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Effect of Clay Stabilizers on Permeability of Clayey Ore

By Kenneth E. Hjelmstad



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William P. Clark, Secretary

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Robert C. Horton, Director

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CONTENTS

| | <u>Page</u> |
|---|-------------|
| Abstract..... | 1 |
| Introduction..... | 2 |
| Equipment and materials..... | 3 |
| Permeameter..... | 3 |
| Ore samples..... | 5 |
| Leach solutions..... | 6 |
| Organic polymer clay stabilizer..... | 6 |
| Experimental procedure, results, and discussion..... | 7 |
| Permeability-leaching tests..... | 7 |
| Effect of clay stabilizers on uranium extraction..... | 9 |
| Clay-swelling test..... | 10 |
| Zeta potential measurements..... | 10 |
| Summary and conclusions..... | 12 |
| References..... | 13 |

ILLUSTRATIONS

| | |
|---|----|
| 1. Permeameter-leaching apparatus..... | 4 |
| 2. Permeabilities of Bear Creek uranium ore leached with sodium carbonate-bicarbonate..... | 7 |
| 3. Permeabilities of Bear Creek uranium ore leached with sulfuric acid..... | 8 |
| 4. Red Desert uranium ore leached with sulfuric acid..... | 9 |
| 5. Noranda copper ore leached with sulfuric acid..... | 9 |
| 6. Ionic concentration in effluent..... | 10 |
| 7. Sodium montmorillonite clay swelling test at 22 h of exposure to liquids of three types..... | 11 |

TABLES

| | |
|--|----|
| 1. Particle size distribution of uranium ore from Bear Creek Mine..... | 5 |
| 2. Particle size distribution of uranium ore from the Red Desert of Wyoming... | 5 |
| 3. Zeta potentials of clay particles measured at pH 7..... | 12 |

UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

| | | | |
|--------------------|-----------------------------------|--------------------|------------------------|
| cm | centimeter | mg/L | milligrams per liter |
| g | gram | min | minute |
| h | hour | mV | millivolt |
| kg | kilogram | pct | percent |
| kg/cm ² | kilogram per square centimeter | lb/in ² | pounds per square inch |
| L | liter | wt pct | weight percent |
| md | millidarcy | | |

EFFECT OF CLAY STABILIZERS ON PERMEABILITY OF CLAYEY ORE

By Kenneth E. Hjelmstad¹

ABSTRACT

In situ leach mining operations often encounter difficulty maintaining adequate leach solution flow into the ore formation. Swelling and dispersion of clay particles in the formation are often responsible for this permeability loss. Permeability and leaching tests were done in the laboratory on clayey ores to evaluate a clay-stabilizing polymer's effectiveness in preventing these problems. Test results indicate that treating the ores with the stabilizer could maintain permeabilities two to five times greater than the long-term permeabilities present in untreated ores. Both alkaline (pH 8.5) and acidic (pH 2.0) leaches were used in the permeability-leaching tests. Since in situ leaching throughput rate is directly related to permeability, these results also indicate a potentially beneficial effect on operating parameters such as capacity and injection pressure. To determine the reasons for the success of the clay stabilizers, an investigation was conducted to determine the effect of the stabilizer on clay swelling and dispersion. Clay-swelling tests indicated that the clay stabilizer reduced clay swelling. Zeta potential measurements made on fine clay particles treated with the stabilizer were compared to measurements made on untreated particles and indicated that the stabilizer was electropositive and, therefore, could reduce the degree of negative charge on the particles and their tendency to disperse or migrate.

¹Geophysicist, Twin Cities Research Center, Bureau of Mines, Minneapolis, MN.

INTRODUCTION

The Bureau of Mines Twin Cities Research Center is engaged in research to help solve problems encountered in in situ leach mining of various metals. In situ leach mining of uranium involves injecting a carbonate-bicarbonate (basic) or sulfate (acidic) leach solution (lixiviant) through injection wells into an ore body where the lixiviant dissolves the uranium from the ore. The lixiviant bearing the complex uranium is then brought to the surface through production wells. Uranium is recovered from the lixiviant by ion-exchange methods.

Plugging of the injection wells is often a problem in in situ leach mining. It may be caused by improper well construction, invasion by solid particles from drilling fluids or cementing operations, precipitation of chemical salts, bacterial effects, fine particles in the injection fluid, and/or clay swelling and dispersion (4).² Acid or water jet perforation can be used to stimulate wells that exhibit high resistance to injection (10), but the treatments are not universally applicable and the benefits are generally temporary.

