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Study of Zeta Potential for Material Particles in Chemical Additive Solutions

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A novel technique has been employed by the U.S. Bureau of Mines to determine the zeta potential of particles for a far-reaching series of material types in a wide variety of baseline waters, both alone and with many different chemical additives. The materials tested ranged from naturally occurring Sioux Quartzite and Tennessee marble to commercially produced magnesium oxide bricks. The waters tested ranged from ultrapure distilled, deionized water to municipal tap water and mine-site water. The chemical solutions tested included inorganic additives, such as aluminum chloride ($AlCl_3$) and sodium chloride (NaCl); organic additives, such as dodecyltrimethyl ammonium bromide (DTAB); and nonionic polymers, such as polyethylene oxide (PEO). The results of precise zeta potential determinations have application in a large number of laboratory studies as well as in various mining and processing operations.

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

°C	degree Celsius	mol/L	mole per liter
g	gram	ppm	part per million
µS/cm	microsiemens per centimeter	pct	percent
mL	milliliter	V/cm	volt per centimeter
mV	millivolt		

STUDY OF ZETA POTENTIAL FOR MATERIAL PARTICLES IN CHEMICAL ADDITIVE SOLUTIONS

By Pamela J. Watson[1] and Patrick A. Tuzinski[2]

ABSTRACT

A novel technique has been employed by the U.S. Bureau of Mines to determine the zeta potential of particles for a far-reaching series of material types in a wide variety of baseline waters, both alone and with many different chemical additives. The materials tested ranged from naturally occurring Sioux Quartzite and Tennessee marble to commercially produced magnesium oxide bricks. The waters tested ranged from ultrapure distilled, deionized water to municipal tap water and mine-site water. The chemical solutions tested included inorganic additives, such as aluminum chloride ($AlCl_3$) and sodium chloride (NaCl); organic additives, such as dodecyltrimethyl ammonium bromide (DTAB); and nonionic polymers, such as polyethylene oxide (PEO). The results of precise zeta potential determinations have application in a large number of laboratory studies as well as in various mining and processing operations.

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INTRODUCTION

There are many areas of research and manufacturing that make use of either zero zeta potential or some other zeta potential value to control desired product properties. A knowledge of a system's unique zeta potential characteristics is therefore required to successfully perform many research or manufacturing tasks. Manufacturing and production applications for zeta potential range from processing techniques for such diverse items as paints and detergents (*1*)[3] to selective mineral flotation by cation or anion control (*2-3*). Optimum flocculation of turbidity-producing particles by zeta potential control is a critical aspect of municipal water treatment and purification systems (*4*). Some research areas related to zeta potential include studies of hardness and dislocation mobilities of rocks and other materials (*5*), understanding the nature of rock weathering (*6*), characterizing differences between minerals of similar chemical composition (*6*), studies of rock penetration by diamond indenters (*7*), and the use of chemical additives in drilling fluids (*8-9*).

With respect to chemical additives in drilling fluids, the Bureau found that optimized drilling performance could be obtained under zero zeta potential conditions (*10*). This zeta potential controlled drilling requires precise knowledge about the point of zero charge (PZC) concentration for a given fluid additive in relation to the rock being drilled. Because of the critical nature of this process, it was necessary to develop a way to accurately predict the PZC concentration for a given material-additive system. These results have also demonstrated that testing the zeta potential of ground particles does indeed represent the whole material zeta potential (*10*). At the PZC concentration demonstrated by the material particle tests, the performance of the drilling tests was maximized, as postulated by many researchers (*5-10*).

The Stern model of the electrical double layer of ions can be employed to explain the electrical equilibrium state set up around a solid in a liquid phase. In that model, the solid has a rigidly fixed electrical charge and the innermost layer of ions, called the Stern layer, is a practically immobile layer of oppositely charged ions in the liquid phase that are absorbed on the solid. Farther away from the solid, next to the Stern layer, is the mobile diffuse layer of ions, which is composed of mobile positively and negatively charged ions in the liquid phase. This layer may have a net charge of the same or opposite sign from that of the Stern layer.

The electrical potential difference that develops between the solid and the bulk solution (across the Stern and diffuse layers) is called the Nernst potential. This potential is the balance between the electrostatic attraction of the solution counter ions to the solid surface and their tendency to diffuse away from the surface. The potential drop that occurs across the diffuse layer is called the zeta potential and it is that potential that is readily varied through changes in bulk solution concentrations (see figure 1). As the zeta potential drops to zero, the diffuse layer thickness approaches zero and the Nernst potential drop occurs totally within the Stern layer. Under these conditions, a PZC or zero surface charge (ZSC) exists on the solid surface.

The zeta potential of materials in water of nearly neutral pH can be negative (usually the case) or positive (chrysotile and magnesium oxide). By adding cations or anions to the water, the magnitude of the charge on the material surface can be reduced until the zeta potential reaches zero. Continued addition of cations or anions will result in a zeta potential of increasing magnitude and opposite sign.

The procedure developed by the Bureau and described herein is a unique and novel approach for zeta potential determinations. Most of the older methods used for determining the zeta potential of any given material particle in a given solution rely on single tests of a unique fluid composition. If the PZC concentration is to be known, several separate and discrete tests must be performed and the PZC concentration determined by interpolation, or worse by extrapolation. If there are any contaminants or foreign particles present during any single test, repeatable results may not be obtained in subsequent tests if the same contaminant is not present or if other contaminants or foreign particles are present. In the technique described in this report, the zeta potentials can be determined for a complete range of additive concentrations with the same contaminant levels being present at all the additive concentrations. By adding small known increments of additive to the closed system, the PZC concentration can be precisely determined in a simple calculation and subsequent graphing procedure.

EXPERIMENTAL LABORATORY PROCEDURE

ZETA POTENTIAL TEST EQUIPMENT

The procedure for determining the zeta potential was the same regardless of the chemical additive or the water (distilled, deionized [DDIW]; tap; or mine) used for a baseline fluid. The same commercially available electrophoretic mobility-type apparatus was used for all the tests.

The electrophoretic apparatus operates on the basis that the surface charge of a material particle is proportional to the speed of the particle in a fluid in an electric field. The zeta potential for each fluid concentration increment was

[3]Italic numbers in parentheses refer to items in the list of references preceding the appendix at the end of this report.

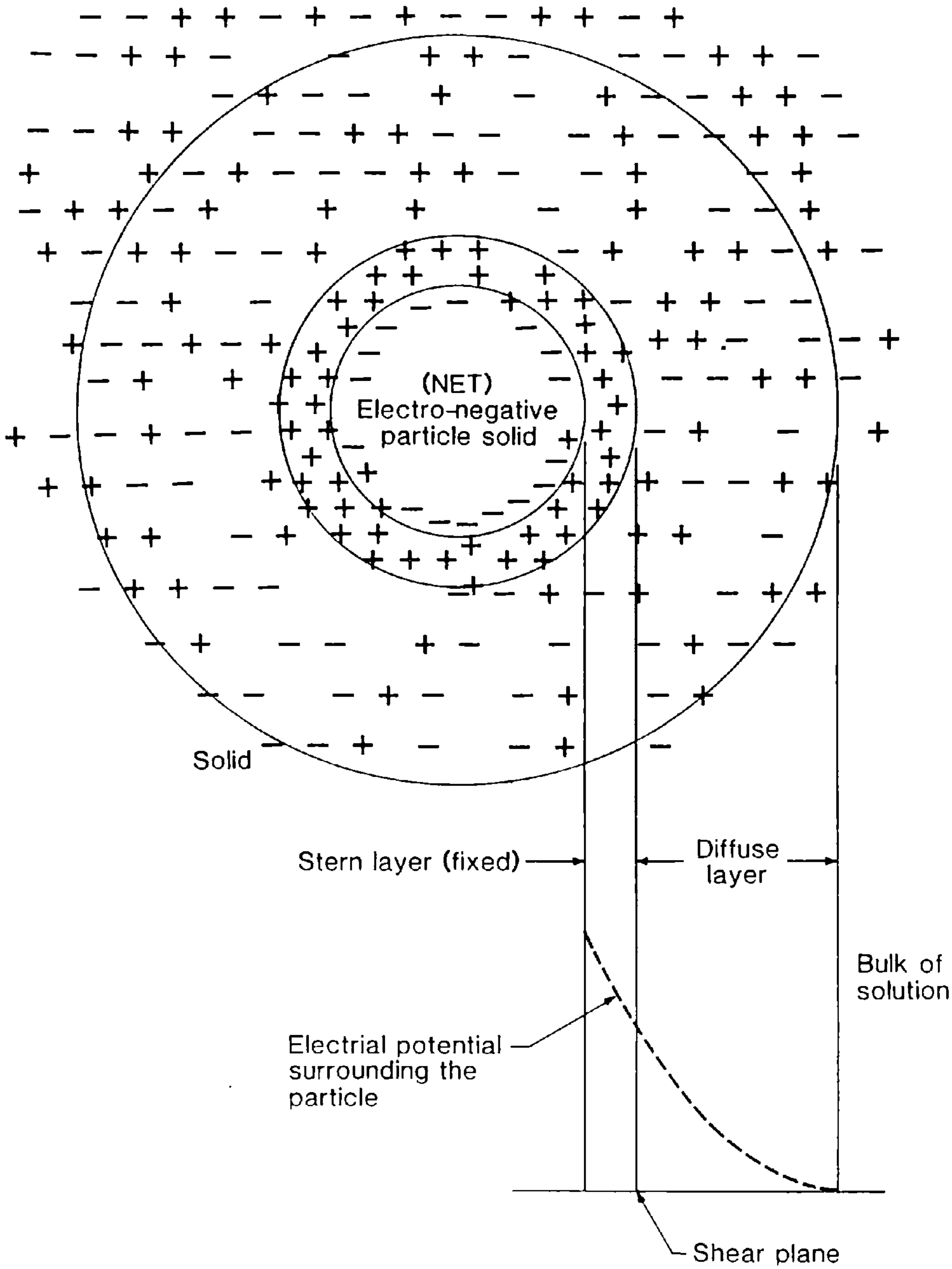

Figure 1.–Stern layer schematic.

determined by following the movement of an individual material particle across a monitor screen in an electric field of 10 V/cm, matching the speed of a grid line on the screen to the particle speed, and noting the zeta potential as displayed on the digital readout. When using calcium chloride ($CaCl_2$), magnesium sulfate ($MgSO_4$), or sodium chloride (NaCl), the required high ionic strength led to electrolysis at 10 V/cm, therefore, 5 V/cm was used, with no loss of accuracy.

Zeta potential values are temperature sensitive, which the zeta reader instrument accounts for in calculating the resulting, displayed zeta potential. All of the tests were conducted at room temperature, and the zeta reader was consistently between 25° and 40° C. The temperature values were noted for each test to assure that the test was conducted within that temperature range.

A plastic beaker was used as the fluid-material particle reservoir for all of the tests in order to prevent erroneous values resulting from possible adherence of ions to a glass beaker. The baseline fluid-particle mixture was kept in suspension with a magnetic stirrer. However, when a magnetic (or suspected magnetic material) was tested, a stirring propeller ("milkshake" stirrer) was employed to prevent biasing the zeta potential results to nonmagnetic particles resulting from removal of magnetic particles by attraction to the magnetic stir bar. In fact, a few materials that were not originally thought to be magnetic proved to be; and those tests were repeated using the milkshake stirrer.

ZETA POTENTIAL TEST PROCEDURE

In preparation for each test, the zeta reader was cleaned by flushing ultrapure distilled, deionized water (DDIW) through the system until no particles were observed on the monitor screen and the specific conductance read <10 μS/cm. After thoroughly cleaning the plastic beaker, 1,000 mL of fresh baseline water was put in it and the appropriate stirring system employed. The apparatus intake and outflow tubes were placed in the water and the stirrer was started. Next, approximately 0.2 g of minus 100-mesh crushed material particles was added to the baseline water. In the few cases (most notably Wausau quartzite) when the particles were very difficult to detect on the screen because of low optical density (semitransparent), 0.5 g of particles was added to make the tracking of particle movement easier.

Thirty zeta potential determinations were made for material particles in the baseline water system. After this test was completed, a precise amount (0.01 to 1.0 mL) of the test additive was added to the system from a concentrated stock solution, and again 30 zeta potential readings were made. Incremental additions of concentrated stock solution and zeta potential determinations (30) were continued until the zeta potential value was positive for several concentrations or until a relatively high concentration of additive was added without attaining a positive zeta potential reading, i.e., the zeta potential remained at or very near to zero or the zeta potential remained constant.

For magnesium oxide (MgO) brick, the zeta potential of particles in DDIW is positive below a pH of 12.4. For those tests, the procedure was identical to that described, except that the MgO zeta potential in DDIW was initially positive and changed to negative with incremental additions of an anionic additive. In tap water, however, the normally positive charge of MgO was more than neutralized by adsorbed anions from the tap water; the resulting initial zeta potential being negative as with most materials.

