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REMOVAL OF SILICA FROM
RAFT RIVER GEOTHERMAL WATER

MASTER

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ABSTRACT

Lack of sufficient quantities of clean surface or near-surface water at Raft River for cooling purposes dictates that cooled geothermal fluid, effluent from the Raft River 5 MW(e) Pilot Power Plant, must also be used as condenser coolant. Prior testing revealed that a water-treatment system would be required to reduce silica and calcium concentrations of the cooling fluid. The water-treatment system specified by the Department of Energy's Architect-Engineer was to use dolomitic lime for both pH adjustment and source of magnesium. The dolomitic lime treatment was investigated and found to be inadequate. Subsequent testing was done to find chemical systems that would adequately reduce silica concentrations.

Three magnesium and two iron compounds were found which reduced silica to acceptable concentration levels. They are magnesium bicarbonate, magnesium chloride, magnesium sulfate, iron sulfate, and iron chloride. Magnesium oxide, using a two-stage countercurrent process, will also reduce silica to adequate levels.

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REMOVAL OF SILICA FROM RAFT RIVER GEOTHERMAL WATER

1. INTRODUCTION

The 5 MW(e) Pilot Power Plant at Raft River is of conventional design with cooling provided by evaporation in a cross-flow cooling tower. This plant differs from other conventional power plants by its use of geothermal water as cooling fluid because of restrictions on the consumptive use of cold aquifer or clean surface waters in the Raft River Valley.

Raft River geothermal water has a high concentration of silica, a major scale former, and its use requires means to limit silica scaling. Standard procedures nominally employ a process called blowdown, by which build-up of silica and other detrimental substances can be regulated by partial removal and dilution. Also, because cooling is by evaporation, water loss must be supplemented by additional water which, in the present system, would be geothermal water with its attendant high silica concentrations. Additional losses occur from wind blowing a portion of the water mist out of the cooling tower. In steady-state operation, the amount of geothermal water added, termed make-up, is the sum of blowdown, evaporation, and wind losses.

Thus, to use geothermal water as coolant for the 5 MW(e) Pilot Power Plant will require means to effectively control silica levels within both coolant and make-up water.

The ratio of silica concentration in the recirculating coolant to its concentration in the make-up is termed "cycles of concentration." This ratio will always be greater than unity owing to the build-up of silica in the recirculating fluid from evaporation and solubility changes during cooling.

A communication (April 20, 1977) from Betz Laboratories, Inc.,¹ stated that it was not possible to control silica scaling by use of dispersants alone and that the best way to handle the problem is to keep

silica at low concentrations (<100 ppm). Because silica concentrations in Raft River geothermal water range from 160 to 200 ppm, use of geothermal water requires that silica concentration be reduced. If the silica content after initial reduction is sufficiently low, some of the costs of this approach can be tempered by use of high cycles of concentration which effectively reduce quantities of make-up required. The volume of make-up required as a function of cycles of concentration has been calculated by Nguyen;² his data are shown in Table 1 and Figure 1.

TABLE 1. MAKE-UP AND BLOWDOWN RATES FOR DIFFERENT CYCLES OF CONCENTRATION

Number of cycles ^a	Make-up		Blowdown rate	
	<u>L/s</u>	<u>gpm</u>	<u>L/s</u>	<u>gpm</u>
1				
2	38.82	616.00	18.43	292.60
3	29.11	462.00	8.73	138.60
4	25.87	410.67	5.50	187.27
5	24.26	385.00	3.88	61.60
6	23.28	369.60	2.91	46.20
7	22.64	359.33	2.26	35.93
8	22.83	352.00	1.80	28.60
9	21.83	346.50	1.46	23.10
10	21.56	342.22	1.19	18.82

a. Temperature change is 36 K (20°F).

Conventional water-treatment systems use magnesium oxide to remove silica, and lime to control pH. Dolomitic lime is frequently used because it provides both MgO and Ca(OH)₂. This method, using a warm-lime softening unit, was proposed by the Architect-Engineer for the Raft River plant.

This report addresses the problem of removing silica from geothermal water by using the system described above. The Architect-Engineer's recommendation was tested and results conclusively demonstrated it to be totally

Figure 1. Volume of make-up required at various cycles of concentration.

inadequate. Thereafter, other sorption-based schemes were investigated to determine effective silica removal techniques, especially those which could reduce silica levels to 10-15 ppm and thereby permit five to ten cycles of concentration to be used.

2. LITERATURE SEARCH

Both Chemical Abstracts and the Engineering Index were researched to gather information on the removal of silica from water. Owing to high silica levels and the chemical composition of geothermal water, only a few of the articles had direct application to the Raft River chemical pre-treatment program. Thus, the Literature provided general guidelines only for interpreting data and establishing test parameters.

2.1 Silica Reduction Mechanisms

Silica is removed by sorption onto magnesium hydroxide particles as they precipitate from solution. The silica sorption reaction is complex; the exact mechanism is not known. The reaction varies with pH, temperature, and form or composition of magnesium compound; however, no silica reduction occurs below the pH at which magnesium hydroxide normally precipitates.³

According to Krauskopf,⁴ the silicic acid monomer (H_4SiO_4) is the dominant species in solution over a pH range of 0-9 and has a solubility of 100-140 ppm at 298 K. Above pH 9, the solubility increases as the silicic acid dissociates according to the following equilibrium reactions at 298 K.

By convention the equilibrium constant is

$$K = \frac{\text{concentration of products}}{\text{concentration of reactants}}$$

and the pK term is defined as

$$pK = \log_{10} \frac{1}{K}$$

For weak acids, at the point where the molar concentrations of the ionic species become equal, the pK and pH values coincide. For example, using the equation above, we have

$$K = \frac{[H_3SiO_4^{-1}][H^+]}{[H_4SiO_4]}$$

which reduces to

$$K = [H^+]$$

at pH = 9.7, since $[H_4SiO_4^{-2}]$ and $[H_3SiO_4^{-1}]$ become equal. Thus,

$$pK = \log_{10} \frac{1}{K} = \log_{10} \frac{1}{[H^+]} = pH = 9.7.$$

The temperature dependence of the dissociation constants has been determined by Ryzhenko⁸ to be

$$pK_1 = \frac{3405.9}{T} - 6.368 + 0.0163436T$$

for T varying from 0 to 350°C,

and

$$pK_2 = \frac{8949.2}{T} - 33.000 + 0.049580T$$

for T varying from 0 to 250°C.

The first ionized form of silicic acid ($\text{H}_3\text{SiO}_4^{-1}$) is the active species in silica reduction.

2.2 pH Effect

Any increase in hydroxide alkalinity above pH 9 will increase the concentration of ionized forms of silicic acid. Therefore, increasing pH should increase silica reduction up to some optimum pH value. Betz et al.⁹ treated water samples having silica contents varying from 7.1 to 26.2 ppm with magnesium oxide. Their tests covered a pH range of 9.5 to 10.6. They concluded that the optimum pH for silica reduction is 10.1. They also stated that as residual silica in the treated water decreases, control of pH becomes less important.