Uranium is most commonly leached from sandstone host rocks, and certain of these formations are water sensitive. Such formations are susceptible to permeability damage by exposure to introduced water that has a chemical composition different from the natural, interstitial water. The introduced water can upset the swelling equilibrium of the clay-water system (1-2, 13-14).

A formation's susceptibility to permeability damage is related to the salinity of the water to which it is exposed and to the type and amount of clay mineral constituents present (1). Reduction in salinity of interstitial water can cause

clay swelling, which may plug pores and reduce permeability. Swelling also causes the clay platelets to break up into finer, negatively charged particles. These negatively charged particles will repel one another and, therefore, disperse through the interstitial fluid until they lodge in constrictions in permeability channels, thereby plugging the channels (6-7).

The common swelling-clay minerals are the montmorillonites, mixed-layer clays, and certain types of illite. The clay particles in their natural state are at equilibrium with the saline water that usually occurs in the formations. Swelling occurs when fresh water replaces the saline water in the formation during drilling or leaching activities. In general the amount of swelling increases with a decrease in salinity of the injected water. Therefore, a concentrated brine would cause the least damage and fresh water the most damage (4). The nature of the clays is also important. Clays in the calcium form do not disperse as easily in low-salinity water as do clays in the sodium form. It is thought that sodium clays dissociate in low-salinity water, creating sodium ions and clay particles with a net negative charge that is great enough to cause the particles to repel one another and thus be dispersed (5).

The form of a clay can be altered by flowing a solution through it. Through cation exchange, a sodium clay may be changed to a calcium clay by passing a concentrated calcium-bearing solution through it. The cation-exchange capacity of the clay minerals is due to broken bonds, substitution within the lattice structure, and replacement of the hydrogen of exposed hydroxyls by the exchangeable cation. It is thought that if at least one-tenth of the dissolved salts in the water are magnesium and calcium, swelling and dispersion of clays will be minimal (5). The hydrated calcium and

²Underlined numbers in parentheses refer to items in the list of references at the end of this report.

magnesium ions seemingly restrict the adsorbed water on the clay to a well-developed configuration of minimal thickness, whereas the sodium ion allows oriented water to grow to very great thicknesses on the clay (3).

For that reason in situ uranium leach mining operators often use native ground water to prepare the leach solution because it usually contains calcium and magnesium ions. The leach solution, however, may still cause changes in formation water chemistry great enough to cause the clay to swell, and if the clay is in the swelling or dispersing form, any fluid flowing through the formation will result in permeability damage (12).

Commercial clay stabilizers have been developed to reduce permeability loss due to clay swelling and dispersion. Inorganic clay stabilizers include hydroxy aluminum (8-9) and zirconium oxychloride solutions. The higher charge cations of these clay stabilizers will adsorb on the clays more readily than monovalent or divalent cations because the attractive force between the negatively charged clay particles and the stabilizer cations is exponentially related to the charge on

these cations (12). These clay stabilizers have been shown to be effective in reducing permeability losses (15-16), but removal of these cations from the clays may occur when and if the wells undergo acid treatment. A series of acid-resistant, organic polymer clay stabilizers have also been developed to prevent permeability losses in water-sensitive formations under a broad range of operating conditions.

Since the organic polymer stabilizers have features that suggest potential application in reducing the permeability losses suffered in in situ leaching operations, the Bureau conducted a series of tests to define the range of conditions under which it would be appropriate to use them and to determine their effectiveness. A hydrocarbon polymer stabilizer with a nitrogen nucleus was chosen for laboratory testing. This report describes laboratory permeability-leaching tests on three clayey ores (two uranium and one copper), employing both alkaline and acidic leach solutions, as well as clay-swelling tests and zeta potential measurements conducted to determine the fundamentals of permeability improvements.

EQUIPMENT AND MATERIALS

PERMEAMETER

Permeability is a measure of a porous medium's capacity for transmitting a fluid and hence is a key parameter in determining the ability of a formation to accept leaching solutions via injection wells. To compare permeabilities of treated and untreated formation samples under controlled laboratory conditions, a permeameter was constructed and accessories assembled. The permeability test apparatus (fig. 1) includes the confining pressure cell, equipment for supplying a compressive load to the sample, and a means to pressurize the influent leach solution reservoir. The cell is a 5-cm-ID stainless steel cylinder with opposing stainless steel platens (pistons) employed to contain the uranium sand sample and test liquids under compression.