Three separate tests were performed for each cationic additive. Because there was no PZC concentration to be determined, only one test was performed for the anionic and nonionic additives to indicate performance trends.

ZERO SURFACE CHARGE CONCENTRATION DETERMINATION

PZC concentrations were determined using the following procedure. The 30 zeta potential determinations made in the baseline water and each additive concentration were respectively averaged. These average zeta potential values were then plotted as a function of additive concentration. Table 1 lists the average zeta potential values for the series of tests for Sioux Quartzite with aluminum chloride ($AlCl_3$) in DDIW. These values (in millivolts) were plotted versus $AlCl_3$ concentration (in moles per liter). The best curve was drawn through the points of each test using a curve-fitting program, and the concentration where the curve crossed the zero zeta potential line was taken as the PZC concentration. Figure 2 illustrates these curves for the Sioux Quartzite-$AlCl_3$-DDIW system.

Table 1.–Average zeta potential values for Sioux Quartzite with $AlCl_3$ in DDIW test series, millivolts

Additive conc, 10^{-7} mol/L	Test 1	Test 2	Test 3
DDIW	-26.00	-25.50	-25.40
1	-24.40	-20.60	-18.00
3	-14.70	-12.50	-11.60
6	-5.90	-3.90	-2.30
10	11.00	10.30	18.50
30	28.30	28.50	31.90
60	35.70	35.70	45.40
90	41.10	43.50	47.80

DDIW Distilled, deionized water.

For cationic additives, PZC concentration values were determined for each of the three replicate tests and then averaged to get a single PZC concentration for each material-additive system. Table 2 lists the average zeta potential values and the average PZC concentration for the Sioux Quartzite-$AlCl_3$-DDIW system. This procedure was followed for all of the cationic additive tests.

Table 2.–PZC concentrations as determined from graphical analysis for Sioux Quartzite with $AlCl_3$ in DDIW

Test	Zeta potential of particles in DDIW, mV	PZC conc, 10^{-7} mol/L
1	-26.0	7.4
2	-25.5	7.2
3	-25.4	6.5
Av	-25.6	7.0

DDIW Distilled, deionized water.
PZC Point of zero charge.

For anionic and nonionic additive tests, the graphing procedure was similar. The average zeta potential values for the single test were plotted versus additive concentration. Figure 3 is a representative graph for the results of Sioux Quartzite in the anionic surfactant, Nalco 8830, while figure 4 illustrates the results for Sioux Quartzite using the nonionic polymer, polyethylene oxide (PEO), with the values used in plotting the curves in these two figures listed in table 3.

Table 3.–Values used in graph of Sioux Quartzite tests using anionic and nonionic additives

Additive conc, ppm	*Zeta potential, mV*
Anionic, Nalco 8830:	
DDIW	-29.14
1	-34.04
5	-42.98
10	-57.21
100	-59.51
190	-75.37
Nonionic, PEO:	
Tap water	-33.01
1	-11.25
3	-1.18
7.48	.00
12.4	.00
122	.00

DDIW Distilled, deionized water.

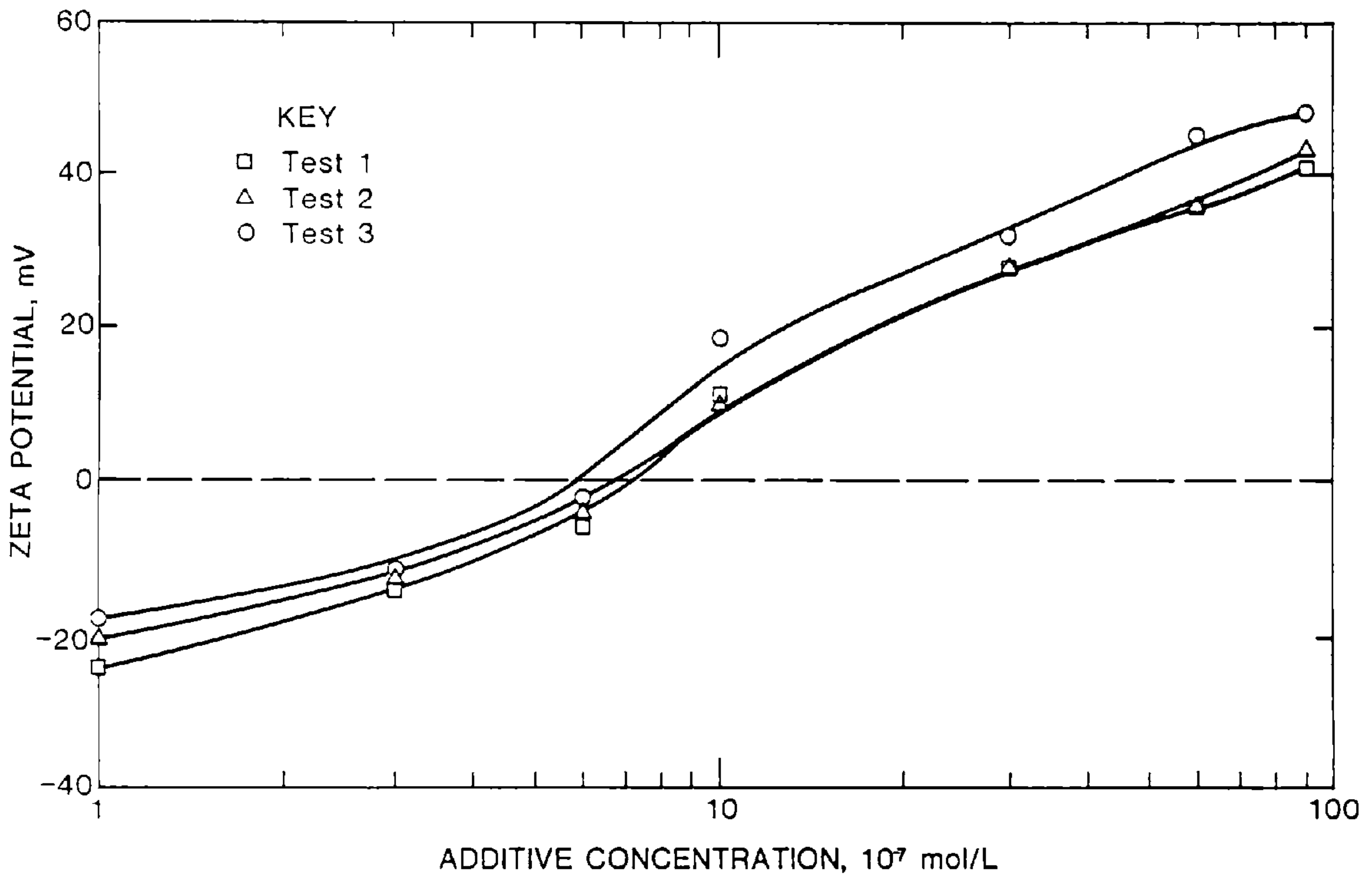

Figure 2.–Example of graphical analysis.

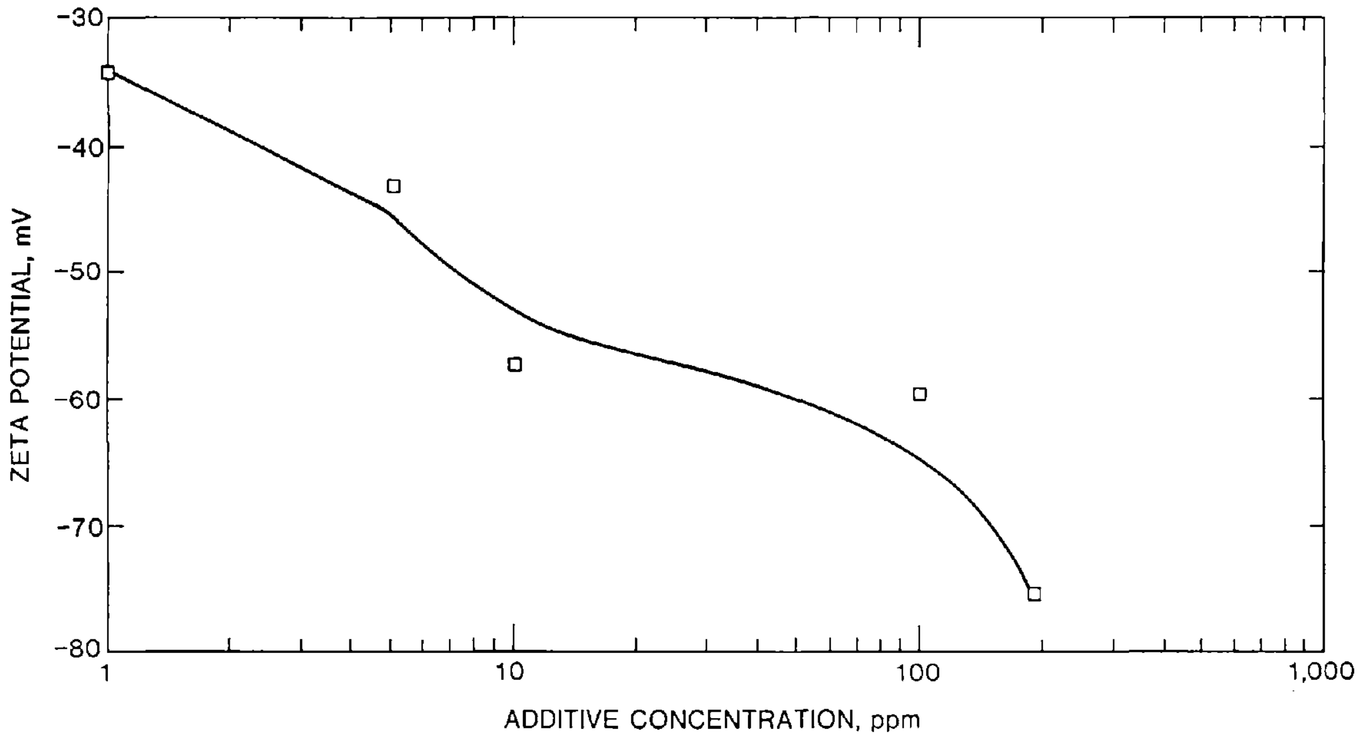

Figure 3.–Example of anionic additive results.

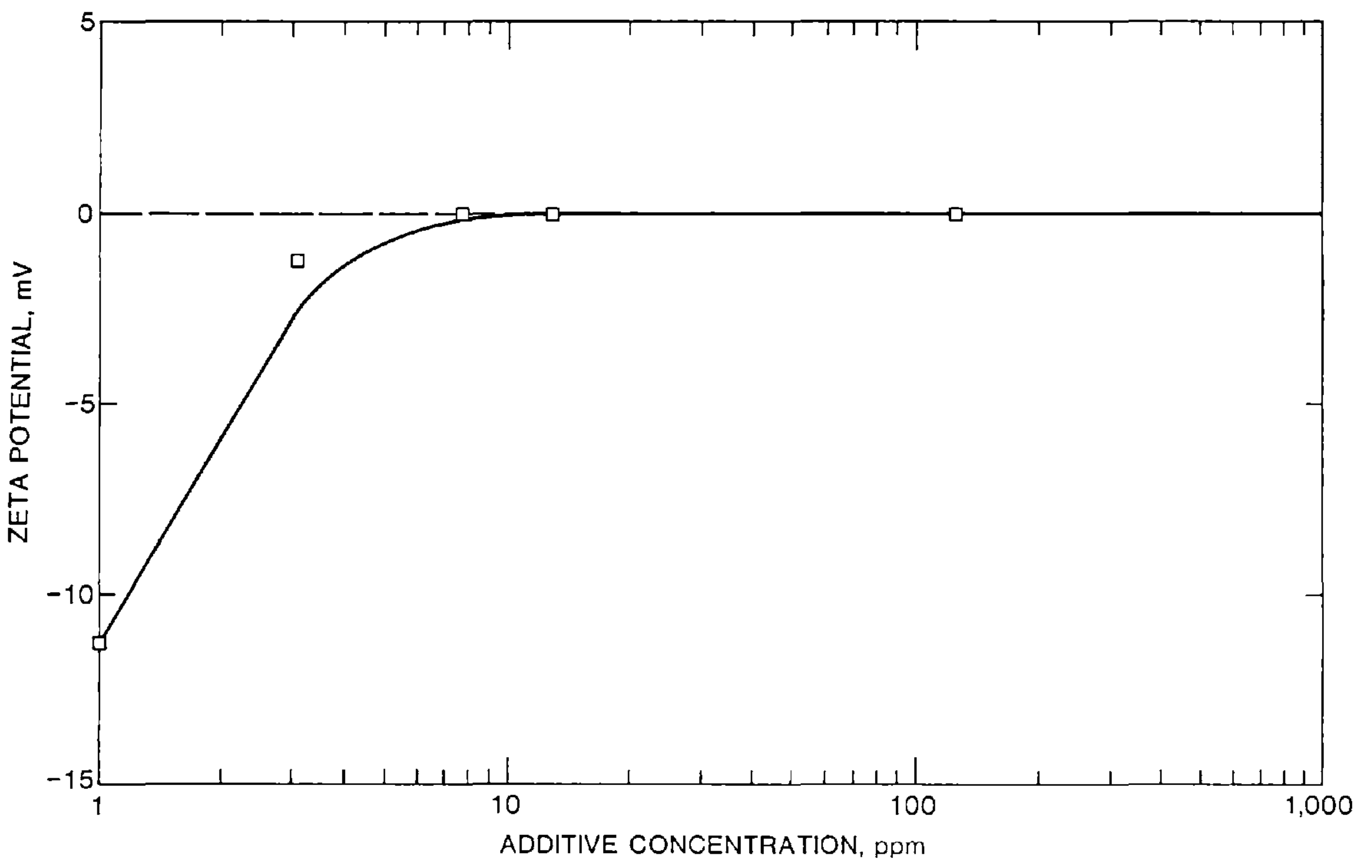

Figure 4.–Example of nonionic additive results.