Wey and Siffert¹⁰ treated solutions containing 140 ppm silica with equivalent amounts of magnesium chloride and determined that the maximum precipitation of silica occurred in the pH range 11.0-11.5.

Mujeriego⁶ treated water containing 100 and 140 ppm silica with several metals, including magnesium, and concluded that reaction pH is the single most important parameter governing silica removal by sorption on all of the hydrous metal oxides studied. He states that in the temperature range from 303 to 313 K (86-104°F), the optimum silica removal occurs at a pH given by the expression

$$\text{pH}_{\text{optimum}} = \frac{\text{pK}_1 + \text{pK}_2}{2} .$$

2.3 Effect of Magnesium Type

2.3.1 Dolomitic Lime

The use of dolomitic lime for removal of silica has several advantages. It is inexpensive and provides both magnesium (37 weight percent

MgO) for silica removal and lime (58 weight percent Ca(OH)_2) for pH adjustment.

Behrman and Gustafson¹¹ treated identical water samples containing 17 ppm silica as follows: one sample was treated with a high calcium lime, the second with dolomitic lime in the amount required to produce the same quantity of calcium hydroxide as in the first sample. They reported that the concentration of residual silica in both samples was 10 ppm and concluded that (a) dolomitic lime is not effective in reducing silica and (b) magnesium hydroxide to be really effective must be formed in situ.

Betz et al.⁹ indicated that dolomitic lime has merit for removal of silica under controlled conditions, although the process alters the water chemistry in such a way as to make the process impractical.

Crossan¹² treated Mississippi River water with dolomitic lime and found that dolomitic lime (on the basis of equivalent magnesium) was at least one-half as effective as ionic magnesium. For water samples with silica content over 4.5 ppm, even better results were obtained.

2.3.2 Nondissolved Magnesium Compounds

There are a number of commercially available sources of magnesium. They include soluble salts of magnesium, such as magnesium chloride, and insoluble magnesium compounds, such as dolomitic lime, magnesium carbonate, and various grades of magnesium oxide. The difference between the two forms is that when a soluble magnesium salt is used, the magnesium hydroxide must be generated by a pH adjustment.

2.3.3 Dissolved Magnesium Compounds (Salts)

The concept of generating the magnesium hydroxide in situ for increased effectiveness in silica reduction has sound basis in the literature. There is, however, some disagreement as to the actual percentage increase in silica removal attributable to soluble magnesium salts

over that of insoluble magnesium compounds. The previously noted literature generally concurs with Wohlberg and Buchholz,¹³ "... silica in water is a metastable system whose behavior is difficult to predict."

3. DESIGN SPECIFICATIONS

Facility Systems Engineering Corp. (FSEC) of Los Angeles was selected as the Architect-Engineer for the 5 MW(e) Pilot Power Plant. FSEC (on the recommendation of their consultant, Garrett Energy Research and Development, Inc.) specified that a conventional warm-lime softener unit would be adequate for water-treatment requirements. A Cochrane Warm Process Water Softener Design "UW3" or equivalent, of 21.8 L/s (346 gpm) capacity will be the system used for the water pretreatment operation.

Chemical reagents specified include dolomitic lime for both pH adjustment and silica removal and soda ash for calcium reduction. Design specifications for inlet and outlet water quality are:

	<u>Inlet Water</u>	<u>Outlet Water</u>
Total silica, as SiO ₂ (ppm)	180	10-15
Total calcium, as CaCO ₃ (ppm)	93.9	342.8
Total bicarbonate, as CaCO ₃ (ppm)	49.8	0
Total (OH) alkalinity, as CaCO ₃ (ppm)	0	156.9

4. EXPERIMENTAL PROCEDURE

The principal method used to study silica removal was to mix cooled geothermal fluid with chemicals used in the treatment test in amounts and sequence required to form the magnesium silicate-magnesium oxide-calcium hydroxide slurry. Flocculation of precipitated materials was used to simulate typical industrial practice. The apparatus and technique used are described below.

The treated and clarified water fraction of the slurry was analyzed to determine changes in chemical composition. The chemical components (species) determined were silica, pH, calcium concentrations, and alkalinity. Methods used are described below.

4.1 Jar Tests

Tests were conducted in accordance with ASTM D-2035-74 (Coagulation-Flocculation Jar Test of Water),¹⁴ using a Phipps and Bird Model 7790-300 six-paddle stirrer. Test apparatus consisted of a constant temperature bath, six 2-litre beakers, and the Phipps and Bird test stirrer. The beakers, each containing 1.8 litres of geothermal water, were placed in the constant temperature bath and were allowed to come to thermal equilibrium. Chemical reagents, as solutions or slurries, were added to each beaker in the quantities and sequence required for each test. Deionized water was added to bring the total volume in each beaker to two litres. Each system was flash-mixed for one minute by using a paddle velocity of 120 rpm, with velocities then reduced to 20 rpm or just rapid enough to keep the resulting floccules in suspension and stirred for fifteen minutes. The beakers were removed from the constant temperature bath and the water samples filtered. The water samples were chemically analyzed for silica, calcium, pH, and alkalinity. Analyses were performed, according to procedures recommended by the Hach Company¹⁵ for water analysis, using reagents that are marketed commercially.

4.2 Chemical Analysis

Silica concentrations were determined as silicomolybdates, using a Beckman Model B spectrophotometer. A calibration curve (Figure 2) was generated by using standard solutions of 1 and 10 ppm silica. A sample of untreated water diluted with distilled water, in the ratio of 1 to 25, gives a percent transmittance between the two standards. The initial silica concentration was then determined and used in subsequent dilutions (2:25, 5:25, etc.). A plot of the log of percent transmittance versus concentration was then used to determine the silica concentration.

Calcium was determined by titrating 50-cm³ samples of treated water with a standard solution of 0.02 N EDTA.^a Alkalinity was determined by titrating 50-cm³ samples of treated water with 0.02 N sulfuric acid. The latter titration was performed by using an automatic titrator to a pH of 4.8. Calcium concentrations are reported as ppm CaCO₃; alkalinities are reported as ppm CaCO₃.

a. EDTA = (Ethylenedinitrilo)tetraacetic acid or ethylenediaminetetraacetic acid.

Figure 2. Log percent transmittance versus concentration of silica.

5. EVALUATION OF SYSTEM SPECIFIED BY THE ARCHITECT-ENGINEER

As noted in Section 3, FSEC specified a dolomitic lime treatment system using a conventional warm-lime softener unit for the silica removal operation. This section addresses test results of the above-mentioned system.

5.1 Dolomitic Lime

The use of dolomitic lime for silica reduction has the distinct advantage of being an inexpensive source of magnesium. It also contains calcium hydroxide which is used to adjust pH. The disadvantage is that the magnesium oxide concentration cannot be varied without changing the pH. To evaluate dolomitic lime, the concentration in the geothermal fluid was varied from 0 to 1200 ppm. Table A-1 summarizes the data with the respective concentrations of magnesium oxide and calcium hydroxide listed as ppm MgO and CaO, respectively.