The cell geometry allowed use of a low sample-length-to-diameter ratio, which prevented arching of sand to the cell walls. A 250-g sample of uranium-bearing sand was loaded into the cell. A constant compressive load (axial) of 30 kg/cm² was applied to the platens to create a confining stress on the sand. The pressurized leach fluid flowed through stainless steel tubing from the reservoir to the upper platen. From there it flowed through the upper platen, the uranium sand sample, the lower platen, and the pressure relief valve into an effluent leach solution collector. O-rings placed around the platens (near the end contacting the sand sample) and the pressure relief valve made it possible to perform tests with fluid pressures as high as 150 lb/in² (11 kg/cm²). Fluid pressure drop

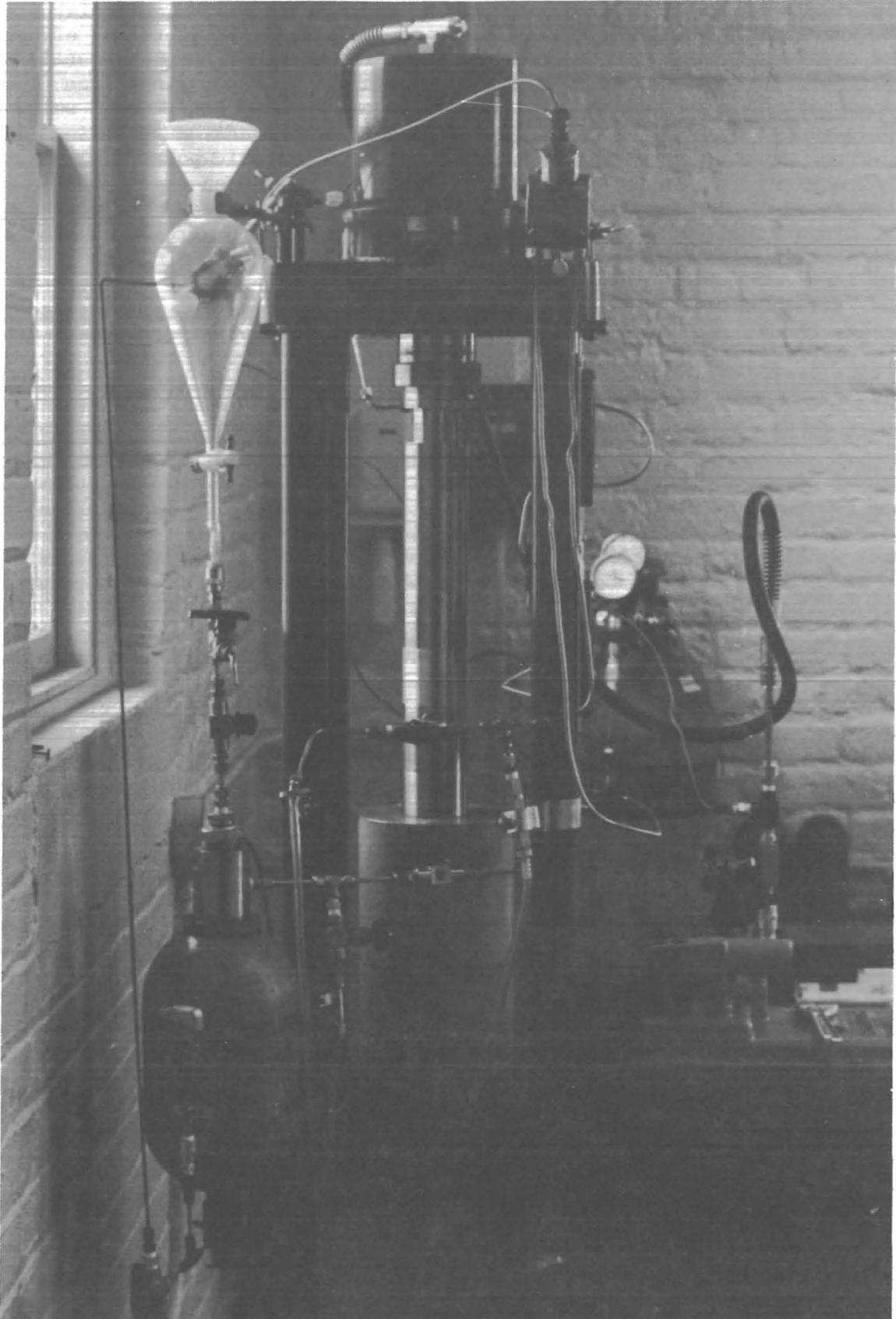


FIGURE 1. - Permeameter-leaching apparatus.

across the sand sample was measured using electronic transducers, which were placed in the fluid lines entering and leaving the cell. This apparatus enabled uranium to be leached from the sand sample while the permeability was simultaneously measured under a variety of test conditions.