RESULTS AND DISCUSSION

The wide variety of materials, the diverse series of chemical additives, and the baseline waters used in these tests are listed in tables 4, 5, and 6, respectively. Test results and additional information is contained in the appendix. Table A-1 compiles the zeta potential tests performed for each additive categorized by material type, while table A-2 lists the same data for each material tested, categorized by chemical additive. Table A-3 is a compilation of the chemical analyses for the waters tested; table A-4 lists the oxide content of the materials tested; and table A-5 describes the special materials of coal, diamond, and cobalt. These tables are presented to explain the differences between the subsequent zeta potential results for the materials. The zeta potential and PZC values for cationic and anionic additives are listed by material type in table A-6 and by additive in table A-7. Table A-8 lists the pH modified zeta potential tests, table A-9 lists the cationic nonionic, and anionic results for Sioux Quartzite and the anionic results for Mahogany granite, table A-10 lists nonionic PEO results, table A-11 lists the results when using combinations of anionic additives with PEO, and table A-12 lists the results when using an excess of additive.

In comparing the results of these tests, several important and interesting correlations can be made from several critical factors in the zeta potential and PZC concentration determinations. These factors are water quality, material composition, inorganic additive cation valence, organic additive carbon-chain length, the effect of anionic and nonionic additives, the effect of anionic plus nonionic additive combinations, and the effect of excess cations on the zeta potential. These results given in the tables are discussed in the following sections.

Table 4.-Materials tested

Material	*Source*
Australian muscovite	Purchased mineral sample.
Barre Granite	Barre, VT.
Biotite	Purchased mineral sample.
Charcoal granite	St. Cloud, MN (known as St. Cloud Gray Granodiorite).
Coal	Jim Walters Resources Coal Mine, Alabama.
Cobalt	Purchased mineral sample.
Cobalt powder	Hard Materials Research Inc., Mississauga, Ontario, Canada.
Diamond	Purchased mineral sample.
Dresser basalt	Dresser Mine, Dresser, WI.
Feldspar series (albite, andesine, anorthite, bytownite, microcline, and oligoclase).	Purchased mineral sample.
INCO section 275:	
Quartzite	Thompson Mine, Thompson, Manitoba, Canada.
Pegmatite	Do.
INCO 2800 level quartzite	Do.
INCO 3400 level nickel-sulfide ore	Do.
LCA pegmatite: Samples A and B	Lithium Corporation of America (LCA) mine, Bessemer City, NC.
Magnesium oxide brick	Sample from previous MgO research project.
Mahogany granite:	
Grindings	Dakota Granite Quarry, Milbank, SD.
Saw cuttings	Do.
Minnesota taconite (whole, magnetic, and nonmagnetic fractions: Samples A, B, and C.	Erie Mining Co., Hoyt Lakes, MN.
Minntac taconite: Samples A and B	Minntac Mine, Eveleth, MN.
Rockville Granite	St. Cloud, MN.
Salida granite	Denver, CO.
Sioux Quartzite	Jasper Stone Quarry, Jasper, MN.
South Dakota feldspar	Purchased mineral sample.
Sudbury granite	Sudbury, Ontario, Canada.
Tennessee marble	Holston Limestone formation, east Tennessee.
Tungsten carbide: Powder and powder with 6 pct Co granules.	Hard Materials Research Inc., Mississauga, Ontario, Canada.
Wausau quartzite	Wisconsin.
Westerly Granite	Bradford, RI.

Table 5.–Additives tested

Additive		Conc range
Cationic:		
Aluminum chloride	mol/L	1×10^{-8}-1×10^{-3}
Aluminum nitrate	mol/L	1×10^{-7}-1×10^{-4}
Calcium chloride	mol/L	1×10^{-3}-1×10^{-1}
Magnesium sulfate	mol/L	1×10^{-3}-1×10^{-1}
Potassium aluminum sulfate	mol/L	1×10^{-7}-1×10^{-4}
Potassium chloride	mol/L	1×10^{-3}-1×10^{-1}
Sodium chloride	mol/L	1×10^{-2}-1×10^{0}
Titanium iodide	mol/L	1×10^{-7}-1×10^{-4}
Zirconium chloride	mol/L	1×10^{-7}-1×10^{-4}
Zirconium nitrate	mol/L	1×10^{-7}-1×10^{-4}
DTAB	mol/L	1×10^{-4}-1×10^{-2}
HTAB	mol/L	1×10^{-7}-1×10^{-3}
TTAB	mol/L	1×10^{-6}-1×10^{0}
Armac series (Akzo Chemie America)	mol/L	1×10^{-4}-1×10^{-2}
Nalco series (Nalco Corp.)[1]	mol/L	1×10^{-7}-1×10^{-4}
Percol series (Allied Colloids, Inc.)	mol/L	1×10^{-7}-1×10^{-4}
Polyacrylamide (American Cyanamid)	ppm	0.01- 1
Nonionic, ppm:		
Tergitol NPX (Union Carbide)		0.1- 10
Surfynol 465 (Air Products and Chemicals, Inc.)		0.1- 100
PEO (Union Carbide)		1 - 125
HEC (Union Carbide)		1 - 100
Revert (UOP Johnson, Inc.)		1 - 100
Anionic, ppm:		
Biocut[2]		1 - 100
Polymer		1 - 100
Solulube (Texaco)		1 - 100
Vibrastop[2]		1 - 100
ZEP Lubeeze (ZEP Manufacturing Co.)		1 -20,000
Dromus B[2]		1 - 5,000

DTAB Dodecyltrimethyl ammonium bromide.
HTAB Hexadecyltrimethyl ammonium bromide.
HEC Hydroxyethyl cellulose.
PEO Polyethylene oxide.
TTAB Tetradecyltrimethyl ammonium bromide.
[1]Nalco 8830 was anionic.
[2]Supplied by Longyear Canada.

Table 6.–Baseline waters

Water	Source
DDIW	Distilled, deionized water from still in laboratory.
Tap water	Minneapolis, MN–3 sources, fresh, and hot and cold left to stand overnight.
	Denver, CO.
	Dresser, WI.
	Farmington, MN.
	Roanoke, VA.
	INCO Thompson Mine (Thompson, Manitoba, Canada).
Mine water	LCA (Lithium Corporation of America, Bessemer, NC).
	Erie Mining Co. (Hibbing, MN)–2 sources, well and pond, well water obtained in November 1986 and May 1987.
	Minntac Mine (Eveleth, MN).
	Dresser Mine (Dresser, WI).
Quarry water	Dakota Granite Company (Milbank, SD).

EFFECT OF WATER QUALITY ON PZC CONCENTRATION

With respect to water quality, the purer the water, the lesser amount of additive needed to neutralize the material surface charge and achieve the PZC condition. For example, in comparing DDIW and Minneapolis tap water results for Sioux Quartzite with $AlCl_3$, the PZC concentration for DDIW was 7.0×10^{-7} mol/L, while with tap water it was 4.5×10^{-5} mol/L. The naturally occurring anions in the relatively hard and chemically treated Minneapolis tap water adsorb onto the material surface and drastically change the amount of Al^{-3} required to reach the PZC condition (tables A-6 and A-7). Because of the critical nature of water quality as demonstrated by these results, chemical analyses were conducted for all the waters tested. These analyses are listed in table A-3. The quality of the water will be a major determining factor in the zeta potential and ultimate PZC concentration. This phenomenon was observed in all the material-additive combinations tested in varying baseline waters (tables A-6 and A-7).

For Al^{3+} ions, water pH is also important because of the propensity of Al^{3+} ions to precipitate and flocculate as $Al(OH)_3$ above a certain pH. Several tests were conducted that used acid (HCl) to lower the pH of the water to a level where the Al^{3+} ion was stable in solution. The presence of the acid markedly affected the PZC concentration for all the materials tested in $AlCl_3$, as was evident when comparing the PZC concentration values for Sioux Quartzite in tap water. Without pH modification, when the water was at pH of 7.0 to 8.0 the PZC concentration was 4.5×10^{-5} mol/L. However, with addition of HCl to keep the pH below 4.0, the PZC concentration rose to 1.17×10^{-4} mol/L. Table A-8 lists the results for this series of tests using tap or mine water and $AlCl_3$ with pH modification to below 4.0.

EFFECT OF MATERIAL COMPOSITION ON PZC CONCENTRATION

It has been suggested in discussions with other researchers that the zeta potential for any material type would be very consistent; i.e., any granite would react the same to any specific additive. However, this research has shown that the zeta potential and PZC concentration values are critically related to specific material composition, in addition to water quality.

In tests of several different granites, the zeta potential and PZC concentrations in the same water with the same additive were quite different. The zeta potential for Charcoal granite in DDIW was -25.20 mV, while that for Westerly Granite was -18.20 mV. The resulting PZC concentrations were 1.40×10^{-6} and 7.26×10^{-7} mol/L, respectively. Even the slight difference in chemical composition between these two granites of similar mineralogy made a considerable difference in the zeta potential and PZC concentration.

This phenomenon was observed for all material types tested (tables A-6 and A-7) since they are composed of differing minerals and materials making up the whole material. Because of this factor, chemical analyses were obtained for most material particles tested to determine which minerals and oxides are present in each material (tables A-4 and A-5).

A separate series of tests was conducted on an artificial material substance, MgO bricks. Magnesium oxide is known to have a positive zeta potential in pure water below a pH of 12.4. These tests were conducted to see if zeta potential modifiers could also be used to approach and obtain the PZC condition if the initial zeta potential of the material was positive. Using an anionic surfactant (Nalco 8830) in DDIW, a PZC condition was realized at 2.15×10^{-4} pct. When testing MgO brick in tap water, however, anions from the impure water adsorbed on the particles to give them negative surface charge just like the other materials with initial negative surface charge. Results of these MgO brick tests are summarized in tables A-6, A-7, and A-10.

EFFECT OF INORGANIC SALT CATION VALENCE ON PZC CONCENTRATION

It is evident from a comparison of results for cations of different valances (tables A-6 and A-7) that, in general, the higher the cation valence, the more effective the cation will be in producing the PZC condition. The exception is Zr^{4-} ions which are not stable in aqueous solution and most likely react with an OH^- ion to form the $Zr(OH)^{3+}$ ion in solution. Using Sioux Quartzite as an example, $AlCl_3$ caused a PZC to occur at 7.0×10^{-7} mol/L for DDIW. However, using $CaCl_2$ in DDIW required much more additive, reaching the PZC at 1.6×10^{-2} mol/L, while NaCl required 2.17×10^{-1} mol/L. This phenomenon held true for all material-additive suites tested, as well as for all waters tested.

Because of an interest in other additives, and since most of the zeta potential tests concentrated on inorganic salts, a series of organic surfactants was also tested. Three long-carbon-chain surfactants were used: dodecyltrimethyl ammonium bromide (DTAB), tetradecyltrimethyl ammonium bromide (TTAB), and hexadecyltrimethyl ammonium bromide (HTAB). The resulting PZC concentrations for Sioux Quartzite in DDIW were 9.35×10^{-4} mol/L for the 12-carbon DTAB, 7.23×10^{-5} mol/L for the 14-carbon TTAB, and 1.56×10^{-6} mol/L for the 16-carbon HTAB. In this case, the longer-chain additives behaved like the higher valence additives. This again held true for all the materials tested with these three additives (tables A-6 and A-7).

EFFECT OF ANIONIC AND NONIONIC ADDITIVES ON ZETA POTENTIAL

Another group of tests was conducted to determine the effect of anionic and nonionic additives on the material particles. As expected, the anionic additives produced a more negative zeta potential without attaining a PZC condition, while all but one of the nonionic additives produced no effect on the zeta potential at all. Table A-9 lists the results for several anionic and nonionic additives in which the zeta potential never reached a zero value, with figure 2 illustrating the results.

The exception to those results was quite interesting and unique. Polyethylene oxide, being nominally nonionic and not expected to affect the zeta potential in any way, did achieve a ZSC concentration. In fact, the most interesting phenomenon is that the ZSC conditions remained constant after a certain concentration was reached, with the zeta potential not changing sign. Table A-10 lists these results for a large suite of materials in various waters. These results are illustrated in figure 3 for Sioux Quartzite in tap water and are representative for all materials tested.