5.2 Effect of pH and Magnesium

Results (Figure 3) show that silica reduction to desired levels was not achieved, at least in the concentration and pH range covered. The increase in residual silica at pH 11.0 was unexpected; it had been anticipated that any increase in magnesium would result in some additional silica removed. This increase in residual silica at pH 11.0 was observed in other tests run with dolomitic lime and other forms of magnesium oxide, and it was noted in those tests that a pH of 10.9 or 11.1 was never reached. This would indicate that at pH 11.0 an equilibrium is being established with the silica in solution as a partially soluble complex, or that the magnesium is complexed in some way that makes it unavailable to react with the silica. The decrease in silica above pH 11.0 is attributed to silica precipitation as a calcium compound.

Figure 3. Water treated with lime at 60°C.

5.3 Temperature Effect

Increases in temperature are known to increase the effectiveness of magnesium in reducing silica. If increased temperature resulted in a significant increase in silica reduction, the hot (403 K, 266°F) geothermal water could be mixed with the power plant effluent to raise the temperature prior to its entering the lime softener. Test results show that a temperature increase from 323 to 353 K (50 to 80°C) resulted in an increase in silica removed, from 42 to 55 percent of the initial silica concentration. The lowest residual silica, 65 ppm, occurred at a pH of 10.5 and a temperature of 353 K (80°C); the highest, 143 ppm, at a pH of 10.8 and a temperature of 323 K (50°C). Data for the four temperatures (50, 60, 70, and 80°C) evaluated are listed in Table A-2. The magnesium oxide concentrations were held constant at 200 ppm MgO for plant operating economy as well as to reduce the time required for

testing and chemical analysis. Also, in this test, and many subsequent tests, the pH did not exceed 10.8. It is not economical, on a large scale, to operate in the higher pH range as this would require additional soda ash for hardness reduction and sulfuric acid for pH reduction to 6.5 as specified for the recirculating coolant.

6. EVALUATION OF MAGNESIUM OXIDE SYSTEMS

Results of the design basis water-treatment system tests (Tables A-1 to A-6) suggest that additional testing be done to determine what modifications of the chemical pretreatment system would be required to reduce silica concentration to acceptable levels. In this regard, additional systems were investigated to find a pretreatment program capable of producing water of required quality.

6.1 Effect of Grade of Magnesium Oxide

Three commercially marketed grades of magnesium oxide (Remosil,^a heavy, and light) were obtained to determine what effect the grades of magnesium have on silica reduction. The magnesium oxide concentration was held constant at 200 ppm and the pH was varied, by lime additions, from 10.2 to 10.8 in each test set.

The Remosil is slightly more efficient in silica removal than either the light or heavy grades of magnesium oxide (Table A-3). The difference between Remosil and heavy grade is only five percent, with a residual silica content of 65 and 74 ppm, respectively, at pH 10.5. Remosil is approximately 20 percent more effective in silica reduction than dolomitic lime at equal magnesium oxide concentration and pH. The heavy and light grades are comparable to each other.

6.2 Temperature Effect Evaluation Using Remosil

Remosil was selected for evaluation of the temperature effect, since it was slightly more effective in silica reduction than the light and heavy grades of magnesium oxide (Table A-3). The same test procedure of holding magnesium oxide addition constant and varying pH by lime addition was followed. The temperature range covered was 323 to 353 K (50-80°C).

a. Remosil is a light grade of magnesium oxide marketed by Betz Laboratories.

Maximum silica reduction occurred at 353 K (80°C) and a pH of 10.2; the residual silica was 68 ppm and corresponded to a silica reduction of 56 percent from the untreated water. The minimum silica reduction occurred at 323 K (50°C) and a pH of either 10.2 or 10.5, the residual silica being 138 ppm, representing a reduction of only 11 percent. The silica content of the feed water was 155 ppm. Data are listed in Table A-4. The most significant feature of the data is the large amount of lime required for pH adjustment at 353 K, compared to that required at 323 K; the ratio is approximately 3 to 1. A similar observation was seen for dolomitic lime (Table A-2) and indicates that any increase in silica reduction with increasing temperature would be offset by the cost of additional lime and soda ash required for pH adjustment and calcium removal.

6.3 Dolomitic Lime Plus Remosil

Due to the large amount of $\text{Ca}(\text{OH})_2$ in the dolomitic lime, the possibility exists of adjusting pH with dolomitic lime, and using a second source of magnesium oxide to achieve the desired reduction in silica. Table A-5 shows results of tests for this hypothesis. In these tests, the magnesium oxide concentrations were held constant at 250 ppm and the pH varied from 10.2 to 10.8. Test samples 1 and 4, 2 and 5, 3 and 6 have identical chemical additions. Duplicate tests were run to determine the reproducibility of results.

The lowest residual silica level was 75 ppm, indicating that the system will not adequately remove silica. The silica reductions in this test series are within 3 percent of each other. The chemical analysis data indicate that possibly a slight excess of dolomitic lime may have been added to Sample 2. Acceptable levels of silica could not be achieved when using geothermal fluid, no matter what level of magnesium oxide was used.

6.4 High Concentrations of Magnesium Oxide

A final magnesium oxide test was run at higher magnesium concentrations, to 750 ppm MgO, to determine what level is required to reduce silica to acceptable levels. Data (Table A-6) show that silica reduction to 73.5 ppm (64 percent removal) at a pH 10.2 and magnesium oxide dose of 625 ppm is neither efficient nor economical.

6.5 Preliminary Conclusions of Magnesium Oxide Systems

Reduction of silica to required levels cannot be achieved with either dolomitic lime, the various grades of magnesium oxide, or any combinations. This suggests that either further testing be done with other chemical reagents or that the lime softener be increased in size to handle the larger volumes of water required at fewer cycles of concentration than the design basic of ten.

Data indicate that the primary factor affecting silica reduction is the pH reached with additions of magnesium oxide. The large quantities of magnesium oxide added for water having high silica contents automatically adjusts the pH to approximately 10.2. At this pH, too little magnesium oxide dissolves for efficient silica sorption. Because the extent of the sorption reaction is dependent on the available surface area of the magnesium hydroxide floccules and because the surface area is pH-dependent, the sorption is pH-dependent. The result of these interactions is reduced silica removal at high pH values.

7. TWO-STAGE COUNTERCURRENT PROCESS UNIT

This test was set up to simulate a two-stage countercurrent processing unit to evaluate a change in the mechanical design system. Remosil was selected as the source of magnesium, and hydrated lime was used for pH adjustment. Equal quantities of all reagents were simultaneously added to each beaker at the start of the test. At the end of the test, water samples were filtered into two-litre beakers and returned to the constant temperature bath. Remosil was then added to each beaker in concentrations varying from 25 to 200 ppm. The systems were stirred slowly for 15 minutes, then allowed to settle. Samples were filtered and analyzed for silica.

Data (Table A-7) show that a two-stage countercurrent process unit would adequately reduce silica concentration. The addition of 400 ppm MgO in two stages reduces silica to 22 ppm and thereby allows 4.6 cycles of concentration of the recirculating coolant. Thus, in a continuous flow processing system silica reduction is enhanced.

