Point Chemical	Methyl-polyoxyethylene (15) talloammonium chloride	Other Ethoxylated Compounds												Although potentially useful as antiscalants because of their activity as precipitation inhibitors, the hydroxyethyl celluloses now (at time of this expt.) appear impractical because they cannot be prepared as low-viscosity high-concentration aqueous solutions (see top gp. of chemicals in Table 2).
Quat 188	Dow Chemical	N-(3-chloro-2-hydroxypropyl) trimethyl ammonium chloride		MW = 1,600											
Emcol CC-36	Witco Chemical	Methyl-diethyl-polyoxypropylene ammonium chloride		MW = 14,000											
Carbowax 14,000	Union Carbide	Polyoxyethylene													
Lipal 200C	PVO International	Polyoxyethylene (200) ricinoleic acid triglyceride													
Ethomeen 18/25	Arnak Chemicals	Polyoxyethylene (15) octadecylamine	Silanes												No activity of silanes was detected. Assuming no reaction actually occurred, this may have been due to unfavorable pH of brine and/or insufficient time in the system for reaction to take place (latter points seem to be discounted by later expt. described at bottom of page).
CMIEC-420L	Hercules	Carboxylated hydroxyethyl-cellulose		MW ~85,000, MS = 4.2											
Tetronic 1504	BASF-Wyandotte	Polyoxyethylene-polyoxypropylene block copolymer													
Jeffex FF-200	Jefferson Chemical	Polyoxyethylene-polyoxypropylene random copolymer													
B-2014-25 ^(a)	Dow Corning	Carboxy-functional amino-siliconate													(Also reported is effect of additive on conc. of suspended solids.)
B-2080-182 ^(a)	Dow Corning	Phosphonate-functional siliconate													Data were obtained on distribution of monomeric silica in this brine: it was found that 90% of the silica was monomeric at 125°C. This is potential difficulty for additives that can inhibit SiO ₂ precipitation only by adsorption on relatively large polymeric silica particles. Inhibition by adsorption on particles should be, and has, thus far, been more effective on the scales formed at the output of the delay stage of test system where brine has higher conc. of particles.
A-1160	Union Carbide	Urea-functional triethoxysilane													
Z-6020	Dow Corning	3-(2-aminoethylamino)-propyl trimethoxysilane													
Z-6071	Dow Corning	Phenyltrimethoxy-silane													
Corcat F-200	Cordova Chemical	Polyethylene imine		MW = 20,000											
Corcat F-145	Cordova Chemical	Polyethylene imine		MW = 40,000											
XD-8779.00 ^(a)	Dow Chemical	Polyethyloxazoline		MW = 60,000											
XD-8779.00 ^(a)	Dow Chemical	Polyethyloxazoline		MW = 100,000											
XD-30469.00 ^(a)	Dow Chemical	1:1 copolymer of acrylic acid and hydroxyethyl acrylate													
Darex 41s	Dearborn	Proprietary carboxylated polyelectrolyte													
Alkaphos Q.S.	Alkaryl Chemicals	Proprietary amphoteric coco-imidazoline derivative													
Alkateric 2C18	Alkaryl Chemicals	Proprietary free acid of complex organic phosphate ester													
Ethoquad 18/25	AS ABOVE	AS ABOVE					As above, except 3.8 Mol/l Cl ⁻ .		As above, but different additive injection locations produced different residence times for the brine. Brine residence time in 1st stage separator (@ 210°C) is ~42 sec. and in 2nd stage separator (@ 125°C) is ~2.3 min.	Not reported, but probably 20 ppm.	Effect of additive introduction in 3 locations tested: injection into the 1st stage separator input, injection between 1st and 2nd stages, and injection into 2nd stage separator	Expt. to test effect of location of additive introduction on additive effectiveness (and alters residence time). Incubation times of 30 min., 1 hr., and 2 hr. Brine residence times given in previous "Comments" column.	Incubation Time Input to 1st Stage Separator Between 1st & 2nd Stages In 2nd Stage Separator Conc. SiO ₂ retained (mg/kg)	Compared to the normal point of addition between 1st and 2nd stages, there is a decrease in effectiveness when injected into 2nd stage separator, and possibly a slight increase when injected into input of 1st stage separator, although latter differences are within usual measurement uncertainties.	Ethoquad 18/25 is quite resistant to the temperature/time conditions at the front end of the test system, and could be injected there in a two-stage flash system.
Z-6020	AS ABOVE	AS ABOVE			Injection temperature not reported, but possibly >210°C due to upstream injection point. Incubation at 90°C.		As at top.	50 gpm (well-head brine prior to entering 1st separator used).	As at top.	Not measured, but estimated to be 20 ppm.	Introduced as methanolic solution (to prevent hydrolysis) into input of 1st stage separator (wellhead brine).	Injection upstream of usual point done to increase brine residence time to allow more time for reaction of silanes and silica since no reaction detected in other tests. Additive injected into unseparated wellhead brine.	No evidence of reaction.	Apparently ineffective.	Seems to support lack of reaction/effectiveness of silanes indicated in other tests.

(a) Experimental chemical, not commercially available in large quantities.

(b) Additive solution in methanol.

Trade Name	Manufacturer	Chemical Name/Formula	Chemical Class	Comments	Temperature	Pressure	Composition	Flow Rate	Comments	Concentration	Method and Location of Introduction	Comments	Quantitative Results	Additive Effectiveness	Comments	Test Conclusions and Recommendations
Ethoquad 18/25	Arnak Company	Methylpolyoxyethylene (15) octadecylammonium chloride	Quaternary ammonium compound.	Strongly cationic.	Injection temperature not reported but probably ~200°C. See "Comments". Sample included at 90°C. Wellhead temperature was 212-22°C. See "Comments".	~265-330 psia. See "Comments".	4.0-4.5 Mol/l Cl ⁻ . See "Comments". 483-509 mg/kg SiO ₂ (virtually constant). Mol/l Cl ⁻ 4.0 4.65 Density 1.164 1.180 @25°C TDS 20.7% 22.9%	Not reported, but possibly could differ from usual test system flow of 7 gpm in each channel due to effects of earthquakes and well cleaning.	Used LLL's Scale Control Test System at Imperial Valley (Niland brine), Magnamax No. 1 well brine. Series of earthquakes during this set of tests affected the brine salinity, density, pressure, particulates content, temperature, scaling rate, quantity of solids precipitated, and the scaling tendency of the brine.	20 ppm	Usual location between 1st and 2nd stage separators. Injection into 200°C brine, and sample collected from 105°C atmospheric flash and incubated anaerobically at 90°C.	The earthquake presented opportunity to study effect of brine salinity on rate of solids and silica precipitation and hence on effectiveness of inhibitors. 1 hr. test.	Brine Cl ⁻ Conc. (Mol/l) 3.63 96 3.84 92 4.02 85 4.16 69 % SiO ₂ Retained	Potency of inhibitor (and similar ones) decreases dramatically as salinity increases.	Data on suspended solids also given. Data on corrosion rates also presented.	The performance of Ethoquad 18/25 as an antiscalant in these tests can be characterized as quite promising and probably justifies further tests in a larger scale facility. The cost of its use appears favorable in comparison with the cost of electricity that could be generated from the brine. Assuming for the Salton Sea Geothermal Field that the cost of power generation would be 33 mill/kWh, and that 1 kW could be generated from 100 lb of brine, the use of 20 ppm of the additive would increase the cost of electricity by 6¢. This also assumes a cost of \$1.00/lb for the chemical additive. This is the current cost, but it could be less expensive since several companies manufacture the same generic compound,* and very large quantities (1 ton/day/50 MW) would be required. This cost of the treatment must be measured against the benefits received, and these are difficult to quantify in some respects. The degree of scale reduction below 100°C is very good, but at 125°C it is not very good. However, since geothermal plants will have to undergo periodic cleaning, use of an organic additive has some advantage if it makes removal of the scale deposits easier as well as less frequent.