EFFECT OF ANIONIC PLUS NONIONIC COMBINATIONS ON ZETA POTENTIAL

Because of the success the nonionic PEO demonstrated in neutralizing surface charge, combinations of anionic additives with PEO were tested. ZEP Lubeeze is a cutting oil currently used in cutting or sawing of granite slabs, while Dromus B is used as a lubricating oil in drilling operations. Because both of these anionic agents are currently used in cutting-drilling operations, it was of interest to see what effect, if any, the PEO would have when added to solutions at concentrations used in the field. While requiring a bit more than when used alone, the PEO nevertheless still neutralized surface charge. The results for the two combinations tested, varying anionic additive concentration as a baseline and adding PEO until neutralization occurred, are summarized in table A-11.

EFFECT OF EXCESS CATIONIC ADDITIVE ON ZETA POTENTIAL

The last test was conducted to see what effect, if any, very high concentrations (much stronger concentrations than required for the PZC condition) of cationic additive would have on the zeta potential and the PZC. Table A-12 lists the values for that test conducted to determine what those excess ions would do to the zeta potential for Sioux Quartzite with $AlCl_3$ in DDIW; figure 5 illustrates the effect of those high zeta potential values. The excess ions only increased the zeta potential to a level that almost exceeded the limitations of the zeta reader, but did not create a measurable second PZC condition as had been predicted by surface science theory.

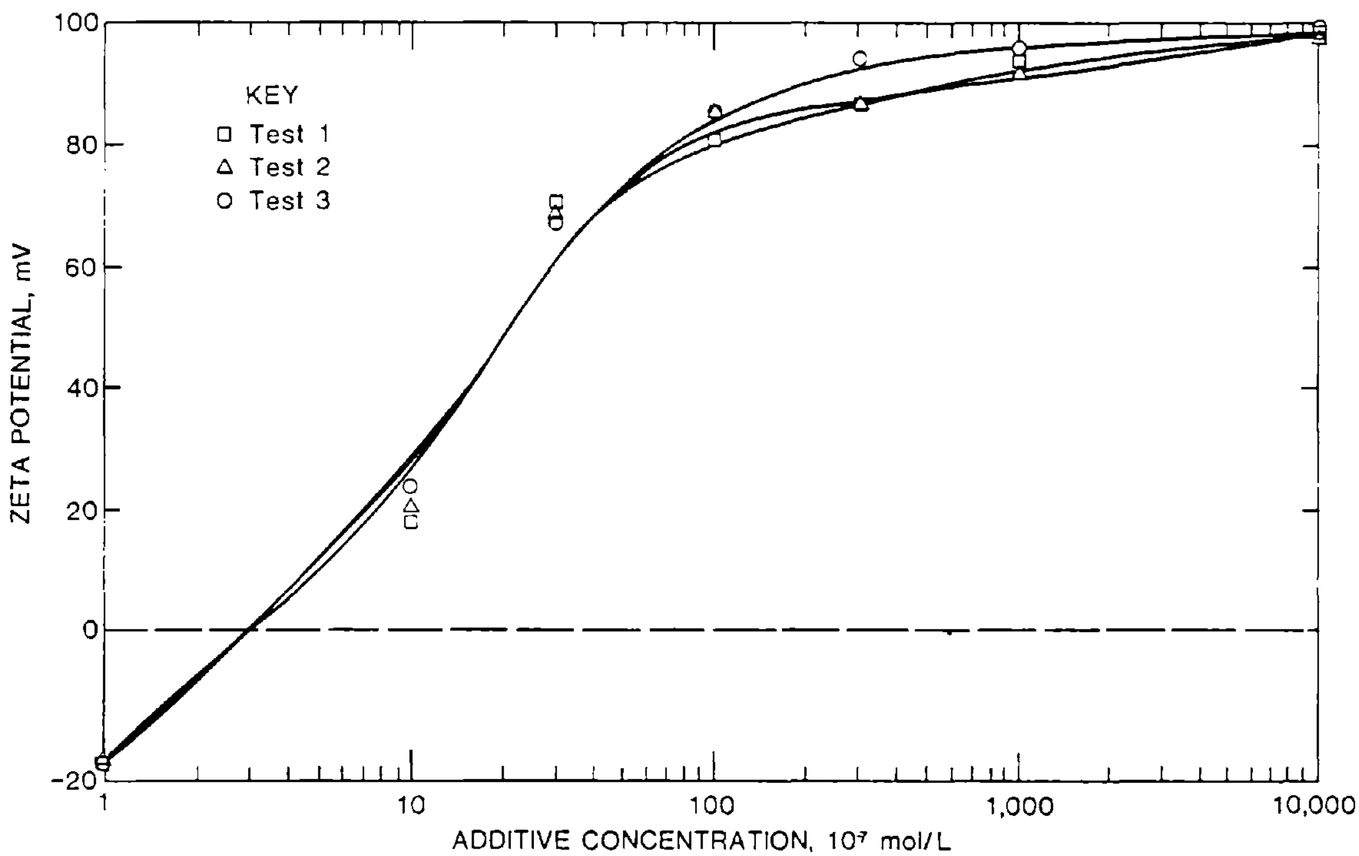

Figure 5.–Example of $AlCl_3$ high concentration test.

CONCLUSIONS

This novel technique for the determination of the zeta potentials and the resulting PZC and/or ZSC concentrations for materials in baseline water and additive solutions under many varied conditions should prove to be useful in other operations as well as in drilling, cutting, and grinding. Any needed zeta potential and/or PZC concentration values for a given system should be obtainable with the use of this closed-system technique and should prove to be very accurate, reliable, and repeatable. Any electrophoretic mobility-type zeta potential equipment can be adapted to this technique. The zeta potential and PZC concentration values in this report, and the noted variations in the values because of changes in additive and/or baseline waters, should further the understanding of how to control zeta potentials in many processes.

Several conclusions can be drawn from the zeta potential results by comparing the diversity of effect on the zeta potential caused by water quality, material type, cationic additives, anionic additives, and/or nonionic additives. The critical effect of each of these parameters must be considered when determining zeta potentials and predicting PZC concentrations for any chemical additive-material system. Generalizations and close approximations can be made regarding the response of any particular material and/or additive in a zeta potential experiment. However, when precise or accurate zeta potentials and/or PZC concentrations are required, special care must be exercised. The use of the closed-system and graphing technique should yield those precise values required by the experimenter.

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APPENDIX

Table A-1.–Summary of zeta potential tests performed, by material type

Material	*Additive*[1]
Australian muscovite	Aluminum chloride.
	Aluminum nitrate.
	Potassium chloride.
	HTAB.
Barre Granite	PEO in Roanoke, VA, tap water.
Biotite	Aluminum chloride.
Charcoal granite	Do.
	Aluminum chloride in tap water.
	Calcium chloride.
	Magnesium sulfate.
	Sodium chloride.
	Zirconium chloride.
	PEO in tap water.
Coal (Jim Walters Resources)	Do.
Cobalt	Aluminum chloride.
Cobalt powder	PEO in tap water.
Diamond	Aluminum chloride.
Dresser basalt	Do.
	Aluminum chloride in Dresser, WI, city water.
	Aluminum chloride in mine water.
	Aluminum chloride, pH modified.
Feldspar series:	
Albite	Aluminum chloride.
Andesine	Do.
Anorthite	Do.
Bytownite	Do.
Microcline	Do.
Oligoclase	Do.
INCO section 275:	
Quartzite	PEO in INCO tap water.
	PEO in tap water.
Pegmatite	Do.
INCO 2800 level quartzite	Do.
INCO 3400 level nickel-sulfide ore	Do.
LCA pegmatite	Aluminum chloride.
	Aluminum chloride in mine water.
	Aluminum nitrate.
	Aluminum nitrate in mine water.
Samples A and B	Aluminum chloride in mine water.
	Aluminum nitrate in mine water.
Sample A	PEO in mine water.
Magnesium oxide brick	Nalco 8830.
	PEO.
	PEO in tap water.
Mahogany granite:	
Grindings	PEO in Dakota Granite quarry water.
Saw cuttings	Do.
	Anionic polymer in tap water.
	ZEP Lubeeze in tap water.
	ZEP Lubeeze in quarry water.
	ZEP Lubeeze plus PEO in quarry water.
Minnesota taconite:	
Whole, magnetic, and nonmagnetic fractions:	
Samples A, B, and C	Aluminum chloride.
Samples A and B	Aluminum chloride in November mine water.
	Aluminum chloride in May mine water.
Whole fractions:	
Samples A and B	Aluminum chloride, pH modified.
	Nalco 7132 in mine water.
	Percol 402 in mine water.
	PEO.
	PEO in tap water.
	PEO in mine water.

See explanatory notes at end of table.

Table A-1.–Summary of zeta potential tests performed, by material type–Continued

Material	*Additive*[1]
Minntac taconite:	
Sample A	Aluminum chloride.
	PEO in mine water.
Sample B	Aluminum chloride.
	PEO in mine water.
Rockville Granite	Aluminum chloride.
	Aluminum chloride in tap water.
	Calcium chloride.
	Magnesium sulfate.
	Sodium chloride.
	Zirconium chloride.
	DTAB.
	HTAB.
	TTAB.
	PEO in tap water.
Salida granite	Aluminum chloride in Denver, CO, tap water, pH modified.
	PEO in Denver, CO, tap water.
Sioux Quartzite	Aluminum chloride.
	Aluminum chloride in tap water.
	Aluminum chloride in tap water, pH modified.
	Aluminum chloride at high concentrations.
	Aluminum nitrate.
	Calcium chloride.
	Magnesium sulfate.
	Potassium aluminum sulfate.
	Sodium chloride.
	Titanium iodide.
	Zirconium chloride.
	Zirconium nitrate.
	DTAB.
	HTAB.
	HTAB in tap water.
	TTAB.
	Armac series.
	Nalco series.
	Percol series.
	Tergitol NPX.
	Surfynol 465 in tap water.
	Biocut in tap water.
	HEC in tap water.
	Revert in tap water.
	Soluble in tap water.
	Vibrastop in tap water.
	Polyacrylamide in tap water.
	PEO.
	PEO in tap water.
	PEO in Farmington, MN, tap water.
South Dakota feldspar	Aluminum chloride.
	Calcium chloride.
	Magnesium sulfate.
	DTAB.
	HTAB.
	TTAB.
Sudbury granite	PEO in tap water.
	PEO plus Dromus B in tap water.
Tennessee marble	Aluminum chloride.
	Aluminum chloride in tap water.
	Calcium chloride.
	Magnesium sulfate.
	Sodium chloride.
	Titanium iodide.
	Zirconium chloride.
	Zirconium nitrate.
	DTAB.
	HTAB.
	TTAB.
	PEO in Farmington, MN, tap water.

[1]See explanatory notes at end of table.

Table A-1.–Summary of zeta potential tests performed, by material type–Continued

Material	*Additive*[1]
Tungsten carbide:	
Powder	PEO in tap water.
Powder with 6 pct Co granules	Do.
Wausau quartzite	Aluminum chloride.
	Calcium chloride.
	Magnesium sulfate.
	Sodium chloride.
	Zirconium chloride.
	Zirconium nitrate.
	DTAB.
	HTAB.
	TTAB.
Westerly Granite	Aluminum chloride.
	Aluminum chloride in tap water.
	Calcium chloride.
	Magnesium sulfate.
	Sodium chloride.
	Zirconium chloride.
	PEO in tap water.

DDIW Deionized, distilled water.
DTAB Dodecyltrimethyl ammonium bromide.
HTAB Hexadecyltrimethyl ammonium bromide.
HEC Hydroxyethyl cellulose.
PEO Polyethylene oxide.
TTAB Tetradecyltrimethyl ammonium bromide.
[1]All tests conducted in DDIW unless otherwise stated. Tap water used was from Minneapolis, MN, unless otherwise stated.