8. SOLUBLE MAGNESIUM COMPOUND SYSTEMS

8.1 Magnesium Bicarbonate

The decision to evaluate a magnesium bicarbonate system was the result of a conversation with Mr. A. B. Mindler of Permutit who indicated that prior to 1940 it was standard practice to bubble carbon dioxide through a magnesium hydroxide slurry prior to addition to the softener unit, to enhance silica removal. This agrees with the preliminary indications that the magnesium should be added in ionic form. To evaluate this hypothesis, four samples of ten grams per litre of magnesium oxide slurry were prepared. These systems used the light, heavy, Remosil, and dolomitic lime forms of magnesium oxide. Carbon dioxide was bubbled through each of these systems until no further pH change was observed over a fifteen-minute period. The light, heavy, and Remosil magnesium oxide systems stabilized at pH 6.9, and all were clear solutions. The dolomitic lime system reached a constant pH value of 7.1. This system resulted in a clear solution above a deep bed of precipitate.

Samples from each system were filtered and analyzed for magnesium to determine the amount of magnesium dissolved. Data are shown in Table 2.

TABLE 2. ANALYSIS OF FILTERED SAMPLES OF MAGNESIUM HYDROXIDE SLURRIES AFTER BUBBLING CARBON DIOXIDE TO CONSTANT pH

Magnesium Source	pH After CO ₂ Bubbling	% Dissolved Magnesium in Samples
1. Light magnesium oxide system	6.9	100
2. Heavy magnesium oxide system	6.9	89
3. Remosil magnesium oxide system	6.9	81
4. Dolomitic lime magnesium oxide system	7.1	100

The dolomitic lime system was analyzed for calcium and was found to contain less than 0.06 percent in solution, indicating that the precipitate was calcium carbonate.

Two additional jar tests were run with each of the four bicarbonate systems in which the magnesium oxide dosage was held constant and the pH varied from 10.2 to 10.8. The 200 ppm magnesium oxide added is based on magnesium in solution, as determined from data of Table 2.

Results indicate that silica reduction using magnesium bicarbonate is a significant improvement over the corresponding magnesium oxide systems. Residual silica concentrations indicate that all four systems are equivalent in silica removal efficiency (variations only to six percent) as shown in Table A-8. The best silica reductions occurred at pH 10.2. The small differences in silica reduction at different pH values indicate little, if any dependence on pH when large amounts of the initial silica are removed.

8.2 Magnesium Sulfate

Based on improved silica reduction with magnesium bicarbonate, five additional tests were run, to evaluate magnesium sulfate for silica removal. Five magnesium sulfate systems were evaluated. The first three tests used Epsom salt ($\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$) as the source of magnesium. The variable in these three tests was the amount of carbonate added as sodium bicarbonate, NaHCO_3 . Sodium bicarbonate, rather than sodium carbonate, was added, prior to magnesium oxide addition, to maintain a low pH of 8. Data and systems used are listed in Tables A-9, A-10, and A-11.

Results are shown in Figure 4. Maximum silica reduction is achieved when no soda ash is added. The least silica is removed with the magnesium sulfate-sodium bicarbonate system, in agreement with Mujeriego⁶ who found that increased alkalinity had a detrimental effect.

Figure 4. Concentration of residual silica versus concentration of magnesium added as (a) Epsom salt, (b) Epsom salt plus soda ash, and (c) Epsom salt plus sodium bicarbonate.

Figure 5. Concentration of residual silica versus concentration of (a) magnesium oxide plus sulfuric acid and (b) magnesium oxide plus soda ash and sulfuric acid.

The next two tests were run as magnesium sulfate systems using Remosil as the source of magnesium. The first system was a 10 g/L slurry of Remosil which was acidified with concentrated sulfuric acid until the solution cleared. The second system used equimolar quantities of Remosil and soda ash, and the slurry was acidified with concentrated sulfuric acid until a clear solution resulted. The results of these two tests are given in Tables A-12 and A-13 and shown in Figure 5. Both systems were superior in silica removal to any previously tested system. The reason for the enhancement over Epsom salt systems is not clear; however, it appears that acidification frees all the magnesium from any chemical complex and, thus, increases silica-reduction activity.

8.3 Magnesium Chloride

Two additional tests were conducted, using magnesium chloride systems. A slurry of Remosil in water was acidified with concentrated hydrochloric acid until clear. Tests were run at pH 10.2 (Table A-14) and 11.2 (Table A-15). Results are shown in Figure 6. Silica reduction at pH 10.2 is equivalent to that achieved with magnesium bicarbonate systems. Silica removal at pH 11.2 is most significant and concurs with data of Wey and Siffert¹⁰ that the optimum pH for silica reduction with magnesium chloride is 11.0-11.5.

Since chloride concentrations in the geothermal water are 1000-1400 ppm Cl^- , all treatment systems should behave as magnesium chloride systems, suggesting that additional jar tests at pH values near 11.2 be conducted to evaluate this hypothesis.

Figure 6. Concentration of residual silica versus concentration of magnesium oxide plus hydrochloric acid at fixed pH.

9. PREACIDIFICATION

Jar tests were conducted using magnesium oxide after first adjusting pH with concentrated sulfuric acid. Magnesium was added in the form of a 10 g/L slurry of magnesium oxide. Results (Table A-16) show that pH adjustment to between 6.2 and 8.3 prior to treatment had no significant effect when using 200 ppm MgO. Even with preacidification, pH reached 10 following slurry addition. For initial pH values as low as 4.0, no significant difference in silica reduction was achieved. However, for preacidification to a pH of 3.0, magnesium oxide additions increased the pH to 3.8 and with pH adjustment to 10.2. In this case, residual silica was reduced to 17.6 ppm as compared to a residual silica value of 82 ppm in the other samples. This finding substantiated previous data which demonstrated that magnesium hydroxide must be generated in situ and must not be the agent for pH adjustment.

10. IRON SYSTEMS

The use of iron as a silica removal agent was previously demonstrated by Leaf.¹⁶ Two tests were run using iron salts to reduce silica. These tests used Fe(II) in the form of ferrous sulfate (FeSO_4) and Fe(III) in the form of ferric chloride (FeCl_3). Table A-17 shows results using FeSO_4 as the source of iron. The silica was reduced from 185 to 27 ppm SiO_2 with 250 ppm Fe(II) at pH 8.6 with no significant increase at higher pH values. Table A-18 shows silica reduction using ferric chloride (FeCl_3) as the source of Fe(III). These data show that iron will adequately reduce silica levels to the 15-20 ppm SiO_2 range when using approximately 180 ppm Fe(III). The primary difference between magnesium and Fe(III) is that iron reduces the pH to about 2.4. This eliminates the use of soda ash for calcium removal and dictates the use of sodium hydroxide rather than the less expensive lime for pH adjustment.

11. DISCUSSION OF RESULTS

Various grades of magnesium oxide and dolomitic lime will adequately reduce silica if carbon dioxide is bubbled through the magnesium slurries to a pH of 7. Dolomitic lime, in this type of system, poses a huge sludge problem. Each 100 lb of dolomitic lime used will produce 78 lb of calcium carbonate in the chemical feed tank. Also, there is a large capital investment for carbon dioxide production. The magnesium oxide systems will not produce sludge, but they require carbon dioxide. The initial capital investment to purchase a carbon dioxide generation unit which will produce 91 kg (2000 lb) of carbon dioxide per day (the requirement for the 5 MW(e) Pilot Power Plant) is estimated at \$150,000. The cost of using liquid carbon dioxide stored in an on-site tank holding 2730 kg (30 tons) is \$2,200 per month (at early 1979 prices).