Ethoquad 18/25 + Dequest 2060	Monosanto	AS ABOVE Diethyltriamine pentamethylene phosphoric acid	AS ABOVE	It is primarily used only for crystalline deposits such as CaCO ₃ , BaSO ₄ , and CaSO ₄ .						20 ppm Ethoquad 18/25 +5 ppm Dequest 2060			Brine Cl ⁻ Conc. (Mol/l) 4.32 60 4.47 50 % SiO ₂ Retained			
Ethoquad 18/25		AS ABOVE			Brine temperature at inhibitor addition not reported. Sample incubated at 90°C.	N/A	4.0 Mol/l Cl ⁻ .	N/A	This was preliminary off-line precipitation test using same brine.	10, 20, 40, and 80 ppm	Off-line test: experimental technique not reported.	30 min., 1 hr., and 2 hr. tests.	SiO ₂ Retained (mg/kg) Time 0 ppm 10 ppm 20 ppm 40 ppm 80 ppm 0 505 505 496 483 505 30 min. 239 478 450 472 496 1 hr. 208 303 422 437 465 2 hr. 202 --- --- --- 395	Steady decrease in activity as conc. lowered; most significant decrease occurs below 20 ppm.	This test was used to select additive conc. to start with for on-line tests (25 ppm).	
Ethoquad 18/25 + Dequest 2060		AS ABOVE			Tests with Brine at 90, 125, and 210°C.	Presumably as at top.	4.0-4.5 Mol/l Cl ⁻ .	Brine flow rate for scaling tests of coupons at 125°C and 210°C not reported, but presumably as at top; flow rate for scaling test for tubing at 90°C was 0.5 l/min.	Significant proportion of this test occurred when "strong" brine was produced by earthquakes.	25 ppm 20 ppm +5 ppm	210°C brine test specimens located between 1st and 2nd stage separators; 125°C brine test specimens located in 2nd stage separator output; 90°C test tubing located after delay stage.	65-9 hr. tests.	Scaling Rate, mil/h Coupon, 210°C Coupon, 125°C Tubing 90°C Additive Mild Steel Hastelloy Teflon Mild Steel Hastelloy Teflon Mild Steel None, Control 0.10 0.03 0.06 0.78 --- 0.68 4.6(a) Ethoquad 18/25 (25 ppm) 0.41 0.20 0.14 0.67 0.42 0.51 2.7(a) Ethoquad 18/25 (20 ppm) 0.15 0.08 0.10 0.44 0.53 0.53 0.6(b) Dequest 2060 (5 ppm)	Assessment complicated by earthquakes, differences between test channels, and other problems. Generally, though, no scale reduction was achieved by E alone or E/D at 210°C; 15-44% scale reduction at 125°C; 44-81% scale reduction at 90°C. At 210°C, scaling may actually have increased. At 125°C, the E is the active compound and D has no benefit.	Formation of high-temp. deposits by additives might be resolved by low-temp. injection points if additives do work for low-temp. scale. Thus far, not found any organic additive that clearly reduces the predominantly sulfidic scale formed at 200°C. The good results obtained at 90°C encouraging because occurred under strongest brine conditions; appears that, in contrast to 125°C, there may be advantage in using Dequest 2060 with Ethoquad 18/25.	In addition, it would be fruitful to examine, as already suggested, a combination of the best organic inhibitor(s) with adjustment of the pH of the brine. For example, with mild acidification, a silica inhibitor should act to suppress the growth of scale during corrosion of the carbon steels that occurs as a result of surface neutralization of the acid. Many of the compounds found to be silica precipitation inhibitors are known to be corrosion inhibitors and this possible benefit also needs to be assessed. A fundamental study of the exact nature of the interaction of the proven precipitation inhibitors would also surely lead to the specification or selection of a better additive.
--	--	Hydrochloric acid HCl	Inorganic acid	Brine acidification well-recognized method for reducing scaling; however, this can increase corrosion.	Tests with 90, 125, and 210°C brine.	Presumably as at top.	3.5-3.7 Mol/l Cl ⁻ . Untreated brine was pH 5.8.	As immediately above.	Acidification tests during "weak" brine conditions.	Acidification to pH 3 and 5 reported; other results, including incomplete tests at pH 4, not reported.	68-88 hr. tests.	Scaling Rate, mil/h Coupon, 210°C Coupon, 125°C Tubing 90°C Additive Mild Steel Hastelloy Teflon Mild Steel Hastelloy Teflon Mild Steel 5.8 (Untreated) 0.05 0.02 0.02 0.10 0.03 0.04 1.2 5.0 0.13 0.01 0.01 0.15 0.01 0.01 0.1 3.0 0.08 0.01 0.01 0.03 0.01 0.01 0.05	Along with results of other acidification tests, this test indicates that at low temp., significant reduction in scaling is obtained. At pH 3, virtually no silica or heavy metal sulfide scale formed in 90°C tubing.	Reduction of pH to at least pH 3 seems to be required to overcome acid neutralization in vicinity of metal surface by corrosion products.	In addition, it would be fruitful to examine, as already suggested, a combination of the best organic inhibitor(s) with adjustment of the pH of the brine. For example, with mild acidification, a silica inhibitor should act to suppress the growth of scale during corrosion of the carbon steels that occurs as a result of surface neutralization of the acid. Many of the compounds found to be silica precipitation inhibitors are known to be corrosion inhibitors and this possible benefit also needs to be assessed. A fundamental study of the exact nature of the interaction of the proven precipitation inhibitors would also surely lead to the specification or selection of a better additive.	
--	--	Hydrogen peroxide, H ₂ O ₂		Oxidizing agent - proposed method to reduce brine pH as more economical alternative to HCl acidification by oxidizing Fe ²⁺ in brine to Fe ³⁺ , thus precipitating Fe(OH) ₃ . H ₂ O ₂ + 2Fe ²⁺ → 2Fe ³⁺ + 2OH ⁻ 2Fe ³⁺ + 6OH ⁻ → 2Fe(OH) ₃ H ₂ O ₂ + 2Fe ²⁺ + 4OH ⁻ → 2Fe(OH) ₃ A "multiplication" factor thus could be created in which one mole of H ₂ O ₂ would result in the consumption of four moles of hydroxide ion. On a strictly per-pound basis, this would be more economical than using HCl.	Injection temperature presumably ~200°C. Sample incubated at 90°C.	Presumably as at top.	4.4 Mol/l Cl ⁻ . 503 mg/kg total initial SiO ₂ , untreated brine was pH 5.7.	Presumably as at top.		25 and 50 ppm			50 ppm H ₂ O ₂ Incubation Time, hr. Brine pH Concentration of Suspended Solids, mg/kg Silica Retained % 0 4.44 - - 5.30 129 78 0.5 4.14 234 86 5.04 258 60 1 3.93 263 78 4.95 329 46	A relatively small amount of H ₂ O ₂ does substantially reduce pH. Under comparable conditions, ~200 ppm HCl would be required to reach pH 5.	However, it appears that SiO ₂ is coprecipitated by the Fe(OH) ₃ , which, although it should decrease the scaling rate, adds to the quantity of suspended solids in brine which may cause plugging problems. Tests in LLL's system are not satisfactory in this case for adequate evaluation of H ₂ O ₂ .	