A large plexiglass column 15 cm in diameter and 180 cm long was used as a constant-head permeameter. A constant level of leach fluid was maintained in the column by means of a constant-head overflow return. Fluid level was maintained at 165 cm above the outlet on the bottom end of the column. A 35-kg uranium sand sample was employed in these tests.

ORE SAMPLES

Two of the three materials used in this investigation were uranium-bearing sandstones from Wyoming. The uranium deposits of Wyoming basins were deposited during the Eocene and Paleocene epochs. They are roll-front deposits in Arkosic sandstone and fine-grained siltstone formations which are sandwiched between relatively impermeable shales or claystones below the water table. Typically in a roll-front deposit, uranium has been deposited along an oxidation-reduction front in any of several configurations--crescent-shaped along channel margins, tabular along zones of abrupt permeability changes, and elliptical or dish-shaped within scour pockets. In theory, uranium was leached from a source material and probably transported by the ground water in a dissolved state. As long as the ground water conditions were oxidizing enough to keep uranium oxidized (+6 valence state), no precipitation of uranium would occur. Uranium deposition would occur when the ground water conditions changed from oxidizing to reducing owing to the presence of reducing agents such as H₂S, pyrite, or carbon. The uranium in roll-front deposits may occur as finely disseminated mineral particles within the sandstone matrix or as a black coating on individual sand grains.

One uranium ore used in this investigation was from the Bear Creek Mine, 21 miles northeast of Casper in the Powder River Basin of Wyoming. The particle size distribution of the disaggregated Bear Creek ore is shown in table 1. The sample contained 19 pct minus 200-mesh material, which was primarily calcium montmorillonite. The plus 200-mesh material was mostly quartz with smaller amounts of feldspar, mica, and calcite. Small amounts of the heavy minerals chlorite, pyrite, magnetite, and clinoziosite were also present. These test samples contained an average of 0.15 pct uranium.

TABLE 1. - Particle size distribution of uranium ore from Bear Creek Mine

| <u>Tyler standard testing sieves,</u> <u>mesh per inch</u> | <u>wt pct</u> |
|---|---------------|
| Plus 20..... | 45.55 |
| Minus 20 plus 65..... | 26.36 |
| Minus 65 plus 200..... | 8.88 |
| Minus 200..... | 19.21 |

The second uranium ore was a low-grade one from a pit in the Red Desert of Wyoming. The particle size distribution of disaggregated Red Desert ore is shown in table 2. The sample contained 13 wt pct minus 200-mesh material, which was primarily calcium montmorillonite with some muscovite. The plus 200-mesh material was mostly quartz and feldspar with smaller amounts of mica and calcite. Small amounts of the heavy minerals chlorite, pyrite, magnetite, and clinoziosite were also present. This ore contained an average of 0.015 pct uranium.

TABLE 2. - Particle size distribution of uranium ore from the Red Desert of Wyoming

| <u>Tyler standard testing sieves,</u> <u>mesh per inch</u> | <u>wt-pct</u> |
|---|---------------|
| Plus 20..... | 17.35 |
| Minus 20 plus 65..... | 51.65 |
| Minus 65 plus 200..... | 17.67 |
| Minus 200..... | 13.33 |

A clayey copper ore from the Lakeshore Mine operated by Noranda Copper Co. near Casa Grande, AZ, was also tested. It had been crushed and screened to minus 4 mesh and contained 13 wt pct minus 200-mesh material. The ore was a porphyry granite made up of quartz, potassium feldspar, albite, muscovite, kaolinite, chlorite, and chrysocolla. Small amounts of martite, goethite, and manganese oxides were also present.

LEACH SOLUTIONS

The common solutions used for in situ uranium leaching are prepared from ammonium carbonate-bicarbonate, sodium carbonate-bicarbonate, carbon dioxide, and sulfuric acid. Oxidizers such as oxygen, hydrogen peroxide, or sodium chlorate are employed to convert uranium from its insoluble +4 valence state to the soluble +6 valence state (11).

The cation associated with the carbonate-bicarbonate anions does not enter into the leaching reactions but can affect ore permeability. As previously pointed out, sodium interacts with the clay to cause swelling and dispersion. Although sodium carbonate-bicarbonate can thus cause permeability loss, its low cost favors its use when clay is not present and would make it an attractive choice for many operations if a method such as the proposed application of clay stabilizers could be developed to prevent the sodium exchange reaction with the clay particles. It was thus a logical choice for an alkaline leaching solution for these experiments. Sulfuric acid is also commonly used if acid-consuming gangue minerals are absent. It was also a logical choice to incorporate into the testing program in order to provide information on the effectiveness of clay stabilizers for acid-leaching operations.