Table A-2.–Summary of zeta potential tests performed, by additive

Additive[1]	*Material*
Aluminum chloride	Australian muscovite.
	Biotite.
	Charcoal granite.
	Cobalt powder.
	Diamond.
	Dresser basalt.
	Feldspar series.
	LCA pegmatite.
	Minnesota taconite.
	Minntac samples A and B.
	Rockville Granite.
	Sioux Quartzite.
	South Dakota feldspar.
	Tennessee marble.
	Wausau quartzite.
	Westerly Granite.
Alumnium chloride in tap water	Charcoal granite.
	Rockville Granite.
	Sioux Quartzite.
	Tennessee marble.
	Westerly Granite.
Aluminum chloride, pH modified	Dresser basalt.
	Sioux Quartzite.
Aluminum chloride in LCA mine water	LCA pegmatite.
Aluminum chloride in Erie mine water	Minnesota taconite.
Aluminum chloride in Dresser, WI, tap water	Dresser basalt.
Aluminum chloride in Denver, CO, tap water, pH modified	Salida granite.
Aluminum chloride in Erie mine water, pH modified	Minnesota taconite.
Aluminum chloride in Dresser, WI, city water	Dresser basalt.
Aluminum nitrate	Australian muscovite.
	LCA pegmatite.
	Sioux Quartzite.
Aluminum nitrate in LCA mine water	LCA pegmatite.
Calcium chloride	Charcoal granite.
	Rockville Granite.
	Sioux Quartzite.
	South Dakota feldspar.
	Tennessee marble.
	Wausau quartzite.
	Westerly Granite.
Magnesium sulfate	Charcoal granite.
	Rockville Granite.
	Sioux Quartzite.
	South Dakota feldspar.
	Tennessee marble.
	Wausau quartzite.
	Westerly Granite.
Potassium aluminum sulfate	Sioux Quartzite.
Potassium chloride	Australian muscovite.
Sodium chloride	Charcoal granite.
	Rockville Granite.
	Sioux Quartzite.
	Tennessee marble.
	Wausau quartzite.
	Westerly Granite.
Titanium iodide	Sioux Quartzite.
	Tennessee marble.
Zirconium chloride	Charcoal granite.
	Rockville Granite.
	Sioux Quartzite.
	Tennessee marble.
	Wausau quartzite.
	Westerly Granite.
Zirconium nitrate	Sioux Quartzite.
	Tennessee marble.
	Wausau quartzite.

See explanatory notes at end of table.

Table A-2.–Summary of zeta potential tests performed, by additive–Continued

Additive[1]	*Material*
DTAB	Rockville Granite.
	Sioux Quartzite.
	South Dakota feldspar.
	Tennessee marble.
	Wausau quartzite.
HTAB	Australian muscovite.
	Rockville Granite.
	Sioux Quartzite.
	South Dakota feldspar.
	Tennessee marble.
	Wausau quartzite.
HTAB in tap water	Sioux Quartzite.
TTAB	Rockville Granite.
	Sioux Quartzite.
	South Dakota feldspar.
	Tennessee marble.
	Wausau quartzite.
Armac series	Sioux Quartzite.
Nalco series	Do.
Nalco 7132 in Erie mine water	Minnesota taconite sample B.
Percol series	Sioux Quartzite.
Percol 402 in Erie mine water	Minnesota taconite sample B.
Polyacrylamide in tap water	Sioux Quartzite.
Anionic polymer in tap water	Mahogany granite.
Biocut in tap water	Sioux Quartzite.
Tergitol NPX	Do.
Solulube in tap water	Do.
Surfynol 465 in tap water	Do.
Vibrastop in tap water	Do.
ZEP Lubeeze in tap water	Mahogany granite.
ZEP Lubeeze in quarry water	Do.
HEC in tap water	Sioux Quartzite.
Revert in tap water	Do.
PEO	Magnesium oxide brick.
	Minnesota taconite sample B.
	Sioux Quartzite.
PEO in tap water	Charcoal granite.
	Coal (Jim Walters Resources).
	Cobalt powder.
	INCO section 275 quartzite.
	INCO section 275 pegmatite.
	INCO 2800 level quartzite.
	INCO 3400 level nickel-sulfide ore.
	Magnesium oxide brick.
	Minnesota taconite sample B.
	Rockville Granite.
	Sioux Quartzite.
	Sudbury granite.
	Tungsten carbide powder.
	Tungsten carbide powder with 6 pct Co granules.
	Westerly Granite.
PEO in Roanoke, VA, tap water	Barre Granite.
PEO in Denver, CO, tap water	Salida granite.
PEO in Farmington, MN, tap water	Sioux Quartzite.
	Tennessee marble.
PEO in INCO tap water	INCO section 275 quartzite.
PEO in LCA mine water	LCA pegmatite sample A.
PEO in Erie mine water	Minnesota taconite sample B.
PEO in Minntac mine water	Minntac sample A.
	Minntac sample B.
PEO in quarry water	Mahogany granite.
PEO plus Dromus B in tap water	Sudbury granite.
PEO plus ZEP Lubeeze in quarry water	Mahogany granite.

DDIW Deionized, distilled water.
DTAB Dodecyltrimethyl ammonium bromide.
HEC Hydroxyethyl cellulose.
HTAB Hexadecyltrimethyl ammonium bromide.
PEO Polyethylene oxide.
TTAB Tetradecyltrimethyl ammonium bromide.
[1]All tests conducted in DDIW unless otherwise stated. Tap water used was from Minneapolis, MN, unless otherwise stated.

Table A-3.-Chemical analyses of waters used

	Al, ppm	Ca, ppm	Mg, ppm	Mn, ppm	Na, ppm	K, ppm	SO_4^{-2}, pct	Si, ppm	Cl^-, pct
DDIW	<0.02	<0.02	<0.01	<0.02	<0.50	<0.50	<2.00	0.54	1.40
Tap water:									
Minneapolis, MN	.06	20.80	6.60	<.10	10.30	2.20	<.50	3.30	<5.00
Denver, CO	.06	14.10	2.40	<.02	ND	.82	ND	3.20	ND
Dresser, WI	<.02	47.90	17.90	<.02	ND	.83	ND	10.10	ND
Farmington, MN (well)	ND	49.00	23.90	<.10	4.30	1.00	20.00	6.50	<5.00
Roanoke, VA	ND	22.00	4.10	<.10	4.20	1.00	23.00	1.60	<5.00
Mine water:									
LCA	<.02	6.70	3.50	<.02	ND	.79	ND	9.50	ND
Erie, MN:									
November (well)	<.02	123.10	133.40	<.02	18.70	13.90	300.00	6.40	ND
May (well)	<.02	113.00	111.60	<.02	15.50	13.60	225.00	5.20	ND
Pond	ND	76.50	45.20	1.80	40.00	7.40	121.00	10.60	54.50
Minntac	ND	67.20	94.30	<.10	44.40	17.30	.39	<5.00	36.00
Dresser, WI	.02	30.70	11.30	<.02	ND	.68	ND	5.80	ND
INCO	ND	10.00	1.80	1.70	7.40	.84	23.00	5.80	<5.00
Quarry water: Milbank, SD	ND	100.00	58.00	.22	37.00	8.80	240.00	4.20	51.00

DDIW Distilled, deionized water.
ND Not determined.

Table A-4.–Oxide content of raw materials, percent

	SiO_2	Al_2O_3	Fe_2O_3	FeO	MgO	CaO	Na_2O	K_2O
Barre Granite	71.05	13.80	ND	0.98	0.86	1.04	3.98	0.61
Charcoal granite	67.41	15.12	2.32	1.89	2.32	3.78	2.84	3.03
Dresser basalt	47.39	13.89	6.65	6.69	6.30	8.96	2.43	.50
Feldspar series:								
Albite	62.47	21.35	.29	<.40	<.17	4.01	8.76	.69
Andesine	52.84	24.50	1.24	<.40	.40	10.54	4.31	.64
Anorthite	43.97	34.77	.87	<.40	.17	21.06	.54	<.60
Bytownite	48.56	29.52	.43	<.40	.32	16.93	2.50	<.60
Microcline	65.46	18.33	.57	<.40	<.17	.66	4.85	6.99
Oligoclase	64.61	21.03	<.29	<.40	<.17	4.25	8.31	.40
INCO section 275:								
Pegmatite	69.34	15.03	ND	.21	<.17	.70	.88	9.08
Quartzite	79.61	5.01	ND	.81	1.66	2.87	.20	.80
INCO 2800 level quartzite	84.21	6.33	ND	.61	.27	1.11	1.82	.24
INCO 3400 level nickel-sulfide ore[1]	4.60	1.14	ND	25.97	.31	.49	.11	.13
LCA pegmatite	72.84	16.25	.61	ND	<.17	<.42	3.10	2.29
Magnesium oxide brick	1.42	.68	.56	ND	92.93	.51	<.07	<.06
Mahogany granite:								
Cuttings	68.91	13.42	ND	1.93	.96	1.54	.68	4.66
Grindings	68.91	13.42	ND	1.93	.96	1.54	.68	4.66
Minnesota taconite:								
Sample A	35.30	.30	28.73	22.26	2.32	3.50	<.067	<.06
Sample B	34.23	.34	27.16	24.31	1.82	4.06	<.067	<.06
Sample C	40.65	.87	35.74	14.28	2.49	2.24	<.067	<.06
Minntac taconite	42.68	1.18	25.25	19.36	2.82	.67	.08	.22
Rockville Granite	65.03	13.23	1.75	3.47	.76	2.94	3.64	4.34
Salida granite	66.96	13.98	2.72	.86	.46	1.68	2.97	5.90
Sioux Quartzite	98.41	.76	.19	<.40	<.17	.69	.09	<.06
South Dakota feldspar	63.11	18.43	.16	ND	.33	<.42	5.80	8.32
Tennessee marble	<.21	.23	.21	ND	.76	97.39	<.067	<.060
Westerly Granite	68.24	16.44	.29	2.19	.78	2.10	4.04	4.34
Wausau quartzite	94.66	2.37	.61	ND	.41	<.42	.18	.20

	H_2O^+	H_2O^-	TiO_2	P_2O_5	MnO	BaO	CO_2	Li_2O
Barre Granite	0.92	0.23	0.94	ND	<0.13	<0.11	ND	ND
Charcoal granite	.33	<.1	.75	<0.046	.13	<.11	ND	ND
Dresser basalt	2.45	<.10	2.26	<.046	.19	<.055	2.86	<0.054
Feldspar series:								
Albite	ND	<.10	<.17	<.02	<.13	ND	ND	ND
Andesine	ND	<.10	.34	.23	<.13	ND	ND	ND
Anorthite	ND	<.1	<.17	ND	<.13	ND	ND	ND
Bytownite	ND	<.10	<.17	.13	<.13	ND	ND	ND
Microcline	ND	<.1	<.17	.136	<.13	ND	ND	ND
Oligoclase	ND	<.10	<.17	<.02	<.13	ND	ND	ND
INCO section 275:								
Pegmatite	.32	.21	<.17	ND	<.13	.26	ND	ND
Quartzite	1.48	.19	<.17	ND	<.13	<.11	ND	ND
INCO 2800 level quartzite	.60	.24	<.17	ND	<.13	<.11	ND	ND
INCO 3400 level nickel-sulfide ore[1]	13.20	.16	<.17	ND	<.13	<.11	ND	ND
LCA pegmatite	.80	<.10	<.33	<.046	.13	<.11	ND	1.40
Magnesium oxide brick	3.85	.61	<.50	<.05	.03	<.06	.64	ND
Mahogany granite:								
Cuttings	.35	.21	<.17	ND	<.13	<.11	ND	ND
Grindings	.35	.21	<.17	ND	<.13	<.11	ND	ND
Minnesota taconite:								
Sample A	4.10	<.10	<.33	<.046	.72	<.11	ND	<.22
Sample B	4.30	<.10	<.33	<.046	.80	<.11	ND	<.22
Sample C	3.40	<.1	<.50	<.046	.90	<.55	5.86	<.054
Minntac taconite	5.85	.34	<.50	<.05	.34	<.06	2.25	ND
Rockville granite	<.10	.30	.62	<.05	.08	.21	<.10	ND
Salida granite	.59	<.10	<.50	<.046	.04	<.055	.44	<.054
Sioux Quartzite	ND	ND	<.17	<.02	<.13	<.11	ND	<.22
South Dakota feldspar	.86	<.10	.62	1.03	<.03	<.06	<.10	ND
Tennessee marble	ND	<.10	<.33	.30	.05	<.11	ND	<.22
Westerly Granite	.60	<.1	.35	<.046	.09	.17	ND	<.22
Wausau quartzite	.56	<.10	<.50	<.05	<.03	<.06	<.10	ND

ND Not determined.
[1]Contains 11.4 ppm Ni.

Table A-5.–Chemical analyses of coal, diamond, and cobalt powder

	pct
Coal:[1]	
Moisture	0.30
Volatile	21.70
Carbon:	
Total	78.90
Fixed	67.30
Ash	10.70
S	.70
O	3.40
H	4.50
N	1.40
Coal[1]--Con.	
Carbon--Con.	
Al	1.80
Si	2.40
Fe	1.10
Ca	.20
Mg	.10
Na	<.10
Diamond: C	100.00
Cobalt powder: Co	99.80

[1]Jim Walters Resources.