--	--	Sodium hydroxide NaOH		If silica is predominantly monomeric at 125°C (reference 3 determined that 90% of SiO ₂ was monomeric in this brine at 125°C), then raising the brine pH might increase the fraction of polymeric SiO ₂ , and thus increase effectiveness of inhibitors that act by absorbing on large polymeric SiO ₂ particles.	Tests with brine at 90 and 125°C; injection temperature probably 210°C.	Not reported; obviously affected by reduction in flow rate.	4.1 Mol/l Cl ⁻ . total SiO ₂ at 2nd stage was 7491 mg/kg.	The flow rate in the test channel used was decreased by a factor of 2, but not reported.	In conjunction with this NaOH test, the brine flow rate was reduced by factor of 2 to increase residence time to allow more time for SiO ₂ to polymerize.	50 and 100 ppm	Presumably usual location between 1st and 2nd stage separators.		210°C Output of 1st Stage Separator 125°C Output of 2nd Stage Separator 90°C Output of Delay Stage NaOH Added Effluent Brine Chloride Concentration Mol/l Monomeric SiO ₂ % Brine pH Monomeric SiO ₂ % Brine pH Monomeric SiO ₂ % 50 ppm 4.1 - 5.98 74 5.87 61 100 ppm 4.1 - 6.16 62 5.77 49	Only a small increase in pH is needed to affect the conc. of monomeric silica. The pH rise of .3 produced by 100 ppm NaOH would probably produce significant change in nature of 125°C scaling, and, aside from the effect of pH on SiO ₂ polymerization, the scaling would also be influenced by presence of additional suspended solids.	Reducing the flow rate did not, on its own, increase the fraction of monomeric silica, perhaps because the delay was not long enough. Raising pH with NaOH, like lowering pH with acid, requires significant amount of chemical because of high buffer capacity of brine. During expts., metal hydroxides, such as Fe(OH) ₃ , were apparently precipitated with just a slight pH increase.	
FAH-HCl	Dynapol	Poly(aminoethylene, HCl salt)		(CH ₂ CH ₂) _n Peak - average MW = 120,000 NH ₂ HCl Strongly cationic.	Injection temperature probably 210°C; incubation at 90°C.	Not reported.	4.2 Mol/l Cl ⁻ .	Not reported -- may have been usual 7 gpm.		20 ppm	Presumably usual location between 1st and 2nd stage separators.		% SiO ₂ Retained Control 41 89	FAH-HCl most potent inhibitor yet discovered, even better than Ethoquad 18/25. Appears that FAH-HCl initially induces some precipitation of SiO ₂ (and/or metal compound), but then precipitation strongly inhibited.	Potency of FAH-HCl somewhat surprising because its MW is above range that appears to be optimum for the polyoxyethylenes, polyethylene imines, and polyethyloxalines.	
XZ-8-5061	Dow-Corning	Quaternary-ammonium-functional silane	Low MW polycarboxylic acid	Another in series of previously tested silanes.						20 ppm						
Belclene 200	Ciba-Geigy		Low MW alkyl aryl sulfonate	Proprietary additives used in other water treatment applications.						20 ppm			44			
Pyronate 40	Witco Chemical									20 ppm			48			
Glyoxal	J. T. Baker	Ethanedial		Showed some promise in LLL's first off-line bench tests.						20 ppm			41			
--	J. T. Baker	Ammonium molybdate		Tried because of known ability to form strong silicomolybdate complexes.						100 ppm as Mo(VI)			39	No significant effect		

*e.g., Tonah Products Q-18-15.

ADDITIVE				BRINE TEST CONDITIONS				ADDITIVE TEST CONDITIONS				TEST RESULTS						
Trade Name	Manufacturer	Chemical Name/Formula	Chemical Class	Comments	Temperature	Pressure	Composition	Flow Rate	Comments	Concentration	Method and Location of Introduction	Comments	Quantitative Results			Additive Effectiveness	Comments	TEST CONCLUSIONS AND RECOMMENDATIONS
Arquad 18/50	Armat	Acetic acid salt of N-tallow-1,3-diamino propane	Quaternary ammonium compounds	No oxyethylene.	Presumably injection temperature of 210°C. Incubation at 90°C.	Not reported.	4.0-4.2 Mol/l Cl ⁻ , 182 mg/kg iron, 474-524 mg/kg SiO ₂ , density @ 25°C was 1.158-1.167 g/cm ³ , pH 5.74-6.01.	Total well flow rate 100-150 gpm (Magma Power Co. also flowing well; when LLL operates alone, 50 gpm)	Used LLL's Test System at Imperial Valley (Miland brine), Magma Power Co. also flowing well. The brine was of intermediate salinity. After the first 2 days of testing, the brine conditions/composition were reasonably constant.	20 ppm of active compound	Usual injection at 220°C between 1st and 2nd stage separators.	1 hr. and 2 hr. tests.	1 hr. incubation 2 hr. incubation					It has been noted previously that the concentration dependence is quite pronounced in certain ranges and that in general, for all of the organic additives LLL has examined, a concentration of 40 ppm is the point at which further improvement is marginal. The reason for this interesting finding is unknown, but this limit may be related to the concentration at which silica particle coverage is complete under these particular kinetic and hydrodynamic conditions. Another possibility in the case of some of the surfactants like Ethoquad 18/25 is that the concentration limit is related to the critical micelle concentration of the additive in this brine.