Both magnesium sulfate and magnesium chloride will reduce silica concentration to acceptable levels. The use of magnesium salts will increase total dissolved solids and may reduce the number of cycles of concentration achievable in the recirculating coolant. The increased sulfate from the magnesium sulfate presents a potential gypsum scaling problem on the tubes in the condenser. The excess chloride, from magnesium chloride addition, may not only reduce cycles of concentration in the system, but may significantly increase the corrosion rate, particularly pitting of the condenser tubes, thereby effectively reducing the service lifetime of the condenser.

Other magnesium oxide systems tested were preacidification of make-up water with sulfuric acid prior to addition of a magnesium oxide slurry.

Two iron systems were also tested: Fe(II) from ferrous sulfate and Fe(III) from ferric chloride. These iron systems pose the same scaling and corrosion problems as their corresponding magnesium systems. They may, however, be more economical. Ferric chloride differs slightly from magnesium chloride in that sodium hydroxide rather than lime is used to adjust pH. The problem with this system is its inability to reduce the calcium concentrations with soda ash.

The use of any chemical systems to reduce silica to acceptable levels in the make-up water will naturally create significant changes in the originally anticipated water chemistry of the cooling tower-condenser system. The effect of these chemical changes must be evaluated and integrated with demands of recirculating and blowdown treatment systems before sound recommendations for pretreatment can be made.

12. CONCLUSIONS AND RECOMMENDATIONS

Analyses of water treatment systems tested lead to the following conclusions.

- (1) The design specification of 10-15 ppm silica in the effluent water from the pretreatment system cannot be achieved by the use of dolomitic lime, nor with any of the other conventional water-treatment systems simulated in the tests reported here.
- (2) The 10-15 ppm residual silica level can be achieved with either a soluble magnesium or iron salt system, where the metal is added as a solution.
- (3) The zero-level bicarbonate is automatically met with pH adjustment.
- (4) The maximum calcium concentration of 340 ppm as CaCO_3 is readily achieved through the addition of soda ash.
- (5) The hydroxide concentration, reported as CaCO_3 , is in the 150-250 ppm range, slightly higher than the 157 ppm specified.

Recommendations are:

- (1) That dolomitic lime should not be used as the source of magnesium for silica reduction, and
- (2) That no specific chemical system can be recommended based on the data reported here.

Several systems can adequately reduce silica, yet each of these systems poses potential problems which have yet to be evaluated.

It is recommended that the chemicals which reduce silica to required levels be tested and evaluated for scaling effects and corrosion rates on carbon steel.

Chemicals recommended for testing for scaling and corrosion on carbon steel after silica removal are $\text{Mg}(\text{HCO}_3)_2$, MgSO_4 , and MgCl_2 . Data in Table A-19 show that these systems are effective in silica removal and also have a low ratio of MgO to SiO_2 removed. The most effective treatment is the $\text{MgO}/\text{Na}_2\text{CO}_3/\text{H}_2\text{SO}_4$ system; however, it is not considered economical and would substantially increase the solids content. Because of the common anions (Cl^- , SO_4^{2-}) of the iron systems, evaluation of the magnesium systems should be indicative of how the iron salt systems would behave with respect to scaling. However, for data confirmation, tests to determine chemical loss and corrosion rates on low-carbon steel using water treated with ferric chloride also should be conducted.

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APPENDIX A

ANALYSIS OF WATER TREATED WITH VARIOUS SYSTEMS

TABLE A-1. WATER TREATED WITH DOLOMITIC LIME^a AT 60°C

Chemical Additions (ppm)	Sample Number						Untreated Water
	1	2	3	4	5	6	
CaO	88	176	264	352	440	528	
MgO	74	148	222	296	370	440	
Adjusted pH	9.2	10.0	10.6	11.0	11.3	11.6	8.1
<u>Analysis (ppm)</u>							
Ca ^b							152
SiO ₂ ^c	160	138	110	140	114	108	164
MgO/SiO ₂ ^d	18.5	5.7	4.1	12.3	6.9	7.9	

a. Dolomitic lime is 58 wt % Ca(OH)₂ and 37 wt % MgO.

b. Calcium is reported as CaCO₃.

c. Silica is reported as SiO₂.

d. MgO/SiO₂ is the ratio of MgO added to SiO₂ removed.

Note: Data representation in succeeding tables identical.

TABLE A-2. WATER TREATED WITH DOLOMITIC LIME AT FOUR TEMPERATURES

Chemical Additions (ppm)	Sample Number						Untreated Water
	1	2	3	4	5	6	
	Temperature 80°C			Temperature 70°C			
CaO	216	216	682	216	250	603	
MgO	200	200	200	200	200	200	
Na ₂ CO ₃	346	346	792	346	384	1020	
<u>Adjusted pH</u>	10.5	10.5	10.8	10.5	10.5	10.8	8.2
<u>Analysis (ppm)</u>							
Ca	26	8	6	8	36	12	113
SiO ₂	79	75	113	85	81	133	165
MgO/SiO ₂	2.3	2.2	3.9	2.5	2.4	6.3	

Chemical Additions (ppm)	Temperature 60°C			Temperature 50°C			
	1	2	3	4	5	6	
	Temperature 60°C			Temperature 50°C			
CaO	216	216	412	216	216	450	
MgO	200	200	200	200	200	200	
Na ₂ CO ₃	346	346	660	346	346	560	
<u>Adjusted pH</u>	10.5	10.5	10.8	10.6	10.6	10.8	8.2
<u>Analysis (ppm)</u>							
Ca	56	44	10	8	12	10	113
SiO ₂	103	96	113	130	123	143	165
MgO/SiO ₂	3.2	2.9	3.9	5.7	4.8	9.1	

TABLE A-3. WATER TREATED WITH DIFFERENT GRADES
OF MAGNESIUM OXIDE AT 60°C

Chemical Additions (ppm)	Sample Number						Untreated Water
	1 ^a	2 ^a	3 ^a	4 ^b	5 ^b	6 ^b	
CaO	200	370	400	284	321	435	
MgO	200	200	200	200	200	200	
Na ₂ CO ₃	180	540	510	235	265	355	
<u>Adjusted pH</u>	10.2	10.5	10.8	10.2	10.5	10.8	8.1
<u>Analysis (ppm)</u>							
Ca	4	6	6	4	14	12	113
SiO ₂	68	65	66	78	74	68	176
MgO/SiO ₂	1.9	1.8	1.8	2.0	2.0	1.9	
Chemical Additions (ppm)	7 ^c	8 ^c	9 ^c	10 ^d	11 ^d	12 ^d	Untreated Water
CaO	152	208	380	387	537	637	
MgO	200	200	200	200	200	200	
Na ₂ CO ₃	125	170	310	145	285	375	
<u>Adjusted pH</u>	10.2	10.5	10.8	10.2	10.5	10.8	8.1
<u>Analysis (ppm)</u>							
Ca	6	6	4	6	4	16	113
SiO ₂	76	81	73	92	88	90	176
MgO/SiO ₂	2.0	2.1	1.9	2.7	2.9	2.9	

a. As Remosil.

b. As heavy grade.

c. As light grade.

d. As dolomitic lime.