Table A-6.–Summary of PZC zeta potential results for cationic and anionic additives, by material type

Material and additive[1]	Potential, mV	PZC conc, mol/L
Australian muscovite:		
Aluminum chloride	-26.81	7.57×10^{-7}
Aluminum nitrate	-29.34	5.20×10^{-7}
Potassium chloride	-27.04	9.50×10^{-2}
HTAB	-28.41	2.15×10^{-6}
Biotite: Aluminum chloride	-11.74	3.03×10^{-6}
Charcoal granite:		
Aluminum chloride	-25.20	1.40×10^{-6}
Aluminum chloride in tap water	-19.00	3.53×10^{-5}
Calcium chloride	-23.50	1.60×10^{-2}
Magnesium sulfate	-21.80	1.95×10^{-2}
Sodium chloride	-22.60	3.50×10^{-1}
Zirconium chloride	-27.10	2.15×10^{-6}
Cobalt: Aluminum chloride	-19.91	2.68×10^{-6}
Diamond: Aluminum chloride	-20.63	2.09×10^{-6}
Dresser basalt:		
Aluminum chloride	-18.25	5.50×10^{-7}
Aluminum chloride, repeat	-37.03	9.80×10^{-7}
Aluminum chloride in Dresser, WI, tap water	-23.04	1.33×10^{-4}
Aluminum chloride in Dresser mine water	-22.23	1.50×10^{-4}
Feldspar series:		
Albite: Aluminum chloride	-21.72	1.35×10^{-6}
Andesine: Aluminum chloride	-23.18	4.10×10^{-7}
Anorthite: Aluminum chloride	-23.89	4.00×10^{-7}
Bytownite: Aluminum chloride	-21.86	2.20×10^{-7}
Microcline: Aluminum chloride	-20.60	1.65×10^{-6}
Oligoclase: Aluminum chloride	-24.77	8.60×10^{-7}
LCA pegmatite:		
Aluminum chloride	-18.61	7.30×10^{-7}
Aluminum chloride in mine water	-24.63	7.38×10^{-6}
Aluminum nitrate	-20.21	1.47×10^{-7}
Aluminum nitrate in mine water	-24.50	3.25×10^{-6}
LCA pegmatite sample A:		
Aluminum chloride in mine water	-20.20	7.33×10^{-6}
Aluminum nitrate in mine water	-18.97	7.80×10^{-6}
LCA pegmatite sample B:		
Aluminum chloride in mine water	-19.27	7.70×10^{-6}
Aluminum nitrate in mine water	-20.56	7.63×10^{-6}
Magnesium oxide brick: Nalco 8830	17.61	2.15×10^{-4}
MINNESOTA TACONITE		
Whole fraction:		
Sample A:		
Aluminum chloride	-17.45	1.40×10^{-6}
Aluminum chloride in November mine water	-20.78	1.38×10^{-4}
Aluminum chloride in May mine water	-19.14	1.65×10^{-4}
Sample B:		
Aluminum chloride	-17.29	1.20×10^{-6}
Aluminum chloride in November mine water	-19.38	1.36×10^{-4}
Aluminum chloride in May mine water	-19.63	1.80×10^{-4}
Nalco 7132 in mine water	-34.70	1.26×10^{-4}
Percol 402 in mine water	-35.20	[2]6.37×10^{-4}
Sample C: Aluminum chloride	-24.89	1.40×10^{-6}

See explanatory notes at end of table.

Table A-6.–Summary of PZC zeta potential results for cationic and anionic additives, by material type–Continued

Material and additive[1]	Potential, mV	PZC conc, mol/L
MINNESOTA TACONITE–Con.		
Magnetic fraction:		
Sample A:		
Aluminum chloride	-18.85	1.15×10^{-6}
Aluminum chloride in November mine water	-19.40	1.38×10^{-4}
Aluminum chloride in May mine water	-20.44	1.25×10^{-4}
Sample B:		
Aluminum chloride	-14.88	6.80×10^{-7}
Aluminum chloride in November mine water	-19.87	1.47×10^{-4}
Aluminum chloride in May mine water	-20.34	1.50×10^{-4}
Sample C: Aluminum chloride	-20.59	8.50×10^{-7}
Nonmagnetic fraction:		
Sample A:		
Aluminum chloride	-16.07	9.30×10^{-7}
Aluminum chloride in November mine water	-19.34	1.40×10^{-4}
Aluminum chloride in May mine water	-20.47	1.25×10^{-4}
Sample B:		
Aluminum chloride	-15.72	9.80×10^{-7}
Aluminum chloride in November mine water	-20.21	1.43×10^{-4}
Aluminum chloride in May mine water	-20.18	1.40×10^{-4}
Sample C: Aluminum chloride	-32.45	1.39×10^{-6}
Minntac taconite:		
Sample A: Aluminum chloride	-27.59	3.25×10^{-6}
Sample B: Aluminum chloride	-27.94	3.52×10^{-6}
Rockville Granite:		
Aluminum chloride	-24.70	1.24×10^{-6}
Aluminum chloride in tap water	-17.70	3.80×10^{-5}
Calcium chloride	-19.15	1.14×10^{-2}
Magnesium sulfate	-13.40	1.85×10^{-2}
Sodium chloride	-23.00	3.38×10^{-1}
Zirconium chloride	-25.70	1.42×10^{-6}
DTAB	-20.80	4.20×10^{-4}
HTAB	-23.80	7.25×10^{-7}
TTAB	-22.90	8.20×10^{-6}
Sioux Quartzite:		
Aluminum chloride	-25.60	6.82×10^{-7}
Aluminum chloride in tap water	-20.40	4.50×10^{-5}
Aluminum nitrate	-21.38	4.33×10^{-7}
Calcium chloride	-22.20	1.60×10^{-2}
Magnesium sulfate	-19.70	1.95×10^{-2}
Potassium aluminum sulfate	-26.35	7.88×10^{-7}
Sodium chloride	-21.90	2.17×10^{-1}
Titanium iodide	-26.30	1.61×10^{-5}
Zirconium chloride	-21.80	1.40×10^{-6}
Zirconium nitrate	-23.60	1.50×10^{-6}
DTAB	-22.40	9.35×10^{-4}
HTAB	-22.83	1.56×10^{-6}
HTAB in tap water	-31.85	2.47×10^{-5}
TTAB	-20.72	7.23×10^{-5}
Armac Cat 11	-30.48	[2]5.35×10^{-5}
Armac Cat 15	-29.59	[2]1.83×10^{-4}
Armac Cat 19	-29.78	[2]7.00×10^{-4}
Arquad 2C-75	-30.14	[2]2.23×10^{-5}
Nalco 7107	-25.69	[2]1.43×10^{-5}
Nalco 7132	-27.65	[2]5.73×10^{-6}
Nalco 8102	-28.19	[2]1.13×10^{-5}
Nalco 8852	-26.95	[2]1.33×10^{-5}
Percol 402	-29.78	[2]2.40×10^{-5}
Percol 403	-27.03	[2]1.43×10^{-5}
Percol 406	-30.24	[2]2.55×10^{-5}
Percol 408	-31.06	[2]7.60×10^{-5}
Polyacrylamide	-43.56	[3]0.250
South Dakota feldspar:		
Aluminum chloride	-22.10	1.41×10^{-6}
Calcium chloride	-11.30	8.80×10^{-3}
Magnesium sulfate	-11.67	9.60×10^{-3}
DTAB	-17.10	7.40×10^{-4}
HTAB	-20.10	3.97×10^{-6}
TTAB	-17.60	6.80×10^{-5}

See explanatory notes at end of table.

Table A-6.-Summary of PZC zeta potential results for cationic and anionic additives, by material type-Continued

Material and additive[1]	Potential, mV	PZC conc, mol/L
Tennessee marble:		
Aluminum chloride	-7.94	1.93×10^{-5}
Aluminum chloride in tap water	-5.50	3.73×10^{-5}
Calcium chloride	-5.30	3.05×10^{-3}
Magnesium sulfate	-5.50	4.20×10^{-3}
Sodium chloride	-6.80	2.80×10^{-1}
Titanium iodide	-5.55	1.51×10^{-5}
Zirconium chloride	-4.90	5.80×10^{-7}
Zirconium nitrate	-5.10	3.20×10^{-6}
DTAB	-7.80	1.30×10^{-3}
HTAB	-3.80	3.70×10^{-7}
TTAB	-4.00	5.15×10^{-6}
Wausau quartzite:		
Aluminum chloride	-14.60	5.80×10^{-7}
Calcium chloride	-15.00	1.80×10^{-2}
Magnesium sulfate	-12.30	2.30×10^{-2}
Sodium chloride	-15.20	4.30×10^{-1}
Zirconium chloride	-16.60	8.40×10^{-7}
Zirconium nitrate	-15.60	3.35×10^{-7}
DTAB	-18.30	2.60×10^{-3}
HTAB	-16.40	3.35×10^{-6}
TTAB	-15.60	5.40×10^{-5}
Westerly Granite:		
Aluminum chloride	-18.20	7.26×10^{-7}
Aluminum chloride in tap water	-15.10	2.40×10^{-5}
Calcium chloride	-17.80	1.08×10^{-2}
Magnesium sulfate	-15.30	1.38×10^{-2}
Sodium chloride	-15.00	1.26×10^{-1}
Zirconium chloride	-14.40	7.40×10^{-7}

DDIW Deionized, distilled water.
DTAB Dodecyltrimethyl ammonium bromide.
HTAB Hexadecyltrimethyl ammonium bromide.
TTAB Tetradecyltrimethyl ammonium bromide.
[1]All tests conducted in DDIW unless otherwise stated. Tap water used was from Minneapolis, MN, unless otherwise stated. Mine waters used came from each material's respective local mine area.
[2]Percent.
[3]Parts per million.

Table A-7.–Summary of PZC zeta potential results for cationic and anionic additives, by additive

Additive and material[1]	Potential, mV	PZC conc, mol/L
Aluminum chloride:		
Australian muscovite	-26.81	7.57×10^{-7}
Biotite	-11.74	3.03×10^{-6}
Charcoal granite	-25.20	1.40×10^{-6}
Cobalt	-19.91	2.68×10^{-6}
Diamond	-20.63	2.09×10^{-6}
Dresser basalt	-18.25	5.50×10^{-7}
Feldspar series:		
Albite	-21.72	1.35×10^{-6}
Andesine	-23.18	4.10×10^{-7}
Anorthite	-23.89	4.00×10^{-7}
Bytownite	-21.86	2.20×10^{-7}
Microcline	-20.60	1.65×10^{-6}
Oligoclase	-24.77	8.60×10^{-7}
LCA pegmatite	-18.61	7.30×10^{-7}
Minnesota taconite:		
Whole fraction:		
Sample A	-17.45	1.40×10^{-6}
Sample B	-17.29	1.20×10^{-6}
Sample C	-24.89	1.40×10^{-6}
Magnetic fraction:		
Sample A	-18.85	1.15×10^{-6}
Sample B	-14.88	6.80×10^{-7}
Sample C	-20.59	8.50×10^{-7}
Nonmagnetic fraction:		
Sample A	-16.07	9.30×10^{-7}
Sample B	-15.72	9.80×10^{-7}
Sample C	-32.45	1.39×10^{-7}
Minntac taconite:		
Sample A	-27.59	3.25×10^{-6}
Sample B	-27.94	3.52×10^{-6}
Rockville Granite	-24.70	1.24×10^{-6}
Sioux Quartzite	-25.60	6.82×10^{-7}
South Dakota feldspar	-22.10	1.41×10^{-6}
Tennessee marble	-7.94	1.93×10^{-6}
Wausau quartzite	-14.60	5.80×10^{-6}
Westerly Granite	-18.20	7.26×10^{-7}
Aluminum chloride in tap water:		
Charcoal granite	-19.00	3.53×10^{-5}
Rockville Granite	-17.70	3.80×10^{-5}
Sioux Quartzite	-20.40	4.50×10^{-5}
Tennessee marble	-5.50	3.73×10^{-5}
Westerly Granite	-15.10	2.40×10^{-5}
Aluminum chloride in mine water:[2]		
Dresser basalt	-22.23	1.50×10^{-4}
LCA pegmatite	-24.63	7.38×10^{-6}
LCA pegmatite:		
Sample A	-20.20	7.33×10^{-6}
Sample B	-19.27	7.70×10^{-6}
Aluminum chloride in November mine water:		
Minnesota taconite:		
Whole fraction:		
Sample A	-20.78	1.38×10^{-4}
Sample B	-19.38	1.36×10^{-4}
Magnetic fraction:		
Sample A	-19.40	1.38×10^{-4}
Sample B	-19.87	1.47×10^{-4}
Nonmagnetic fraction:		
Sample A	-19.34	1.40×10^{-4}
Sample B	-20.21	1.43×10^{-4}
Aluminum chloride in May mine water:		
Minnesota taconite:		
Whole fraction:		
Sample A	-19.14	1.65×10^{-4}
Sample B	-19.63	1.80×10^{-4}
Magnetic fraction:		
Sample A	-20.44	1.25×10^{-4}
Sample B	-20.34	1.50×10^{-4}

See explanatory notes at end of table.