Ethoquad 18/25	Armat			Contain oxyethylene.									SiO ₂ retained (mg/kg)	Initial SiO ₂ retained (mg/kg)	SiO ₂ retained (mg/kg)			
Duoquad T-50	Armat												Control 240	493	196			
Ethoquad HT-60MS	Armat												424	474	280			
Duomac T	Armat												406	493	303			
Corcat P-18	Cordova		Polyethylene imines	Chosen to test as corrosion inhibitor, not silica precipitation inhibitor.									378	474	304			
Corcat P-100	Cordova			MW = 1,800									348	495	288			
Corcat P-200	Cordova			MW ~10,000									270	505	251			
P-100, quaternized	Cordova			MW ~20,000									423	502	325			
P-100, chloroacetic derivative	Cordova			Quaternized with methyl chloride.									405	502	267			
P-100, glycidol derivative	Cordova	Polydiquaternary ammonium chloride	Polymeric diquat	Quaternized with methyl chloride.									355	502	276			
FAE-HCl	Dynapol			MW = 120,000									340	502	285			
FAE-HCl	Dynapol			MW = 25,000									318	509	270			
FAE-HCl	Dynapol			MW = 25,000, Hofmann route									270	509	252			
Mirapol A-15	Miranol Chemical Co.			MW = 2200, small polymer, cationic									406	505	251			
HC-413	American T			MW = 30,000									364	500	307			
HC-412	American T			MW = 10,000									312	501	252			
Crota BTA	Croda, Inc.			MW = 10,000									230	501	230			
Schercoquat DAB-90	Scher Chemicals			MW = 5,000									184	491	186			
Mirapol A-15 + Cycloeryl MA				Sodium lauryl ether sulfonate	Anionic surfactant	This combination used in hair preparations and used here as attempt to form more tenacious adsorbed film on SiO ₂ particles.						20 ppm + 20 ppm	Mirapol A-15 injected at usual point and at same time cycloeryl MA injected in 2nd stage 125°C separator because they formed precipitate together.	This method meant effect of combination on 220°C scale could not be tested, but was desirable to test idea of bilayer film.	Initial SiO ₂ retained (mg/kg)			
		508	404												321			
Ethoquad 18/25 + Duoquad T		AS ABOVE	AS ABOVE	Duoquad T has virtually no activity as a SiO ₂ precipitation inhibitor.						25 ppm + 7 ppm	Mixed together before injection at usual point.		506	425	357			
													506	416,412	339			
Ethoquad 18/25 + HCl		AS ABOVE	AS ABOVE	Reducing pH with acid to point where SiO ₂ precipitation and scaling are decreased requires large quantity of acid; this test was to determine if synergistic combination of acid and organic inhibitor effective.						27 ppm + 100 ppm	Mixed together before injection at usual point.	These chemicals were tested in earlier studies at 20 ppm and 20-25 ppm. This test at 35 ppm carried out to judge effect of concentration on effectiveness. However, this not single conc. vs. effectiveness test under same conditions.	486	462	458			
Ethoquad 18/25 + Duoquad T		AS ABOVE	AS ABOVE	Reducing pH with acid to point where SiO ₂ precipitation and scaling are decreased requires large quantity of acid; this test was to determine if synergistic combination of acid and organic inhibitor effective.						35 ppm	Usual point of injection.		486	436	321			
FAE-HCl		AS ABOVE	AS ABOVE							35 ppm	Usual point of injection.		505	431	327			
Mirapol A-15 + Cycloeryl MA		AS ABOVE	AS ABOVE							20 ppm + 20 ppm	Presumably usual injection location at 220°C.	Scaling tests including scale thickness measurement and weight changes of coupons (tests 100 hr. too short for accurate comparisons by thickness measurements for 220°C tests). 60 hr. exposures at 125°C and 220°C, 7-22.5 hr. exposures at 90°C.	Control 7.9	6.7, 6.1				
Ethoquad 18/25 + Duoquad T		AS ABOVE	AS ABOVE							25 ppm + 7 ppm	Mixed together before injection at usual point.	Scaling rate measurements made with full complement of specimens, including sections of 3/2" and 1/4" tubing placed at outlet of delay stage for 90°C data.	21	1.9				
Ethoquad 18/25 + HCl		AS ABOVE	AS ABOVE							27 ppm + 100 ppm	Mixed together before injection at usual point.	Scaling rate measurements made with full complement of specimens, including sections of 3/2" and 1/4" tubing placed at outlet of delay stage for 90°C data.	21	.35				
Ethoquad 18/25 + Duoquad T		AS ABOVE	AS ABOVE							35 ppm	Usual point of injection.		22.5	1.0				
FAE-HCl		AS ABOVE	AS ABOVE							35 ppm	Usual point of injection.		22.5	1.4				
Mirapol A-15 + Cycloeryl MA		AS ABOVE	AS ABOVE							20 ppm + 20 ppm	Presumably usual injection location at 220°C.	Scaling tests including scale thickness measurement and weight changes of coupons (tests 100 hr. too short for accurate comparisons by thickness measurements for 220°C tests). 60 hr. exposures at 125°C and 220°C, 7-22.5 hr. exposures at 90°C.	Control 7.9	6.7, 6.1				
Ethoquad 18/25 + Duoquad T		AS ABOVE	AS ABOVE							25 ppm + 7 ppm	Mixed together before injection at usual point.	Scaling rate measurements made with full complement of specimens, including sections of 3/2" and 1/4" tubing placed at outlet of delay stage for 90°C data.	21	1.9				
Ethoquad 18/25 + HCl		AS ABOVE	AS ABOVE							27 ppm + 100 ppm	Mixed together before injection at usual point.	Scaling rate measurements made with full complement of specimens, including sections of 3/2" and 1/4" tubing placed at outlet of delay stage for 90°C data.	21	.35				
Ethoquad 18/25 + Duoquad T		AS ABOVE	AS ABOVE							35 ppm	Usual point of injection.		22.5	1.0				
FAE-HCl		AS ABOVE	AS ABOVE							35 ppm	Usual point of injection.		22.5	1.4				
Mirapol A-15 + Cycloeryl MA		AS ABOVE	AS ABOVE							20 ppm + 20 ppm	Presumably usual injection location at 220°C.	Scaling tests including scale thickness measurement and weight changes of coupons (tests 100 hr. too short for accurate comparisons by thickness measurements for 220°C tests). 60 hr. exposures at 125°C and 220°C, 7-22.5 hr. exposures at 90°C.	Control 7.9	6.7, 6.1				
Ethoquad 18/25 + Duoquad T		AS ABOVE	AS ABOVE							25 ppm + 7 ppm	Mixed together before injection at usual point.	Scaling rate measurements made with full complement of specimens, including sections of 3/2" and 1/4" tubing placed at outlet of delay stage for 90°C data.	21	1.9				
Ethoquad 18/25 + HCl		AS ABOVE	AS ABOVE							27 ppm + 100 ppm	Mixed together before injection at usual point.	Scaling rate measurements made with full complement of specimens, including sections of 3/2" and 1/4" tubing placed at outlet of delay stage for 90°C data.	21	.35				
Ethoquad 18/25 + Duoquad T		AS ABOVE	AS ABOVE							35 ppm	Usual point of injection.		22.5	1.0				
FAE-HCl		AS ABOVE	AS ABOVE							35 ppm	Usual point of injection.		22.5	1.4				
Mirapol A-15 + Cycloeryl MA		AS ABOVE	AS ABOVE							20 ppm + 20 ppm	Presumably usual injection location at 220°C.	Scaling tests including scale thickness measurement and weight changes of coupons (tests 100 hr. too short for accurate comparisons by thickness measurements for 220°C tests). 60 hr. exposures at 125°C and 220°C, 7-22.5 hr. exposures at 90°C.	Control 7.9	6.7, 6.1				
Ethoquad 18/25 + Duoquad T		AS ABOVE	AS ABOVE							25 ppm + 7 ppm	Mixed together before injection at usual point.	Scaling rate measurements made with full complement of specimens, including sections of 3/2" and 1/4" tubing placed at outlet of delay stage for 90°C data.	21	1.9				
Ethoquad 18/25 + HCl		AS ABOVE	AS ABOVE							27 ppm + 100 ppm	Mixed together before injection at usual point.	Scaling rate measurements made with full complement of specimens, including sections of 3/2" and 1/4" tubing placed at outlet of delay stage for 90°C data.	21	.35				
Ethoquad 18/25 + Duoquad T		AS ABOVE	AS ABOVE							35 ppm	Usual point of injection.		22.5	1.0				
FAE-HCl		AS ABOVE	AS ABOVE							35 ppm	Usual point of injection.		22.5	1.4				
Mirapol A-15 + Cycloeryl MA		AS ABOVE	AS ABOVE							20 ppm + 20 ppm	Presumably usual injection location at 220°C.	Scaling tests including scale thickness measurement and weight changes of coupons (tests 100 hr. too short for accurate comparisons by thickness measurements for 220°C tests). 60 hr. exposures at 125°C and 220°C, 7-22.5 hr. exposures at 90°C.	Control 7.9	6.7, 6.1				