Permeability and leaching tests for evaluating the clay stabilizer were made with either a sodium bicarbonate leach solution near pH 8.5 or a sulfuric acid solution near pH 2. Hydrogen peroxide was the chosen oxidizer in each case.

ORGANIC POLYMER CLAY STABILIZER

The commercial clay stabilizer Cla-Sta-B³ was arbitrarily selected for the tests. Cla-Sta-B was developed for use in the oil drilling industry to reduce permeability losses. Its success in that industry led to it being selected for testing under simulated in situ leaching conditions. It is a water-soluble cationic polymer comprised of a long-chain hydrocarbon molecule with attached nitrogen atoms, some of which are quaternary (16). Polymers of this type often have molecular weights greater than 1,000. Based on oil industry experience, a polymer concentration of 2 pct in water was recommended by the supplier for treating the ore used in permeability-leaching tests.

A number of diluents or carriers are used to make the clay-stabilizing polymer more water soluble. Among these are ammonium chloride (2 pct), sodium chloride (8 pct), hydrochloric acid (5 to 15 pct), potassium chloride (4 pct), and methyl alcohol (5 pct). Although ammonium chloride is the most efficient diluent, the environmental problems associated with the ammonium ion dictate that an alternate diluent be selected for in situ leaching applications. Potassium chloride was the diluent employed in these permeability tests.

³Reference to specific products does not imply endorsement by the Bureau of Mines.

EXPERIMENTAL PROCEDURE, RESULTS, AND DISCUSSION

PERMEABILITY-LEACHING TESTS

Simultaneous permeability and leaching tests on 250-g samples of Bear Creek uranium ore were conducted in the confining pressure cell apparatus using both basic and acidic leach solutions. A 30-kg/cm² compressive load was applied and maintained on the sample while leach fluid was forced through it under a measured pressure gradient, which was regulated in order to maintain a flow rate of approximately 1 pore volume per hour.

Tests with sodium bicarbonate leach solutions were made after pretreatment with three types of solutions: (1) 2 pct clay stabilizer and 4 pct potassium chloride in tapwater, (2) tapwater, and (3) 4 pct potassium chloride in tapwater. Tests with sulfuric acid leach solutions were made after pretreatment with two types of solutions: (1) 2 pct clay stabilizer and 4 pct potassium chloride in tapwater and (2) tapwater. In each instance the sample was allowed to retain the pore volume of preflush fluid for 1/2 h before leaching with sodium carbonate-bicarbonate or sulfuric acid leach solutions. Effluent samples were taken and permeability was determined at intervals during the tests. The leach solution was not recycled in either case.

Results of the sodium carbonate bicarbonate leach tests on Bear Creek uranium ore are shown in figure 2. Results of the sulfuric acid leach tests on this ore are shown in figure 3. Points on the curves represent the average of two tests with each type of preflush. The results for the sodium carbonate-bicarbonate leaching indicate that, after 12 h of leaching, the ore pretreated with the clay stabilizer had a permeability about five times higher than that of the untreated (tapwater pretreated) ore. These results also confirm that the potassium chloride diluent does not prevent permeability loss but actually causes some additional permeability loss. Thus the increased permeability is owing to the clay stabilizer. The results for the sulfuric acid leaching indicate that, after 12 h of leaching, the ore pretreated with the clay stabilizer had a permeability about twice that of the untreated (tapwater pretreated) ore. Comparison of the results in figure 3 and those in figure 2 indicates that the permeability loss is not as great for the sulfuric acid leach as the sodium carbonate-bicarbonate leach. After 12 h of leaching the permeability is about 380 md for sulfuric-acid-leached ore and only about 150 md for sodium-carbonate-bicarbonate-leached ore.