TABLE A-4. WATER TREATED WITH REMOSIL AT FOUR TEMPERATURES

Chemical Additions (ppm)	Sample Number						Untreated Water
	1	2	3	4	5	6	
	Temperature 80°C			Temperature 70°C			
CaO	483	920	1320	189	265	605	
MgO	200	200	200	200	200	200	
Na ₂ CO ₃	600	1070	1600	208	288	774	
Adjusted pH	10.2	10.5	10.8	10.2	10.5	10.8	8.0
<u>Analysis (ppm)</u>							
Ca	10	16	6	4	6	6	120
SiO ₂	68	73	80	80	91	100	155
MgO/SiO ₂	2.3	2.4	2.7	2.7	3.1	3.6	
Chemical Additions (ppm)	Temperature 60°C			Temperature 50°C			
	1	2	3	4	5	6	
	Temperature 60°C			Temperature 50°C			
CaO	189	265	605	121	181	363	
MgO	200	200	200	200	200	200	
Na ₂ CO ₃	300	397	900	180	271	545	
Adjusted pH	10.2	10.5	10.8	10.2	10.5	10.8	8.0
<u>Analysis (ppm)</u>							
Ca	16	12	4	12	20	8	120
SiO ₂	123	103	113	138	138	130	155
MgO/SiO ₂	6.3	3.9	4.8	11.8	11.8	8.0	

TABLE A-5. WATER TREATED WITH DOLOMITIC LIME AND REMOSIL AT CONSTANT
MAGNESIUM DOSAGE AT 60°C

Chemical Additions (ppm)	Sample Number						Untreated Water
	1	2	3	4	5	6	
CaO	129	208	296	129	208	296	
MgO	110	175	250	110	175	250	
MgO (Remosil)	140	75	0	140	75	0	
<u>Adjusted pH</u>	10.2	10.5	10.8	10.2	10.6	10.8	8.5
<u>Analysis (ppm)</u>							
Ca	182	290	330	186	308	332	117
SiO ₂	103	84	77	98	80	75	178
MgO/SiO ₂	1.7	2.7	2.5	1.6	2.6	2.4	

TABLE A-6. WATER TREATED WITH REMOSIL AT 60°C
(pH ADJUSTED WITH NaOH)

Chemical Additions (ppm)	Sample Number						Untreated Water
	1	2	3	4	5	6	
MgO	125	250	375	500	625	750	
NaOH as CaCO ₃	0.014	0.010	0.003	0.002	0	0	
<u>Adjusted pH</u>	10.2	10.2	10.2	10.2	10.2	10.2	8.4
<u>Analysis</u>							
SiO ₂ (ppm)	142	165	76	76	74	80	206
MgO/SiO ₂ (ppm)	2.0	6.2	2.9	3.9	4.7	6.0	
pH after MgO addition	9.4	9.8	10	10.1	10.2	10.2	

TABLE A-7. WATER TREATED WITH REMOSIL TO SIMULATE
A TWO-STAGE COUNTERCURRENT PROCESS

<u>Chemical Additions (ppm)</u>	<u>Sample Number</u>						<u>Untreated Water</u>
	<u>1</u>	<u>2</u>	<u>3</u>	<u>4</u>	<u>5</u>	<u>6</u>	
CaO	302	302	302	302	302	302	
MgO	200	200	200	200	200	200	
Na ₂ CO ₃	428	428	428	428	428	428	
<u>Adjusted pH</u>	10.4	10.4	10.4	10.4	10.4	10.4	8.4
<u>Analysis (ppm)</u>							
SiO ₂	92	92	86	97	84	94	165
MgO/SiO ₂	2.7	2.7	2.5	2.9	2.5	2.8	

(Samples were filtered and returned to constant temperature bath.)

<u>Chemical Additions (ppm)</u>						
MgO	25	50	75	100	150	200
<u>Analysis (ppm)</u>						
SiO ₂	50	40	29	34	25	22
MgO/SiO ₂ (Step 2)	0.6	1.0	1.3	1.6	2.5	2.9
MgO/SiO ₂ (Process)	2.0	2.0	2.0	2.3	2.5	2.8

TABLE A-8. WATER TREATED WITH CARBONATED SOLUTIONS
OF MAGNESIUM OXIDE AT 60°C

Chemical Additions (ppm)	Sample Number						Untreated Water
	1 ^a	2 ^a	3 ^a	4 ^b	5 ^b	6 ^b	
CaO	386	483	569	334	427	540	
MgO	200	200	200	200	200	200	
<u>Adjusted pH</u>	10.2	10.5	10.8	10.2	10.5	10.8	8.3
<u>Analysis (ppm)</u>							
SiO ₂	32	33	38	32	34	36	180
MgO/SiO ₂	1.4	1.4	1.4	1.4	1.4	1.4	
Chemical Additions (ppm)	7 ^c	8 ^c	9 ^c	10 ^d	11 ^d	12 ^d	Untreated Water
CaO	357	439	556	340	436	550	
MgO	200	200	200	200	200	200	
<u>Adjusted pH</u>	10.2	10.5	10.8	10.2	10.5	10.8	8.3
<u>Analysis (ppm)</u>							
SiO ₂	32	39	41	35	36	30	180
MgO/SiO ₂	1.4	1.4	1.4	1.4	1.4	1.3	

a. As light grade.

b. As heavy grade.

c. As dolomitic Lime.

d. As Remosil.

TABLE A-9. WATER TREATED WITH MAGNESIUM SULFATE
(EPSOM SALT) AT 60°C

Chemical Additions (ppm)	Sample Number						Untreated Water
	1	2	3	4	5	6	
CaO	740	740	740	740	815	890	
MgO	50	100	150	200	225	250	
<u>Adjusted pH</u>	10.2	10.2	10.2	10.2	10.2	10.2	8.3
<u>Analysis (ppm)</u>							
Ca	206	300	480	520	560	600	140
SiO ₂	85	50	25	12	5	3.6	163
MgO/SiO ₂	0.6	0.9	1.1	1.3	1.4	1.6	

TABLE A-10. WATER TREATED WITH MAGNESIUM SULFATE
AND SODA ASH AT 60°C

Chemical Additions (ppm)	Sample Number						Untreated Water
	1	2	3	4	5	6	
CaO	350	350	500	620	780	900	
MgO	50	100	150	200	225	250	
Na ₂ CO ₃	375	375	600	750	1020	1200	
<u>Adjusted pH</u>	10.2	10.2	10.2	10.2	10.2	10.2	8.3
<u>Analysis (ppm)</u>							
Ca	ND ^a	32	2	16	24	20	140
SiO ₂	95	74	43	23	9	7	163
MgO/SiO ₂	0.7	1.1	1.3	1.4	1.5	1.8	

a. ND denotes none detected.