Table A-7.–Summary of PZC zeta potential results for cationic and anionic additives, by additive–Continued

Additive and material[1]	Potential, mV	PZC conc, mol/L
Aluminum chloride in May mine water–Con.		
Minnesota taconite–Con.		
Nonmagnetic fraction:		
Sample A	-20.47	1.25 X 10^{-4}
Sample B	-20.18	1.40 X 10^{-4}
Aluminum chloride in Dresser, WI, tap water:		
Dresser basalt	-23.04	1.33 X 10^{-4}
Aluminum nitrate:		
Australian muscovite	-29.34	5.20 X 10^{-7}
LCA pegmatite	-20.21	1.47 X 10^{-7}
Sioux Quartzite	-21.38	4.33 X 10^{-7}
Aluminum nitrate in LCA mine water:		
LCA pegmatite	-24.50	3.25 X 10^{-6}
LCA pegmatite:		
Sample A	-18.97	7.80 X 10^{-6}
Sample B	-20.56	7.63 X 10^{-6}
Calcium chloride:		
Charcoal granite	-23.50	1.60 X 10^{-2}
Rockville Granite	-19.15	1.14 X 10^{-2}
Sioux Quartzite	-22.20	1.60 X 10^{-2}
South Dakota feldspar	-11.30	8.80 X 10^{-3}
Tennessee marble	-5.30	3.05 X 10^{-3}
Wausau quartzite	-15.00	1.80 X 10^{-2}
Westerly Granite	-17.80	1.08 X 10^{-2}
Magnesium sulfate:		
Charcoal granite	-21.80	1.95 X 10^{-2}
Rockville Granite	-13.40	1.85 X 10^{-2}
Sioux Quartzite	-19.70	1.95 X 10^{-2}
South Dakota feldspar	-11.67	9.60 X 10^{-3}
Tennessee marble	-5.50	4.20 X 10^{-3}
Wausau quartzite	-12.30	2.30 X 10^{-2}
Westerly Granite	-15.30	1.38 X 10^{-2}
Potassium aluminum sulfate: Sioux Quartzite	-26.35	7.88 X 10^{-7}
Potassium chloride: Australian muscovite	-27.04	9.50 X 10^{-2}
Sodium chloride:		
Charcoal granite	-22.60	3.50 X 10^{-1}
Rockville Granite	-23.00	3.38 X 10^{-1}
Sioux Quartzite	-21.90	2.17 X 10^{-1}
Tennessee marble	-6.80	2.80 X 10^{-1}
Wausau quartzite	-15.20	4.30 X 10^{-2}
Westerly Granite	-15.00	1.26 X 10^{-1}
Titanium iodide:		
Sioux Quartzite	-26.30	1.51 X 10^{-5}
Tennessee marble	-5.55	1.61 X 10^{-5}
Zirconium chloride:		
Charcoal granite	-27.10	2.15 X 10^{-6}
Rockville Granite	-25.70	1.42 X 10^{-6}
Sioux Quartzite	-21.80	1.40 X 10^{-6}
Tennessee marble	-4.90	5.80 X 10^{-7}
Wausau quartzite	-16.60	8.40 X 10^{-7}
Westerly Granite	-14.40	7.40 X 10^{-7}
Zirconium nitrate:		
Sioux Quartzite	-23.60	1.50 X 10^{-6}
Tennessee marble	-5.10	3.20 X 10^{-6}
Wausau quartzite	-15.60	3.35 X 10^{-7}
DTAB:		
Rockville Granite	-20.80	4.20 X 10^{-4}
Sioux Quartzite	-22.40	9.35 X 10^{-3}
South Dakota feldspar	-16.10	7.40 X 10^{-4}
Tennessee marble	-7.80	1.30 X 10^{-3}
Wausau quartzite	-18.30	2.60 X 10^{-3}
HTAB:		
Australian muscovite	-28.41	2.15 X 10^{-6}
Rockville Granite	-23.80	7.25 X 10^{-7}
Sioux Quartzite	-22.83	1.56 X 10^{-6}
South Dakota feldspar	-20.10	3.97 X 10^{-6}
Tennessee marble	-3.80	3.70 X 10^{-7}
Wausau quartzite	-16.40	3.35 X 10^{-6}
HTAB in tap water: Sioux Quartzite	-31.85	2.47 X 10^{-5}

See explanatory notes at end of table.

Table A-7.–Summary of PZC zeta potential results for cationic and anionic additives, by additive–Continued

Additive and material[1]	Potential, mV	PZC conc, mol/L
TTAB:		
Rockville granite	-22.90	8.20×10^{-6}
Sioux Quartzite	-20.72	7.23×10^{-5}
South Dakota feldspar	-17.60	6.80×10^{-5}
Tennessee marble	-4.00	5.15×10^{-6}
Wausau quartzite	-15.60	5.40×10^{-5}
Armac series:[2]		
Cat 11: Sioux Quartzite	-30.48	5.35×10^{-5}
Cat 15: Sioux Quartzite	-29.59	1.83×10^{-4}
Cat 19: Sioux Quartzite	-29.78	7.00×10^{-4}
Arquad 2C-75: Sioux Quartzite	-30.14	2.23×10^{-5}
Nalco series:[2]		
7107: Sioux Quartzite	-25.69	1.43×10^{-5}
7132: Sioux Quartzite	-27.65	5.73×10^{-6}
7132 in mine water: Minnesota taconite, whole fraction, sample B	-34.70	1.26×10^{-4}
8102: Sioux Quartzite	-28.19	1.13×10^{-5}
8830: Magnesium oxide brick	17.61	2.15×10^{-4}
8852: Sioux Quartzite	-26.95	1.33×10^{-5}
Percol series:[2]		
402: Sioux Quartzite	-29.78	2.40×10^{-5}
402 in mine water: Minnesota taconite, whole fraction, sample B	-35.20	6.37×10^{-4}
403: Sioux Quartzite	-27.03	1.43×10^{-5}
406: Sioux Quartzite	-30.24	2.55×10^{-5}
408: Sioux Quartzite	-31.06	7.60×10^{-5}
Polyacrylamide:[3] Sioux Quartzite	-43.56	0.250

DTAB Dodecyltrimethyl ammonium bromide.
HTAB Hexadecyltrimethyl ammonium bromide.
TTAB Tetradecyltrimethyl ammonium bromide.
[1]All tests conducted in DDIW unless otherwise stated. Tap water used was from Minneapolis, MN, unless otherwise stated. Mine waters used came from each material's respective local mine area.
[2]Concentration in percent.
[3]Concentration in parts per million.

Table A-8.–PZC zeta potential results for $AlCl_3$ when using pH modification

Material and water tested	Zeta potential, mV		$AlCl_3$ conc, 10^{-4} mol/L
	Before modification	After modification	
Dresser basalt: Dresser, WI, tap water	-20.47	-11.01	1.13
Minnesota taconite:			
Whole fraction, sample A:			
Erie November mine water, pH 5.5	-19.98	-14.61	1.22
Erie November mine water, pH 4.0	-20.79	-9.14	.71
Erie May mine water, pH 5.5	-21.43	-12.57	.80
Whole fraction, sample B:			
Erie November mine water, pH 5.5	-21.19	-15.83	1.13
Erie November mine water, pH 4.40	-21.10	-10.04	1.00
Erie May mine water, pH 5.5	-22.15	-11.41	.83
Salida granite: Denver, CO, tap water	-31.47	-26.46	1.20
Sioux Quartzite:			
Fresh Minneapolis tap water[1]	-28.55	-22.93	1.17
Cold Minneapolis tap water[2]	-30.28	-26.53	1.87
Hot Minneapolis tap water[3]	-34.96	-30.14	1.68

[1]Fresh, direct from cold water tap.
[2]From cold water tap, left to stand overnight.
[3]From hot water tap, left to stand overnight.

Table A-9.–Zeta potential test results for nonionic and anionic additives with Sioux Quartzite, and anionic additives with Mahogany granite

Baseline water and additive conc, ppm	Zeta potential, mV	Standard deviation
	SIOUX QUARTZITE	
NONIONIC ADDITIVES		
Tap water before adding HEC	-37.10	±0.52
HEC:		
1	-34.98	±.43
5	-34.16	±.65
10	-35.00	±.36
50	-35.37	±.57
100	-35.30	±.60
Tap water before adding Revert	-37.58	±.86
Revert:		
1	-35.67	±.39
5	-36.86	±.33
10	-37.14	±.39
50	-36.68	±.66
100	-36.39	±.60
Tap water before adding Surfynol 465	-40.74	±1.80
Surfynol 465:		
0.1	-41.34	±.38
0.5	-40.98	±.47
1	-40.65	±.56
5	-40.55	±.56
10	-41.12	±.90
50	-41.11	±.49
100	-42.15	±.58
DDIW before adding Tergitol NPX	-33.51	±1.49
Tergitol NPX:		
0.1	-32.20	±1.20
0.5	-34.54	±.98
1	-35.52	±.42
5	-35.35	±.64
10	-37.68	±.37
ANIONIC ADDITIVES		
Tap water before adding Biocut	-43.38	±.36
Biocut:		
1	-42.94	±.32
5	-44.80	±.58
10	-63.22	±.74
50	-67.61	±.67
100	-71.98	±.98
DDIW before adding Nalco 8830	-29.14	±1.54
Nalco 8830:		
1	-34.04	±1.50
5	-42.98	±.88
10	-57.21	±2.49
100	-59.51	±1.96
190	-75.37	±.66
Tap water before adding Solulube	-42.63	±.56
Solulube:		
1	-41.49	±.90
5	-43.41	±.33
10	-45.90	±.47
50	-59.95	±1.96
100	-60.30	±.45
Tap water before adding Vibrastop	-42.58	±1.29
Vibrastop:		
1	-44.90	±1.92
5	-53.94	±.30
10	-57.69	±.42
50	-58.69	±2.13
100	-63.41	±.46

Table A-9.–Zeta potential test results for nonionic and anionic additives with Sioux Quartzite, and anionic additives with Mahogany granite–Continued

Baseline water and additive conc. ppm	Zeta potential, mV	Standard deviation
	MAHOGANY GRANITE	
ANIONIC ADDITIVES		
Tap water before adding anionic polymer	-37.73	±0.24
Anionic polymer:		
1	-39.41	±1.37
5	-39.32	±1.19
10	-47.81	±1.01
50	-44.24	±2.23
100	-47.35	±.81
Tap water before adding ZEP Lubeeze	-36.00	±1.12
ZEP Lubeeze:		
1	-38.69	±1.11
5	-44.15	±.76
10	-48.47	±1.03
50	-60.88	±1.42
100	-65.93	±1.87
Quarry water before adding ZEP Lubeeze	-29.63	±.58
ZEP Lubeeze:		
1	-29.41	±1.17
5	-30.51	±.51
10	-33.17	±.64
50	-35.21	±.47
100	-37.21	±.74
250	-37.33	±.98
500	-38.97	±.32
1,000	-41.73	±.96
2,500	-43.90	±.42
5,000	-44.75	±.34
10,000	-46.84	±.28
20,000	-47.31	±.43

DDIW Deionized, distilled water.
HEC Hydroxyethyl cellulose.

Table A-10.–Zeta potential test results for nonionic PEO

(All tests conducted with 5 million molecular weight PEO and stock solution of 1,000 ppm unless otherwise noted)

Baseline water and PEO conc, ppm	Zeta potential, mV	Standard deviation
BARRE GRANITE		
ROANOKE, VA, TAP WATER		
Water	-34.80	±1.80
1	-14.26	±1.33
5	-1.18	±.52
10	.00	±.00
50	.00	±.00
100	.00	±.00
CHARCOAL GRANITE		
MINNEAPOLIS, MN, TAP WATER		
Water	-32.22	±1.41
1	-13.55	±1.74
5	.00	±.00
10	.00	±.00
50	.00	±.00
100	.00	±.00
COAL (JIM WALTERS RESOURCES)		
MINNEAPOLIS, MN, TAP WATER		
6 million molecular weight PEO:		
Water	-31.47	±0.98
1	-10.28	±1.37
5	-1.68	±.32
10	.00	±.00
50	.00	±.00
100	.00	±.00
COBALT POWDER		
MINNEAPOLIS, MN, TAP WATER		
Water	-25.02	±0.42
1	-18.15	±.57
5	-4.02	±.47
10	.00	±.00
50	.00	±.00
100	.00	±.00
INCO SECTION 275		
MINNEAPOLIS, MN, TAP WATER		
Quartzite:		
Water	-33.54	±0.52
1	-11.70	±.75
5	-4.54	±.29
10	.00	±.00
50	.00	±.00
100	.00	±.00
Pegmatite:		
Water	-36.59	±.14
1	-17.35	±.89
5	-4.12	±.18
10	.00	±.00
50	.00	±.00
100	.00	±.00
INCO TAP WATER		
Quartzite:		
Water	-31.15	±.60
1	-10.50	±.41
5	.00	±.00
10	.00	±.00
50	.00	±.00
100	.00	±.00
INCO 2800 LEVEL QUARTZITE		
MINNEAPOLIS, MN, TAP WATER		
Water	-33.50	±0.35
1	-11.01	±.31
5	-4.33	±.37
10	.00	±.00
50	.00	±.00
100	.00	±.00