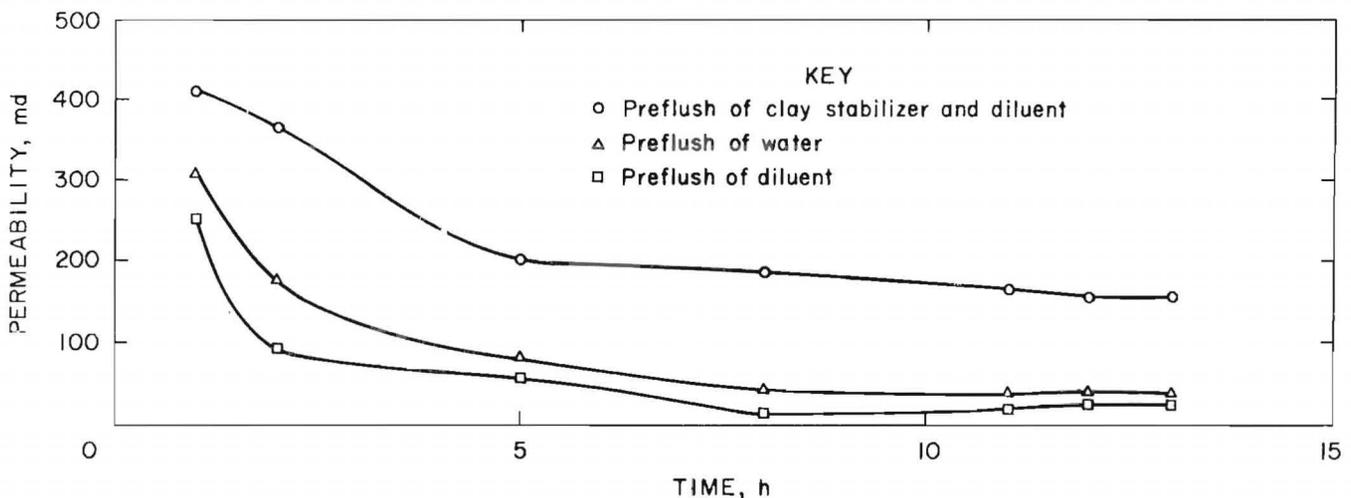


FIGURE 2. - Permeabilities of Bear Creek uranium ore leached with sodium carbonate-bicarbonate.

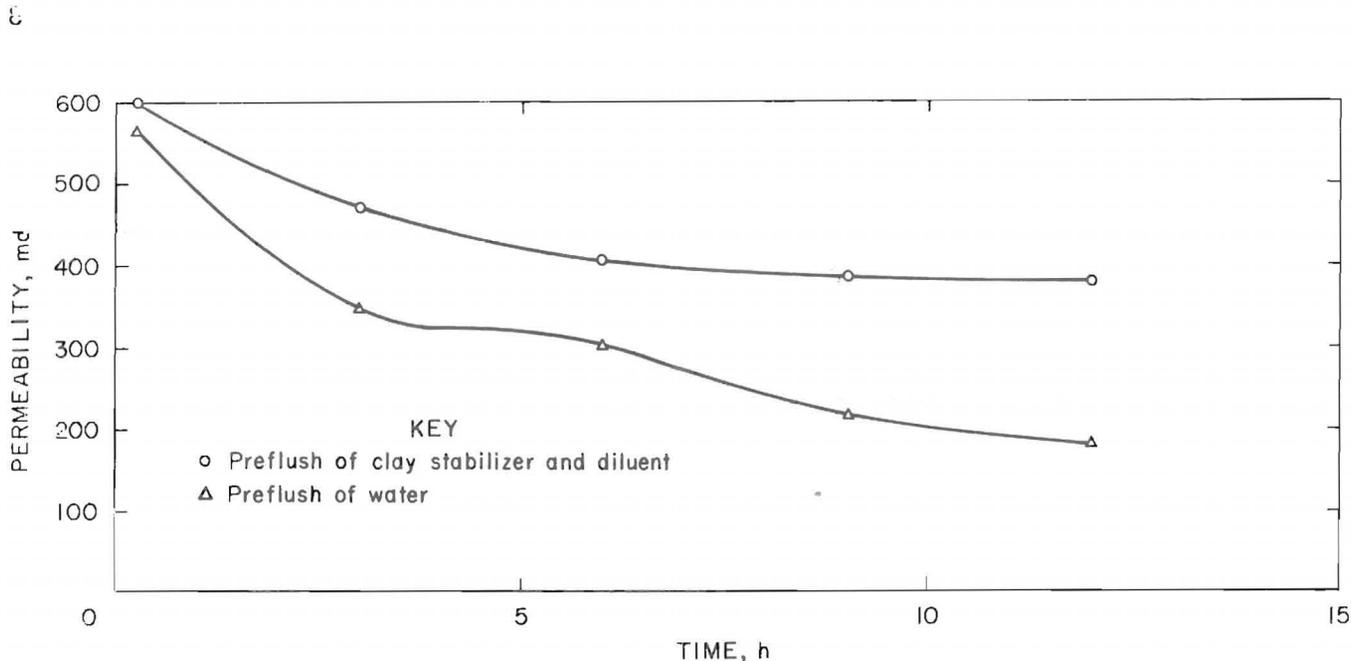


FIGURE 3. - Permeabilities of Bear Creek uranium ore leached with sulfuric acid.