Ethoquad 18/25 + Duoquad T		AS ABOVE	AS ABOVE							25 ppm + 7 ppm	Mixed together before injection at usual point.	Scaling rate measurements made with full complement of specimens, including sections of 3/2" and 1/4" tubing placed at outlet of delay stage for 90°C data.	21	1.9				
Ethoquad 18/25 + HCl		AS ABOVE	AS ABOVE							27 ppm + 100 ppm	Mixed together before injection at usual point.	Scaling rate measurements made with full complement of specimens, including sections of 3/2" and 1/4" tubing placed at outlet of delay stage for 90°C data.	21	.35				
Ethoquad 18/25 + Duoquad T		AS ABOVE	AS ABOVE							35 ppm	Usual point of injection.		22.5	1.0				
FAE-HCl		AS ABOVE	AS ABOVE							35 ppm	Usual point of injection.		22.5	1.4				
Mirapol A-15 + Cycloeryl MA		AS ABOVE	AS ABOVE							20 ppm + 20 ppm	Presumably usual injection location at 220°C.	Scaling tests including scale thickness measurement and weight changes of coupons (tests 100 hr. too short for accurate comparisons by thickness measurements for 220°C tests). 60 hr. exposures at 125°C and 220°C, 7-22.5 hr. exposures at 90°C.	Control 7.9	6.7, 6.1				
Ethoquad 18/25 + Duoquad T		AS ABOVE	AS ABOVE							25 ppm + 7 ppm	Mixed together before injection at usual point.	Scaling rate measurements made with full complement of specimens, including sections of 3/2" and 1/4" tubing placed at outlet of delay stage for 90°C data.	21	1.9				
Ethoquad 18/25 + HCl		AS ABOVE	AS ABOVE							27 ppm + 100 ppm	Mixed together before injection at usual point.	Scaling rate measurements made with full complement of specimens, including sections of 3/2" and 1/4" tubing placed at outlet of delay stage for 90°C data.	21	.35				
Ethoquad 18/25 + Duoquad T		AS ABOVE	AS ABOVE							35 ppm	Usual point of injection.		22.5	1.0				
FAE-HCl		AS ABOVE	AS ABOVE							35 ppm	Usual point of injection.		22.5	1.4				
Mirapol A-15 + Cycloeryl MA		AS ABOVE	AS ABOVE							20 ppm + 20 ppm	Presumably usual injection location at 220°C.	Scaling tests including scale thickness measurement and weight changes of coupons (tests 100 hr. too short for accurate comparisons by thickness measurements for 220°C tests). 60 hr. exposures at 125°C and 220°C, 7-22.5 hr. exposures at 90°C.	Control 7.9	6.7, 6.1				
Ethoquad 18/25 + Duoquad T		AS ABOVE	AS ABOVE							25 ppm + 7 ppm	Mixed together before injection at usual point.	Scaling rate measurements made with full complement of specimens, including sections of 3/2" and 1/4" tubing placed at outlet of delay stage for 90°C data.	21	1.9				
Ethoquad 18/25 + HCl		AS ABOVE	AS ABOVE							27 ppm + 100 ppm	Mixed together before injection at usual point.	Scaling rate measurements made with full complement of specimens, including sections of 3/2" and 1/4" tubing placed at outlet of delay stage for 90°C data.	21	.35				
Ethoquad 18/25 + Duoquad T		AS ABOVE	AS ABOVE							35 ppm	Usual point of injection.		22.5	1.0				
FAE-HCl		AS ABOVE	AS ABOVE							35 ppm	Usual point of injection.		22.5	1.4				
Mirapol A-15 + Cycloeryl MA		AS ABOVE	AS ABOVE							20 ppm + 20 ppm	Presumably usual injection location at 220°C.	Scaling tests including scale thickness measurement and weight changes of coupons (tests 100 hr. too short for accurate comparisons by thickness measurements for 220°C tests). 60 hr. exposures at 125°C and 220°C, 7-22.5 hr. exposures at 90°C.	Control 7.9	6.7, 6.1				
Ethoquad 18/25 + Duoquad T		AS ABOVE	AS ABOVE							25 ppm + 7 ppm	Mixed together before injection at usual point.	Scaling rate measurements made with full complement of specimens, including sections of 3/2" and 1/4" tubing placed at outlet of delay stage for 90°C data.	21	1.9				
Ethoquad 18/25 + HCl		AS ABOVE	AS ABOVE							27 ppm + 100 ppm	Mixed together before injection at							

TABLE 6

ADDITIVE					BRINE TEST CONDITIONS				ADDITIVE TEST CONDITIONS			TEST RESULTS																																																																																			
Trade Name	Manufacturer	Chemical Name/Formula	Chemical Class	Comments	Temperature	Pressure	Composition	Flow Rate	Comments	Concentration	Method and Location of Introduction	Comments	Quantitative Results		Additive Effectiveness	Comments	TEST CONCLUSIONS AND RECOMMENDATIONS																																																																														
Geomate 256	Dearborn	Proprietary additives	Phosphonate & polymer	Studies of other geothermal fluids and other industrial systems have shown that, in general, phosphonate-type compounds are effective in controlling scales formed from crystalline compounds such as CaCO ₃ , CaSO ₄ , and BaSO ₄ .	Wellhead temperature 200-200°C.	Wellhead pressure 290-320 psia.	3.60-4.12 Mol/l Cl ⁻ , 425-516 mg/kg SiO ₂ , density @ 25°C 1.145-1.163 g/cm ³ , pH 5.72-5.97	7.0 gpm (w/ 1b/s) in each test channel.	Used LLL's Scale Control Test System at Imperial Valley (Midland brine), Magnamax No. 1 well brine.	None, Control	Visual injection between 1st and 2nd stage separators (210°C). Samples taken from effluent of 125°C flash vessel. Additive solution flow maintained at .3 gpm. Injection w/8 ft. upstream of first test specimen.	Due to restricted time, only single concs. of each additive tested; the concs. used were decided on in consultation with manufacturers, and generally were the maximum cost-effective concs. likely to show beneficial effect. w/70 hr. tests for the proprietary additives. Natrosol was 113 hr. test. First control was 113 hr. and second control was 65 hr.	<u>125° Scaling</u> (Scale thickness in mils; scaling rate in mils/hr.) <table><tr><th colspan="2">Mild Steel</th><th colspan="2">Hastelloy</th><th colspan="2">Teflon</th></tr><tr><th>Total</th><th>Rate</th><th>Total</th><th>Rate</th><th>Total</th><th>Rate</th></tr><tr><td>24</td><td>.21</td><td>11</td><td>.10</td><td>12</td><td>.11</td></tr><tr><td>25</td><td>.38</td><td>4</td><td>.06</td><td>6</td><td>.09</td></tr><tr><td>18</td><td>.26</td><td>30</td><td>.43</td><td>31</td><td>.44</td></tr><tr><td>10</td><td>.14</td><td>17</td><td>.25</td><td>23</td><td>.33</td></tr><tr><td>9</td><td>.13</td><td>5</td><td>.07</td><td>7</td><td>.10</td></tr><tr><td>8</td><td>.10</td><td>22</td><td>.31</td><td>21</td><td>.10</td></tr><tr><td>12</td><td>.19</td><td>6</td><td>.09</td><td>8</td><td>.13</td></tr><tr><td>19</td><td>.30</td><td>7</td><td>.11</td><td>8</td><td>.13</td></tr><tr><td>15</td><td>.22</td><td>3</td><td>.05</td><td>5</td><td>.08</td></tr><tr><td>55</td><td>.83^a</td><td>24</td><td>.36^a</td><td>25</td><td>.38</td></tr><tr><td>17</td><td>.15</td><td>10</td><td>.09</td><td>15</td><td>.13</td></tr></table> (^a Plant upset caused higher rates)		Mild Steel		Hastelloy		Teflon		Total	Rate	Total	Rate	Total	Rate	24	.21	11	.10	12	.11	25	.38	4	.06	6	.09	18	.26	30	.43	31	.44	10	.14	17	.25	23	.33	9	.13	5	.07	7	.10	8	.10	22	.31	21	.10	12	.19	6	.09	8	.13	19	.30	7	.11	8	.13	15	.22	3	.05	5	.08	55	.83 ^a	24	.36 ^a	25	.38	17	.15	10	.09	15	.13	Neither Natrosol nor any of the proprietary additives had a very large effect on the scaling rates at 125 and 210°C when taken into account different scaling rates in the 2 test channels.	Comparison of test results complicated by differing scaling rates of the 2 test channels.	Tentative recommendation that Natrosol, Drawspere 747, and Bets 419 deserve further attention. Of the substance tested by LLL by the time of these tests, only Natrosol and the Ethomene have shown activity toward silica at 210°C. It should be noted that deposit inhibitors which operate to decrease scale adherence would not be expected to show retardation of silica precipitation. Thus, the incubation test is not regarded as valid for all approaches to scale control, but for all of the proprietary additives except Cortron R-16, the incubation test tended to corroborate their small effect on the scaling rates. In the case of the results for Natrosol, good performance in the incubation test may be a necessary, but not a sufficient condition, for reduction of scale. (Data on effect of additives on suspended solids also presented.) See Table 7 for a brief summary of these scaling and precipitation inhibition tests for the 8 proprietary additives.