Table A-10.–Zeta potential test results for nonionic PEO–Continued

Baseline water and PEO conc, ppm	Zeta potential, mV	Standard deviation
INCO 3400 LEVEL NICKEL-SULFIDE ORE		
MINNEAPOLIS, MN, TAP WATER		
Water	-28.62	±0.26
1	-12.17	±.81
5	-.99	±1.16
10	.00	±.00
50	.00	±.00
100	.00	±.00
LCA LITHIUM PEGMATITE		
LCA MINE WATER		
Water	-27.40	±0.85
1	-6.78	±.28
5	.00	±.00
10	.00	±.00
50	.00	±.00
100	.00	±.00
MAGNESIUM OXIDE BRICK		
DDIW		
DDIW	18.92	±0.59
1	.00	±.00
5	.00	±.00
10	.00	±.00
100	.00	±.00
MINNEAPOLIS, MN, TAP WATER		
Water	-6.81	±1.21
1	-3.54	±.83
5	.00	±.00
10	.00	±.00
100	.00	±.00
MAHOGANY GRANITE		
SOUTH DAKOTA GRANITE QUARRY WATER		
Grindings:		
Water	-28.32	±0.48
1	-10.62	±.26
5	-.92	±.35
10	.00	±.00
50	.00	±.00
100	.00	±.00
Saw cuttings:		
Water	-26.40	±.57
1	-7.58	±.26
5	.00	±.00
10	.00	±.00
50	.00	±.00
100	.00	±.00
MINNESOTA TACONITE, SAMPLE B		
DDIW		
DDIW	-31.54	±0.92
1	-17.43	±.59
3	-11.74	±.75
7.48	.00	±.00
12.4	.00	±.00
122	.00	±.00
MINNEAPOLIS, MN, TAP WATER		
Water	-33.60	±2.25
1	-23.35	±1.21
3	-6.59	±.44
7.48	-6.10	±.91
12.4	.00	±.00
122	.00	±.00
MINE WATER		
Water	-40.68	±1.17
1	-10.29	±.59
3	-2.37	±.64
7.48	-2.29	±.94
12.4	.00	±.00
122	.00	±.00

Table A-10.–Zeta potential test results for nonionic PEO–Continued

Baseline water and PEO conc, ppm	Zeta potential, mV	Standard deviation
MINNTAC TACONITE		
MINE WATER		
Sample A:		
Water	-41.79	±0.97
1	-18.73	±1.52
3	-10.44	±1.54
7.5	-2.03	±1.40
12.5	.00	±.00
100	.00	±.00
Sample B:		
Water	-40.02	±2.69
1	-18.11	±2.63
3	-4.53	±2.12
7.5	.00	±.00
12.5	.00	±.00
100	.00	±.00
ROCKVILLE GRANITE		
MINNEAPOLIS, MN, TAP WATER		
Water	-29.57	±1.14
1	-13.01	±1.68
5	-1.90	±.15
10	.00	±.00
50	.00	±.00
100	.00	±.00
SALIDA GRANITE		
DENVER, CO, TAP WATER		
Water	-28.34	±0.41
1	-11.61	±.33
5	-4.22	±.75
10	.00	±.00
50	.00	±.00
100	.00	±.00
SIOUX QUARTZITE		
DDIW		
DDIW	-29.77	±0.50
1	-16.61	±.95
3	-7.06	±.88
7.48	-3.68	±.77
12.4	-1.30	±.83
122	.00	±.00
MINNEAPOLIS, MN, TAP WATER		
Water	-33.01	±1.69
1	-11.25	±1.29
3	-1.18	±.68
7.48	.00	±.00
12.4	.00	±.00
122	.00	±.00
Water	-41.77	±1.22
1	-21.19	±2.998
3	-7.77	±.69
5	-1.29	±.47
7.5	.00	±.00
10	.00	±.00
15	.00	±.00
Water	-41.60	±.39
1	-28.56	±.76
5	-15.99	±4.71
10	-.93	±.64
50	.00	±.00
100	.00	±.00
Water	-41.83	±.56
1	-32.24	±.71
5	-13.01	±2.65
10	-.87	±.43
50	.00	±.00
100	.00	±.00

Table A-10.–Zeta potential test results for nonionic PEO–Continued

Baseline water and PEO conc, ppm	Zeta potential, mV	Standard deviation
SIOUX QUARTZITE–Continued		
MINNEAPOLIS, MN, TAP WATER–Continued		
0.1 million molecular weight PEO:		
Water	-42.33	±1.02
1	-29.46	±.57
5	-14.01	±2.56
10	-.73	±.75
50	.00	±.00
100	.00	±.00
0.4 million molecular weight PEO:		
Water	-42.86	±.58
1	-30.24	±1.49
5	-14.20	±2.09
10	-.46	±.41
5	0.00	±.00
100	.00	±.00
0.9 million molecular weight PEO:		
Water	-44.05	±1.69
1	-28.75	±2.15
5	-12.98	±1.99
10	-.30	±.49
50	.00	±.00
100	.00	±.00
6 million molecular weight PEO:		
Water	-36.83	±.86
1	-18.53	±.44
5	-3.61	±.70
10	.00	±.00
50	.00	±.00
100	.00	±.00
5 million molecular weight PEO made with isopropyl alcohol:		
Water	-41.88	±1.55
1	-29.21	±1.63
3	-9.07	±1.99
5	-.47	±.69
7.5	.00	±.00
10	.00	±.00
15	.00	±.00
100	.00	±.00
Water	-41.19	±1.26
1	-19.73	±.58
3	-9.37	±1.08
5	-1.62	±1.03
7.5	.00	±.00
10	.00	±.00
15	.00	±.00
100	.00	±.00
MINNEAPOLIS, MN, TAP WATER WITH IRON		
Water	-41.70	±.53
1	-18.76	±2.03
5	-9.30	±.82
10	.00	±.00
50	.00	±.00
100	.00	±.00
FARMINGTON, MN, TAP WATER		
Water	-35.75	±.40
1	-10.41	±2.59
5	.00	±.00
10	.00	±.00
50	.00	±.00
100	.00	±.00
SUDBURY GRANITE		
MINNEAPOLIS, MN, TAP WATER		
Water	-32.86	±1.29
1	-14.37	±.38
5	.00	±.00
10	.00	±.00

Table A-10.–Zeta potential test results for nonionic PEO–Continued

Baseline water and PEO conc, ppm	Zeta potential, mV	Standard deviation
	TENNESSEE MARBLE	
FARMINGTON, MN, TAP WATER		
Water	-5.28	±0.47
1	-.90	±.30
5	.00	±.00
10	.00	±.00
50	.00	±.00
100	.00	±.00
	TUNGSTEN CARBIDE POWDER	
MINNEAPOLIS, MN, TAP WATER		
Powder:		
Water	-28.23	±0.63
1	-17.21	±1.52
5	.00	±.00
10	.00	±.00
50	.00	±.00
100	.00	±.00
Powder with 6 pct Co granules:		
Water	-26.93	±2.34
1	-14.16	±1.33
5	-3.86	±.46
10	.00	±.00
50	.00	±.00
100	.00	±.00
	WESTERLY GRANITE	
MINNEAPOLIS, MN, TAP WATER		
Water	-34.74	±1.03
1	-16.80	±.39
5	-2.65	±.55
10	.00	±.00
50	.00	±.00
100	.00	±.00

DDIW Deionized, distilled water.
PEO Polyethylene oxide.

Table A-11.–Summary of zeta potential test results using combinations of anionic additives with nonionic PEO

Baseline water and PEO conc, ppm	Zeta potential, mV	Standard deviation
DROMUS B IN MINNEAPOLIS, MN, TAP WATER–SUDBURY GRANITE		
DROMUS B AT 10 ppm		
Water	-33.12	±0.59
Add 10 ppm Dromus B	-40.92	±.40
1	-28.67	±.90
5	-12.77	±.74
10	.00	±.00
50	.00	±.00
DROMUS B AT 50 ppm		
Water	-33.66	±.41
Add 50 ppm Dromus B	-55.01	±1.37
1	-21.39	±.97
10	-7.38	±.59
20	.00	±.00
50	.00	±.00
DROMUS B AT 100 ppm		
Water	-33.64	±.51
Add 100 ppm Dromus B	-61.61	±.44
1	-31.67	±.47
10	-12.78	±.59
20	.00	±.00
50	.00	±.00
DROMUS B AT 250 ppm		
Water	-33.78	±.44
Add 250 ppm Dromus B	-75.70	±.94
1	-41.51	±.96
10	-26.52	±.60
30	.00	±.00
50	.00	±.00
DROMUS B AT 500 ppm		
Water	-33.48	±.78
Add 500 ppm Dromus B	-79.30	±.96
1	-48.45	±.55
10	-28.62	±1.22
35	.00	±.00
50	.00	±.00
DROMUS B AT 1,000 ppm		
Water	-33.88	±.33
Add 1,000 ppm Dromus B	-81.25	±.88
1	-60.65	±.45
10	-43.49	±.71
50	-15.81	±2.26
85	.00	±.00
DROMUS B AT 2,500 ppm		
Water	-34.16	±.48
Add 2,500 ppm Dromus B	-93.01	±.70
1	-66.13	±1.32
10	-52.83	±.38
50	-24.14	±1.20
100	.00	±.00
DROMUS B AT 5,000 ppm		
Water	-33.84	±.70
Add 5,000 ppm Dromus B	-95.23	±.46
1	-66.87	±.22
50	-15.19	±.23
100	.00	±.00
ZEP LUBEEZE IN SOUTH DAKOTA QUARRY WATER–MAHOGANY GRANITE		
ZEP LUBEEZE AT 10 ppm		
Water	-29.61	±0.28
Add 10 ppm ZEP Lubeeze	-30.39	±.14
1	-22.16	±.25
5	-14.11	±.42
10	-6.73	±.58
15	-2.91	±.52
30	.00	±.00

Table A-11.–Summary of zeta potential test results using combinations of anionic additives with nonionic PEO–Continued

Baseline water and PEO conc, ppm	Zeta potential, mV	Standard deviation
ZEP LUBEEZE IN SOUTH DAKOTA QUARRY WATER–MAHOGANY GRANITE–Continued		
ZEP LUBEEZE AT 50 ppm		
Water	-29.44	±0.52
Add 50 ppm ZEP Lubeeze	-31.62	±.27
1	-19.93	±2.28
10	-12.78	±.72
30	-3.44	±.22
45	.00	±.00
ZEP LUBEEZE AT 100 ppm		
Water	-29.72	±.35
Add 100 ppm ZEP Lubeeze	-32.44	±.87
1	-18.08	±.43
10	-12.52	±.38
30	-4.59	±.45
45	-1.69	±.54
60	.00	±.00
ZEP LUBEEZE AT 250 ppm		
Water	-29.66	±.22
Add 250 ppm ZEP Lubeeze	-34.14	±.30
1	-20.91	±.73
10	-12.43	±.46
30	-6.00	±.36
45	-3.33	±.34
60	.00	±.00
ZEP LUBEEZE AT 500 ppm		
Water	-29.79	±.22
Add 500 ppm ZEP Lubeeze	-34.79	±.72
1	-24.68	±.19
10	-16.11	±.99
30	-7.44	±.36
60	-1.34	±.40
75	.00	±.00
ZEP LUBEEZE AT 1,000 ppm		
Water	-29.61	±.28
Add 1,000 ppm ZEP Lubeeze	-35.48	±.43
1	-23.23	±1.14
10	-16.73	±.64
30	-12.09	±.55
60	-7.41	±.72
90	.00	±.00
ZEP LUBEEZE AT 2,500 ppm		
Water	-29.40	±.23
Add 2,500 ppm ZEP Lubeeze	-34.26	±.72
1	-22.36	±.33
10	-14.76	±.63
30	-9.02	±.59
60	-6.04	±.35
90	.00	±.00
ZEP LUBEEZE AT 5,000 ppm		
Water	-29.61	±.43
Add 5,000 ppm ZEP Lubeeze	-39.56	±.29
1	-27.32	±1.16
10	-16.91	±.56
30	-10.94	±.46
60	-7.74	±.34
90	.00	±.00
ZEP LUBEEZE AT 10,000 ppm		
Water	-29.48	±.36
Add 10,000 ppm ZEP Lubeeze	-35.28	±1.24
1	-22.18	±.23
10	-18.24	±1.62
30	-16.20	±1.45
90	-4.39	±.46
120	.00	±.00

PEO Polyethylene oxide.

Table A-12.–Average zeta potential values for Sioux Quartzite with $AlCl_3$ in DDIW at higher than normal concentrations, millivolts

Additive conc, mol/L	Test 1	Test 2	Test 3
DDIW	-24.91	-27.58	-27.49
1.0×10^{-7}	-20.60	-21.24	-22.33
1.0×10^{-6}	18.14	21.21	23.79
3.0×10^{-6}	70.87	69.04	67.30
1.0×10^{-5}	80.88	85.05	85.60
3.0×10^{-5}	87.09	87.24	94.94
1.0×10^{-4}	94.28	92.31	96 65
1.0×10^{-3}	98.91	98.63	99.36

DDIW Distilled, deionized water.

* U.S. GOVERNMENT PRINTING OFFICE: 611-012/00,115