TABLE A-11. WATER TREATED WITH EQUIMOLAR QUANTITIES OF
MAGNESIUM SULFATE AND SODIUM BICARBONATE AT 60°C

Chemical Additions (ppm)	Sample Number						Untreated Water
	1	2	3	4	5	6	
CaO	1037	1133	1200	1333	1451	1667	
MgO	50	100	150	200	225	250	
<u>Adjusted pH</u>	10.2	10.2	10.2	10.2	10.2	10.2	8.3
<u>Analysis (ppm)</u>							
Ca	40	40	10	40	20	16	140
SiO ₂	124	102	71	50	35	31	163
MgO/SiO ₂	1.3	1.6	1.6	1.8	1.6	1.7	

TABLE A-12. WATER TREATED WITH MAGNESIUM SULFATE^a AT 60°C

Chemical Additions (ppm)	Sample Number						Untreated Water
	1	2	3	4	5	6	
CaO	378	503	631	923	1134	1304	
MgO	50	100	150	200	300	400	
Na ₂ CO ₃	658	874	1100	1710	1975	2270	
<u>Adjusted pH</u>	10.4	10.4	10.4	10.4	10.4	10.4	8.4
<u>Analysis (ppm)</u>							
SiO ₂	63	42	22	13	6	5	173
MgO/SiO ₂	0.5	0.8	1.0	1.3	1.8	3.0	

a. System made by acidification of MgO suspension with H₂SO₄.

TABLE A-13. WATER TREATED WITH MAGNESIUM SULFATE AND SODA ASH^a AT 60°C

Chemical Additions (ppm)	Sample Number						Untreated Water
	1	2	3	4	5	6	
CaO	121	129	129	118	57	57	
MgO	50	100	150	200	300	400	
Adjusted pH	10.4	10.4	10.4	10.4	10.4	10.4	8.6
<u>Analysis (ppm)</u>							
SiO ₂	29	14	5	4	3	3	176
MgO/SiO ₂	0.3	0.6	0.9	1.2	1.7	2.3	

a. System produced by addition of equimolar quantities of MgO and Na₂CO₃, then H₂O and H₂SO₄ until solution clears.

TABLE A-14. WATER TREATED WITH MAGNESIUM CHLORIDE^a AT 60°C AND pH 10.2

Chemical Additions (ppm)	Sample Number						Untreated Water
	1	2	3	4	5	6	
CaO	260	296	335	407	453	475	
MgO	25	50	75	100	125	150	
Na ₂ CO ₃	332	372	426	518	577	605	
Adjusted pH	10.2	10.2	10.2	10.2	10.2	10.2	8.3
<u>Analysis (ppm)</u>							
Ca	16	14	12	10	12	8	140
SiO ₂	106	94	62	55	39	30	163
MgO/SiO ₂	0.4	0.7	0.7	0.9	1.0	1.1	

a. System produced by addition of HCl to MgO suspension until solution clears.

TABLE A-15. WATER TREATED WITH MAGNESIUM CHLORIDE^a
AT 60°C AND pH 11.2

Chemical Additions (ppm)	Sample Number						Untreated Water
	1	2	3	4	5	6	
CaO	1000	1000	1000	1000	1000	1000	
MgO	40	80	100	125	140	155	
<u>Adjusted pH</u>	11.2	11.2	11.2	11.2	11.2	11.2	8.3
<u>Analysis (ppm)</u>							
SiO ₂	23	15	14	12	11	9	163
MgO/SiO ₂	0.3	0.5	0.7	0.8	0.9	1.0	

a. System produced by addition of concentrated HCl to MgO suspension until solution clears.

TABLE A-16. WATER TREATED WITH MAGNESIUM OXIDE
FOLLOWING pH ADJUSTMENT AT 60°C

Chemical Additions	Sample Number						Untreated Water
	1	2	3	4	5	6	
pH following H ₂ SO ₄ addition	8.2	8.1	7.6	7.1	6.6	6.2	8.3
MgO (ppm)	200	200	200	200	200	200	
pH following MgO addition	10.1	10.0	10.0	10.0	10.0	10.0	
Adjusted pH	10.2	10.2	10.2	10.2	10.2	10.2	
<u>Analysis (ppm)</u>							
SiO ₂	112	95	94	93	92	90	185
MgO/SiO ₂	2.7	2.2	2.2	2.2	2.1	2.1	
Chemical Additions	7	8	9	10	11	12	
pH after H ₂ SO ₄ addition	5.6	5.0	4.0	3.0	2.4	2.2	8.3
MgO (ppm)	200	200	200	200	200	200	
pH after MgO addition	10.0	10.0	10.0	10.0	10.0	10.0	
Adjusted pH	10.2	10.4	10.2	10.2	10.2	10.2	
<u>Analysis (ppm)</u>							
SiO ₂	90	82	84	18	18	18	185
MgO/SiO ₂	2.1	1.9	2.0	1.2	1.2	1.2	

TABLE A-17. WATER TREATED WITH FERROUS SULFATE
AT 60°C AND VARYING pH (pH ADJUSTED WITH NaOH)

<u>Chemical Additions (ppm)</u>	<u>Sample Number</u>						<u>Untreated Water</u>
	<u>1</u>	<u>2</u>	<u>3</u>	<u>4</u>	<u>5</u>	<u>6</u>	
Fe	250	250	250	250	250	250	
NaOH as CaCO ₃	0.066	0.071	0.078	0.083	0.102	0.138	
<u>Adjusted pH</u>	8.0	8.6	9.0	9.6	10.0	10.4	8.3
<u>Analysis (ppm)</u>							
SiO ₂	65	27	23	20	21	22	185
Fe/SiO ₂	2.1	1.6	1.5	1.5	1.5	1.5	

TABLE A-18. WATER TREATED WITH FERRIC CHLORIDE AT 60°C

<u>Chemical Additions (ppm)</u>	<u>Sample Number</u>						<u>Untreated Water</u>
	<u>1</u>	<u>2</u>	<u>3</u>	<u>4</u>	<u>5</u>	<u>6</u>	
Fe	36	72	108	144	180	226	
CaO	166	333	394	787	1157	1483	
<u>Adjusted pH</u>	8.2	7	7.1	6.5	8.8	8.8	8.3
<u>Analysis (ppm)</u>							
SiO ₂	125	113	93	47	17.0	12	185
Fe/SiO ₂	0.6	1.0	1.2	1.0	1.1	1.3	