Mild Steel			Hastelloy		Teflon																																																																																										
Total	Rate		Total		Rate	Total	Rate																																																																																								
24	.21		11		.10	12	.11																																																																																								
25	.38		4		.06	6	.09																																																																																								
18	.26		30		.43	31	.44																																																																																								
10	.14		17		.25	23	.33																																																																																								
9	.13		5		.07	7	.10																																																																																								
8	.10	22	.31	21	.10																																																																																										
12	.19	6	.09	8	.13																																																																																										
19	.30	7	.11	8	.13																																																																																										
15	.22	3	.05	5	.08																																																																																										
55	.83 ^a	24	.36 ^a	25	.38																																																																																										
17	.15	10	.09	15	.13																																																																																										
CL-165	Calgon	Polymer mixture	Scaling test temperatures of 125 and 210°C	Pressure at exit of 125°C 2nd stage separator where samples taken was w/15 psig.	↓	↓	↓	↓	35 ppm	↓	↓	2	.02	1	.01	5	.05																																																																														
Drawspere 747	Drew Chemical	Phosphonate & polymer	↓	↓	↓	↓	↓	↓	None, Control	↓	↓	5	.08	1	.02	2	.03																																																																														
Bets 419	Bets Labs.	Phosphonate	↓	↓	↓	↓	↓	↓	18 ppm	↓	↓	8	.10	2	.03	4	.05																																																																														
Thermosol APS	Far-East Corp.	Polyalkyl-phosphonate	↓	↓	↓	↓	↓	↓	15 ppm	↓	↓	10	.15	--	--	21	.30																																																																														
S-404	C-E Natco	Organic polymer	↓	↓	↓	↓	↓	↓	20 ppm	↓	↓	8	.10	11	.16	10	.14																																																																														
SC-210	Southwest Specialty Chemicals	Low molecular weight carboxylic acid	↓	↓	↓	↓	↓	↓	18 ppm	↓	↓	3	.04	--	--	4	.06																																																																														
Cortron R-16	Champion Chemicals	Filming Amine	↓	↓	↓	↓	↓	↓	20 ppm	↓	↓	4	.06	--	--	5	.08																																																																														
Natrosol 250LR	Hercules	Hydroxyethylcellulose	↓	↓	↓	↓	↓	↓	18 ppm	↓	↓	12	.20	12	.20	5	.08																																																																														
										10 ppm	↓	↓	10	.15	--	--	7	.11																																																																													
										20 ppm	↓	↓	8	.12	4	.06	4	.06																																																																													
										18 ppm	↓	↓	.5	.005	.5	.005	--	--																																																																													
													<u>210° Scaling</u>																																																																																		
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Mild Steel		Hastelloy		Teflon																																																																																											
Total	Rate	Total	Rate	Total	Rate																																																																																										
2	.02	1	.01	5	.05																																																																																										
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8	.12	4	.06	4	.06																																																																																										
.5	.005	.5	.005	--	--																																																																																										
													<u>SiO₂ retained (mg/kg)</u>																																																																																		
													<u>Incubation Time</u>																																																																																		
													<table><tr><th>0 min.</th><th>15 min.</th><th>30 min.</th></tr><tr><td>481</td><td>264</td><td>213</td></tr><tr><td>460</td><td>236</td><td>203</td></tr><tr><td>454</td><td>241</td><td>191</td></tr><tr><td>448</td><td>222</td><td>213</td></tr><tr><td>467</td><td>271</td><td>212</td></tr><tr><td>467</td><td>246</td><td>203</td></tr><tr><td>464</td><td>252</td><td>184</td></tr><tr><td>473</td><td>252</td><td>199</td></tr><tr><td>470</td><td>252</td><td>203</td></tr><tr><td>466</td><td>247</td><td>206</td></tr><tr><td>462</td><td>447</td><td>388</td></tr></table>		0 min.	15 min.	30 min.	481	264	213	460	236	203	454	241	191	448	222	213	467	271	212	467	246	203	464	252	184	473	252	199	470	252	203	466	247	206	462	447	388																																													
0 min.	15 min.	30 min.																																																																																													
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470	252	203																																																																																													
466	247	206																																																																																													
462	447	388																																																																																													
Geomate 256	←	AS ABOVE			↓	↓	↓	↓	↓	None, Control	↓	Precipitation inhibition tests with 0 min., 15 min., and 30 min. incubation times.	481	264	213	Only Natrosol has significant effect on rate of SiO ₂ precipitation.	↓																																																																														
CL-165	←	AS ABOVE			↓	↓	↓	↓	↓	None, Control	↓	↓	460	236	203	↓																																																																															
Drawspere 747	←	AS ABOVE			↓	↓	↓	↓	↓	35 ppm	↓	↓	454	241	191	↓																																																																															
Bets 419	←	AS ABOVE			↓	↓	↓	↓	↓	18 ppm	↓	↓	448	222	213	↓																																																																															
Thermosol APS	←	AS ABOVE			↓	↓	↓	↓	↓	15 ppm	↓	↓	467	271	212	↓																																																																															
S-404	←	AS ABOVE			↓	↓	↓	↓	↓	20 ppm	↓	↓	467	246	203	↓																																																																															
SC-210	←	AS ABOVE			↓	↓	↓	↓	↓	20 ppm	↓	↓	464	252	184	↓																																																																															
Cortron R-16	←	AS ABOVE			↓	↓	↓	↓	↓	18 ppm	↓	↓	473	252	199	↓																																																																															
Natrosol 250LR	←	AS ABOVE			↓	↓	↓	↓	↓	10 ppm	↓	↓	470	252	203	↓																																																																															
					↓	↓	↓	↓	↓	20 ppm	↓	↓	466	247	206	↓																																																																															
					↓	↓	↓	↓	↓	18 ppm	↓	↓	462	447	388	↓																																																																															

TABLE 7 - Reference 7

ADDITIVE					BRINE TEST CONDITIONS					ADDITIVE TEST CONDITIONS					TEST RESULTS					TEST CONCLUSIONS										
Trade Name	Manufacturer	Chemical Name/ Formula	Chemical Class	Comments	Temperature	Pressure	Composition	Flow Rate	Comments	Concentration	Method and Location of Introduction	Comments	Quantitative Results					Additive Effectiveness	Comments	AND RECOMMENDATIONS										
													% Reduction of Scale on Mild Steel																	
													Pipe 210°C Pipe 125°C 90°C precipitation Spool Coupon Spool Coupon test																	
Geogate 256	Dearborn	Proprietary additives	Phosphonate & polymer	Well temps. 209-209°C. Scaling tests at 125 and 210°C, precipitation test at 90°C. Wellhead pressure 250-315 psia. 3.60-4.12 Mol/l Cl ⁻ , pH 5.72-5.96, density @ 25°C 1.145-1.163 g/cm ³ , 425-516 mg/kg SiO ₂ . 7.0 gpm in test chemicals Used LLL's Scale Control Test System at Imperial Valley (Wiland brine), Magmax No. 1 well brine.	Wellhead pressure 250-315 psia.	3.60-4.12 Mol/l Cl ⁻ , pH 5.72-5.96, density @ 25°C 1.145-1.163 g/cm ³ , 425-516 mg/kg SiO ₂ .	7.0 gpm in test chemicals	Used LLL's Scale Control Test System at Imperial Valley (Wiland brine), Magmax No. 1 well brine.	—	35 ppm	Usual LLL procedure	Additive conc. maintained within ± 10%.	—	0	0	0	32	No effect	Apparent 125°C reduction. No precipitation effect.	210°C results possibly due to additive decomposition.	From the results of the tests of proprietary additives, i.e., the chemical mixtures and the Austral-Erwin process, we conclude that none of these brine treatments have a very beneficial effect on the rates of scaling from the brine of Magmax No. 1 well. Among the chemical additives, Southwest Specialty Chemical's SC-210 shows marginal promise, and a modification of the method of addition of the Austral-Erwin additive might be more effective than the one we tested. Its principal effect is in altering the consistency and adherence of the scale.									