The Red Desert of Wyoming ore was leached in the large constant-head permeameter using sulfuric acid solutions. One test was made after a preflush of 2 pct clay stabilizer and 4 pct potassium chloride in tapwater, and the other test was made after a preflush of tapwater alone. The preflush solutions were bottom-fed into the column through the outlet and allowed to rise to the constant fluid level 165 cm above the outlet. The sample was allowed to retain the preflush solution for 1/2 h before leaching with sulfuric acid solution was begun. Results of these tests are shown in figure 4 and indicate that the clay-stabilizer-treated ore had a permeability twice as great as the untreated (tapwater preflush) ore throughout the 14-day test. Because there was no confining pressure, the permeability did not drop with time as it did in the constant-pressure-cell permeameter. These results further confirm that the clay stabilizer could be used to reduce permeability losses when uranium ore is leached with acid.

Permeability-leaching tests were also made on 250-g samples of the clayey copper ore in the confined-pressure-cell apparatus with a sulfuric acid leach

solution of pH 2. These tests were conducted to determine the effect of clay stabilizer pretreatment on a clayey-type, metal-bearing ore other than those containing uranium. One test was made after a preflush of 2 pct clay stabilizer and 4 pct potassium chloride in tapwater, and the other test was made after a preflush of tapwater alone. The sample was allowed to retain the pore volume of preflush fluid for 1/2 h before leaching with sulfuric acid solutions. Results of these tests are shown in figure 5 and indicate that after 9 h the permeability of the clay-stabilizer-treated ore was five times greater than the permeability of the untreated (tapwater-pretreated) ore. The permeability had stabilized at about 1 md in the tapwater pretreatment test and therefore, the test was discontinued at 5 h. It was assumed that if the test was continued, the permeability would be about 1 md at the end of 9 h. Subsequent large-scale column leaching tests on treated and untreated ore by Noranda have confirmed these results, which indicate that clay stabilizer pretreatment also reduces the permeability loss in acid leaching of a clayey copper ore.

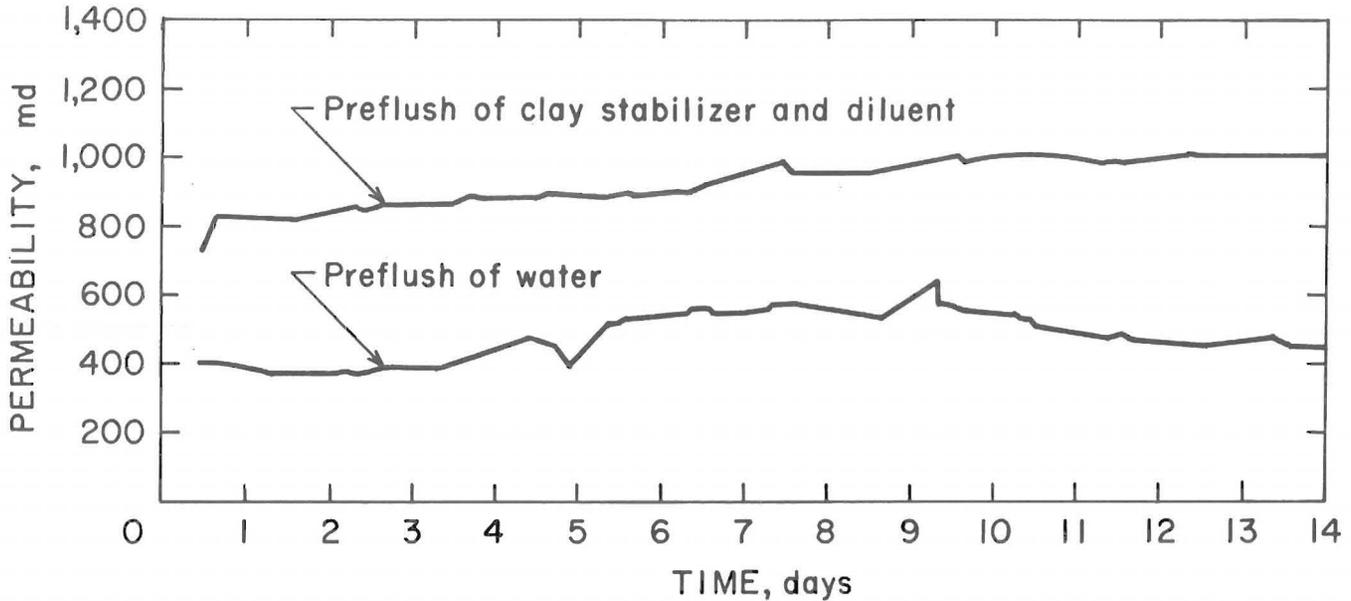


FIGURE 4. - Red Desert uranium ore leached with sulfuric acid.