TABLE A-19. TABULATION OF MAGNESIUM SYSTEMS AT 60°C

Original SiO ₂ (ppm)	Additions		Final SiO ₂ (ppm)	pH	MgO Source (ppm)	MgO/SiO ₂ Removed (ppm)
	MgO (ppm)	CaO (ppm)				
164	74	88	160	9.2	DL	18.5
164	148	176	138	10.0	DL	5.7
164	222	264	110	10.6	DL	4.1
164	296	352	140	11.0	DL	12.3
164	370	440	114	11.2	DL	6.9
164	444	528	108	11.3	DL	7.9
176	200	200	68	10.2	M(R)	1.9
176	200	370	65	10.5	M(R)	1.8
176	200	400	66	10.8	M(R)	1.8
176	200	284	78	10.2	M(H)	2.0
176	200	321	74	10.5	M(H)	2.0
176	200	435	68	10.8	M(H)	1.9
176	200	152	76	10.2	M(L)	2.0
176	200	208	81	10.5	M(L)	2.1
176	200	380	73	10.8	M(L)	1.9
176	200	387	92	10.2	DL	2.7
176	200	537	88	10.5	DL	2.9
176	200	637	90	10.8	DL	2.7
178	250	129	103	10.2	DL+M(R)	1.7
178	250	208	84	10.5	DL+M(R)	2.7

TABLE A-19. (Continued)

Original SiO ₂ (ppm)	Additions		Final SiO ₂ (ppm)	pH	MgO Source (ppm)	MgO/SiO ₂ Removed (ppm)
	MgO (ppm)	CaO (ppm)				
178	250	296	77	10.8	DL	2.5
178	250	129	98	10.2	DL+M(R)	1.6
178	250	208	80	10.6	DL+M(R)	2.6
178	250	296	75	10.8	DL	2.4
206	125	0	142	10.2	M(R)	2.0
206	250	0	165	10.2	M(R)	6.2
206	375	0	76	10.2	M(R)	2.9
206	500	0	76	10.2	M(R)	3.9
206	625	0	74	10.2	M(R)	4.7
206	750	0	80	10.2	M(R)	6.0
180	200	386	32	10.2	M(L)+CO ₂	1.4
180	200	483	33	10.5	M(L)+CO ₂	1.4
180	200	569	38	10.8	M(L)+CO ₂	1.4
180	200	334	32	10.2	M(H)+CO ₂	1.4
180	200	427	34	10.5	M(H)+CO ₂	1.4
180	200	540	36	10.8	M(H)+CO ₂	1.4
180	200	357	32	10.2	DL+CO ₂	1.4
180	200	439	39	10.5	DL+CO ₂	1.4
180	200	556	41	10.8	DL+CO ₂	1.4
180	200	340	35	10.2	M(R)+CO ₂	1.4
180	200	436	36	10.5	M(R)+CO ₂	1.4

TABLE A-19. (Continued)

Original SiO ₂ (ppm)	Additions		Final SiO ₂ (ppm)	pH	MgO Source (ppm)	MgO/SiO ₂ Removed (ppm)
	MgO (ppm)	CaO (ppm)				
180	200	550	30	10.8	M(R)+CO ₂	1.3
163	50	740	85	10.2	EPS	0.6
163	100	740	50	10.2	EPS	0.9
163	150	740	25	10.2	EPS	1.1
163	200	740	12	10.2	EPS	1.3
163	225	815	5	10.2	EPS	1.4
163	250	890	4	10.2	EPS	1.6
163	50	350	95	10.2	EPS+SA	0.7
163	100	350	74	10.2	EPS+SA	1.1
163	150	500	43	10.2	EPS+SA	1.3
163	200	620	23	10.2	EPS+SA	1.4
163	225	780	9	10.2	EPS+SA	1.5
163	250	900	7	10.2	EPS+SA	1.8
163	50	1037	124	10.2	EPS+NAB	1.3
163	100	1133	102	10.2	EPS+NAB	1.6
163	150	1200	71	10.2	EPS+NAB	1.6
163	200	1333	50	10.2	EPS+NAB	1.8
163	225	1451	35	10.2	EPS+NAB	1.6
163	250	1667	31	10.2	EPS+NAB	1.7
173	50	378	63	10.4	MgSO ₄ (R)	0.5
173	100	503	42	10.4	MgSO ₄ (R)	0.8

TABLE A-19. (Continued)

Original SiO ₂ (ppm)	Additions		Final SiO ₂ (ppm)	pH	MgO Source (ppm)	MgO/SiO ₂ Removed (ppm)
	MgO (ppm)	CaO (ppm)				
173	150	631	22	10.4	MgSO ₄ (R)	1.0
173	200	923	13	10.4	MgSO ₄ (R)	1.3
173	300	1134	6	10.4	MgSO ₄ (R)	1.8
173	400	1304	5	10.4	MgSO ₄ (R)	3.0
176	50	121	29	10.4	M(A)	0.3
176	100	129	14	10.4	M(A)	0.6
176	150	129	5	10.4	M(A)	0.9
176	200	118	4	10.4	M(A)	1.2
176	300	57	3	10.4	M(A)	1.7
176	400	57	3	10.4	M(A)	2.3
163	25	260	106	10.2	MgCl ₂ (R)	0.4
163	50	296	94	10.2	MgCl ₂ (R)	0.7
163	75	335	62	10.2	MgCl ₂ (R)	0.7
163	100	407	55	10.2	MgCl ₂ (R)	0.9
163	125	453	39	10.2	MgCl ₂ (R)	1.0
163	150	475	30	10.2	MgCl ₂ (R)	1.1
163	40	1000	23	11.2	MgCl ₂ (R)	0.3
163	80	1000	15	11.2	MgCl ₂ (R)	0.5
163	100	1000	14	11.2	MgCl ₂ (R)	0.7
163	125	1000	12	11.2	MgCl ₂ (R)	0.8
163	140	1000	11	11.2	MgCl ₂ (R)	0.9

TABLE A-19. (Continued)

Original SiO ₂ (ppm)	Additions		Final SiO ₂ (ppm)	pH	MgO Source (ppm)	MgO/SiO ₂ Removed (ppm)
	MgO (ppm)	CaO (ppm)				
163	155	1000	9	11.2	MgCl ₂ (R)	1.0
185	200	0	112	8.2, ^a 10.2 ^b	M(R)	2.7
185	200	0	95	8.1, 10.2	M(R)	2.2
185	200	0	94	7.6, 10.2	M(R)	2.2
185	200	0	93	7.1, 10.2	M(R)	2.2
185	200	0	92	6.6, 10.2	M(R)	2.1
185	200	0	90	6.2, 10.2	M(R)	2.1
185	200	0	90	5.6, 10.2	M(R)	2.1
185	200	0	82	5.0, 10.2	M(R)	1.9
185	200	0	84	4.0, 10.2	M(R)	2.0
185	200	0	18	3.0, 10.2	M(R)	1.2
185	200	0	18	2.4, 10.2	M(R)	1.2
185	200	0	18	2.2, 10.2	M(R)	1.2

a. pH following preacidification.

b. Final pH.

TABLE A-19. (Continued)

DL = Dolomitic Lime.

M(R) = Remosil.

M(H) = "Heavy" MgO.

M(L) = "Light" MgO.

EPS = Epsom Salt (MgSO_4).

SA = Soda Ash (Na_2CO_3).

NAB = Sodium Bicarbonate (NaHCO_3).

$\text{MgSO}_4(\text{R})$ = Acidified Remosil using Sulfuric Acid (H_2SO_4).

M(A) = Acidified Mixture of Remosil and Soda Ash.

$\text{MgCl}_2(\text{R})$ = Acidified Remosil using Hydrochloric Acid (HCl).