CL-165	Calgon		Polymer mixture							—				18 ppm	Additive solution flow ~.020-.040 gpm	0	0 ^a	0				32	No effect							
Drewspers 747	Drew Chemical		Phosphonate & polymer							—				15 ppm		0	0 ^a	30				50	No effect							
Petz 419	Betz Labs.		Phosphonate & acrylic polymer							—				20 ppm		0	0	0				52	No effect							
Thermosol APS	Far-Best Corp.		Polyalkylphosphonate							—				20 ppm		30	30	0				50	No effect							
S-604	C-E Natco	Proprietary additives	Organic polymer	Injected at 210°C with 90°C precipitation test.	Assume as above.	—	—	—	18 ppm	Usual LLL precipitation test procedures.	As above. None of these subjected to complete scale-abatement test.	—	0	0	0	21	No effect	Apparent 125°C reduction. No precipitation effect.	210°C results possibly due to additive decom- position. Effective at 125°C on both spool and coupon.	Although not detailed here, our parallel studies of generic chemical compounds for geothermal scale control have led to a number of types of compounds that inhibit the precipitation of silica and scale formation at the lower temperatures. ^{3-6,18} Cationic (nitrogen-containing) polymers and surfactants, and compounds containing polyoxyethylene are the most promising. ¹⁸ Two of these compounds were found to retard the growth of the 125°C scale by a factor of 2 to 4, and the 90°C scale by a factor of 10. Combi- nation of silica precipitation inhibitors with mild acidification is also very effective. Acidification remains as the only method found that reduces the scale formed at 210°C.										
SC-210	Southwest Spe- cialty Chemicals		Low molecular weight carboxylic acid						—				10 ppm	0	0 ^a	80	42				No effect									
Cortron R-16	Champion Chemicals		Filming amine						—				20 & 120 ppm	0	0	0	0				No effect									
Polysperse Plus	Betz Labs		?						Experiments at GLEF by NUS Corp. indi- cated SiO ₂ precipi- tation activity.				—	40 ppm	No quantitative results reported	None of these showed any activity toward silica at 90°C.	Polysperse Plus failed these tests, and no reason was found for the disagreement with NUS' results at GLEF.				—	—	—	—	—	—	—	—	—	These anionic-type polymer water treatment additives do not appear promising for hypersaline geothermal brine.
Geogate 259	Dearborn Chemical		?						—				40 ppm																	
XFS-43075	Dow Chemical	?	—	20 ppm																										
XD-30469.00	Dow Chemical	Copolymer of acrylic acid and hydroxyethyl- acrylate	—	20 ppm																										
Darex 41s	M. R. Grace	Proprietary additives	Carboxylated polyelectrolyte	Represent industry's best guess as to effective anti- scalants for hyper- saline geothermal brine. Most are anionic-type poly- mers traditionally used in various water treatment applications.	Wellhead temp. 203-15°C.	Wellhead pressure 254-309 psia.	3.52-3.67 Mol/l Cl ⁻ , pH 5.83-5.95, density @ g/cm ³ 1.141-1.149 g/cm ³ , 461-79 mg/kg SiO ₂	As above, but LLL sole user of well (GLEF not operating) and, as usual in this case, brine is less concen- trated and scaling rates lower than when well at full flow.	N/A	Water @ 2 gal./hr. and oil- additive mixture @ ~.3 gal./day as fine spray at entrance to brine at usual 210°C location.	In theory, the process is said to involve a reaction of the fatty acids in the oils with the calcium of the brine to form a soap. In addition, the surface active compounds thus formed, or present in the emulsion, are supposed to coat the metal of the plant and render it hydrophobic. This surface then would have a tendency to repel colloidal silica, which is hydrophilic in nature, thus retarding its adherence and the formation of scale.	210°C, 125°C, and 90°C scaling tests (65 hr. exposure); 90°C precipitation inhibition test (usual procedure).	Scaling Rates at 210°C (mil/hr)					Only in the pipe spool at 210°C was the scaling rate lower than untreated brine.	It appears that the Austral-Erwin process may decrease the adherence of the scale on surfaces such as the pipe spools where there is a high velocity flow without excessive eddies. At points where the flow velocity is lower (e.g., in the 2-in pipe), and where there is turbulent flow such as around our specimen coupons, the accumulation of solids is increased. Except for the effect on altering the consis- tency and adherence of the scale, this process was generally not very satisfactory.											
Visco 3744	Nalco Chemical		Acrylic polymer and surfactant										—	20 ppm	Coupons															
Belclene 200	Ciba-Geigy		Low MW carboxylic acid										—	20 ppm	Steel Pipe Spool Steel Hastelloy Teflon															
Pyronate 40	Witco Chemical		Low MW alkyl aryl sulfonate										—	20 ppm	Untreated ^a 0.07 0.05 0.02 0.02															
Austral-Erwin Process	Austral-Erwin Co.		Water emulsion of proprietary mixture of cottonseed oil with small amounts of tall oil and other additives which aid in emulsi- fying the oils.										Had shown promise at Cerro Prieto and Brawley fields.	—	20 ppm	Austral-Erwin ^b 0.02 0.08 0.10 0.08														
													Scaling Rates at 125°C (mil/hr)																	
													Coupons																	
													Steel Pipe Spool Steel Hastelloy Teflon																	
													Untreated ^a 0.11-0.16 0.10 0.03 0.04																	
													Austral-Erwin ^b 0-0.96 0.60 0.10 0.12																	
													Scaling Rates at 90°C																	
													No Quantitative Results Reported																	
													Precipitation at 90°C																	
													No Quantitative Results Reported																	

TABLE 8 - Reference 10 (Carbonate Scale

ADDITIVE					BRINE TEST CONDITIONS					ADDITIVE TEST CONDITIONS			TEST RESULTS					TEST CONCLUSIONS AND RECOMMENDATIONS	
Trade Name	Manufacturer	Chemical Name/Formula	Chemical Class	Comments	Temperature	Pressure	Composition	Flow Rate	Comments	Concentration	Method and Location of Introduction	Comments	Quantitative Results		Additive Effectiveness	Comments	TEST CONCLUSIONS AND RECOMMENDATIONS		
Dequest 2060	Monsanto	Diethylenetriamine pentamethylene phosphonic acid	Phosphonate	Carbonate scale inhibitor															
↓	↓		↓	↓					Tests carried out at 2 wells in Republic Geo-thermal, Inc.'s field at East Mesa. Test set-ups at both wells included test loops with 4 pipe spools, each with different orifice plates to carefully control pressure and temperature. Both loops located upstream of separator. Downhole pump.								The formation of CaCO ₃ scale at RGI's East Mesa wells and facilities can be prevented by even less than 1.0 μl/l Dequest 2060. Pseudo-scale (calcium phosphonate) formed at concentrations >7.5 μl/l additive.		
↓	↓		↓	↓															
					Wellhead 320°F (baseline test) (160°C)	Wellhead 220 psig (baseline test)	Not reported.	Average Production rate of 375,000 lb/hr.	TEST AT WELL #16-29	10 μl/l	Constant flow injection approximately 10 feet downstream of wellhead.	Dilution of 1 part inhibitor to 3 parts produced water used. Specific weight of delivered additive was 1.4 and activity was 50%.	93-hr. Untreated Brine Test		Additive reduced scale by a factor of at least 20; in addition, no scale was formed either upstream or downstream of test loop.	CaCO ₃ deposition was completely eliminated in the test loop. Scale that was present was a pseudo-scale formed by reaction of the additive and Ca ions in brine to form fairly insoluble Ca salt. Formation of pseudo-scale was still vast improvement over untreated brine.			
					304°F (151°C)	64 psig			Spool 1	↓	↓	↓	SPOOL NO. (STARTING UPSTREAM)	SPOOL LENGTH IN FEET	SCALE THICKNESS IN INCH TOP: BOTTOM	AVERAGE SCALE THICKNESS IN INCH			
					296°F (143°C)	32 psig			Spool 2	↓	↓	↓	1	10	1/64; 1/64	0.0625			
					256°F (121°C)	23 psig			Spool 3	↓	↓	↓	2	12	1/16; 3/8	0.22			
					245°F (118°C)	14 psig			Spool 4	↓	↓	↓	"Horn"	10	1/16; 3/8	0.22			
					↓	↓							3	12	3/8; 1/2	0.44			
					↓	↓							4	10	1/8; 3/16	0.156			
					↓	↓							AVERAGE	54		0.22			
													110.5-hr. Test @ 10 μl/l additive						
													SPOOL NO. (STARTING UPSTREAM)	SPOOL LENGTH IN FEET	MAXIMUM SCALE THICKNESS IN INCH TOP: BOTTOM	AVERAGE SCALE THICKNESS IN INCH			
													1	10	1/16** 1/16**	approx. 1/64			
													2	12	1/16-1/32 1/16-1/32	1/16-1/32			
													"Horn"	10	1/16-1/32 1/16-1/32	1/16-1/32			
													3	12	NONE NONE	NONE			
													4	10	NONE NONE	NONE			
													AVERAGE	54		approx. 0.01			
													** Scale extended only 2 feet from each end into spool. Center of spool was clean.						
									Test at 2.5 μl/l limited to 24 hrs. due to operational problem.	2.5 μl/l			No quantitative results reported because no scale produced anywhere in loop.		No scale anywhere in loop.	This 24-hr. test may have been too short to produce realistic results, but result encouraging.			
					Wellhead 315-316°F (158°C)	Wellhead 142-147 psig	4.9-5.0 mg/l Ca, 530-40 mg/l Cl ⁻ , pH 7.2-7.9, 140 mg/l SiO ₂ .	Average production rate of 722,000 lb/hr.	TEST AT WELL #56-30		Not detailed - Test system differed from other well.		108-hr. Untreated Brine Test						
					315-316°F (156°C)	117 psig			Spool 1	7.5 μl/l			SPOOL NO. (STARTING UPSTREAM)	SPOOL LENGTH IN FEET	AVERAGE SCALE THICKNESS IN INCH				
					312°F (156°C)	88-90 psig			Spool 2	↓			1	18	Thin Film				
					--	74-75 psig			Spool 3	↓			2	18	Thin Film				
					298°F (148°C)	55 psig			Spool 4	↓			3 ("Horn")	8.75	0.10				
					266°F (130°C)	24-26 psig			Spool 5	↓			4	18	1.25				
						↓							5	18	1.50				
						↓							Average	80.75	0.62				
						↓							No quantitative results reported						
										2.0 μl/l				↓					
										↓				↓					
										↓				↓					
										1.0 μl/l									
			</																

ADDITIVE				BRINE TEST CONDITIONS					ADDITIVE TEST CONDITIONS			TEST RESULTS					
Trade Name	Manufacturer	Chemical Name/ Formula	Chemical Class	Comments	Temperature	Pressure	Composition	Flow Rate	Comments	Concentration	Method and Location of Introduction	Comments	Quantitative Results		Additive Effectiveness	Comments	TEST CONCLUSIONS AND RECOMMENDATIONS
REF. 25 Dearborn 8010 Calgon CL-77W Calgon SL-500 Drexplex 502 Dearborn 8010	Alphabetical listing stops here.			Threshold-type Threshold-type Chelating-type Threshold-type	Wellhead 300-40°F (149-171°C) ↓ ↓ ↓ ↓	Not reported. ↓ ↓ ↓ ↓	Compositions of brines from 4 wells reported, but the report does not relate them to the tests or results. 500-16, 850 mg/l Cl ⁻ , 269-389 mg/l SiO ₂ , pH 5.45-6.27, 1,600-23,600 mg/l TDS. Concentrations of variety of other constituents reported.	Not reported. ↓ ↓ ↓ ↓	Tests carried out on East Mesa brine from 4 wells to screen 4 chemicals for inhibi- ting activity toward CaCO ₃ and BaSO ₄ scales in a vertical tube evaporator in desalina- tion process.	25-30 ppm 25-30 ppm 70-80 ppm 25-30 ppm 10 ppm gradually down to 2-3 ppm	Not reported. ↓ ↓ ↓ ↓		Average % Recovery <u>Calcium</u> 140 82 128 105 No quantitative results reported.	<u>Barium</u> 104 65 65 87	Completely kept Ba in sus- pension and apparently cleared some Ca off surfaces Effectiveness near Dear- born 8010. ≤5 ppm led to plugging of VTE tube nozzles with CaCO ₃ .	Crude test with no real analysis.	Reference 25 ↓ ↓ ↓ ↓
REF. 29 CaO (slaked lime) + hypochlorite + polyflok 90 AP (flocculant) ↓ 																	