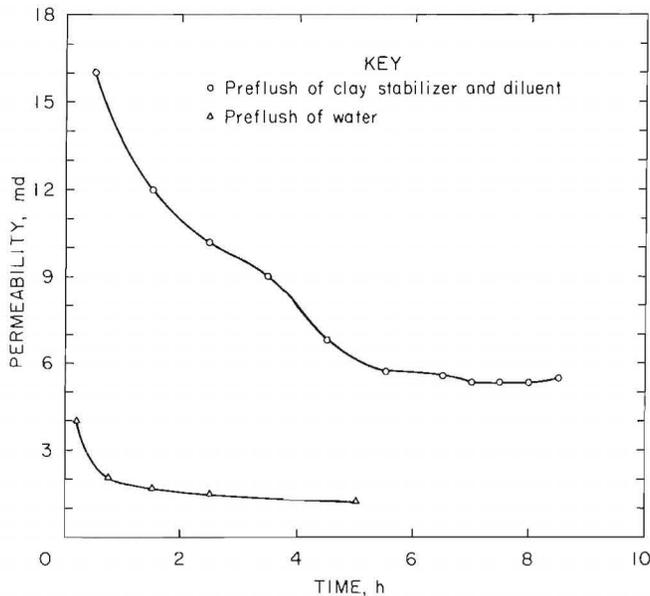


FIGURE 5. - Noranda copper ore leached with sulfuric acid.

EFFECT OF CLAY STABILIZERS ON URANIUM EXTRACTION

Because of the apparent success of clay stabilizers in reducing permeability losses, the effect of clay stabilizer pretreatment on uranium extraction was studied. The maximum concentration of uranium in the effluent for both alkaline

and acidic leaches occurred with the passage of 2 pore volumes of leach solution through the ore. The maximum uranium concentration in the effluent was 400 mg/L for the sodium carbonate-bicarbonate leach and about 500 mg/L for the sulfuric acid leach. After 4 h of leaching the uranium content in the effluent had decreased to about 100 mg/L with both leach solutions. When untreated Bear Creek ore was leached with sodium carbonate-bicarbonate solution, 44 pct of available uranium was recovered in the first 4 h. When Bear Creek ore was treated with the clay stabilizer and diluent, 30 pct of the available uranium was extracted with the sodium carbonate-bicarbonate solution in the first 4 h. It is concluded that the clay stabilizer apparently retards the leaching process and thus may reduce uranium recovery. However, it may be that with time the maximum possible uranium extraction would be attained for both treated and untreated ores. If the stabilizer is used to treat only the ore within a 3-ft radius of the well bore, where the fluid velocity is highest and where the fines movement would thus be greatest, the reduced recovery in this small ore volume would be more than compensated for by the increased leach flow into the rest of the ore body.

CLAY-SWELLING TEST

To understand the mechanisms by which clay stabilizers reduce permeability losses, the swelling tendencies of sodium montmorillonite clay were analyzed.

The predominant clay in the uranium ores tested was a calcium montmorillonite. As described in the Introduction, calcium in the clay lattice can be replaced by sodium ions in the leach solutions. This results in a clay form that is more likely to swell and disperse. An analysis of calcium and sodium in the effluent from tests using sodium carbonate-bicarbonate leaching solutions demonstrated that as leaching proceeds, calcium is in fact displaced by sodium and appears in the effluent solution. Figure 6 shows the calcium and sodium concentrations in the effluent as a function of time. If there was no exchange of sodium ions for calcium ions in the montmorillonite of the Bear Creek ore, the sodium content of the effluent would be about 650 to 700 mg/L while the calcium content of the effluent would be near zero. However, after 1 h of leaching with $\text{NaHCO}_3\text{-NaCO}_3$, the calcium content is about 400 mg/L and the sodium content is about 280 mg/L, thereby proving that sodium ions have displaced calcium ions in the clay. As time increases, the clay has become more saturated with sodium ions, fewer calcium ions are displaced, and therefore fewer calcium ions appear in the effluent. The exchange of sodium ions for calcium ions in the clay fraction during sodium carbonate-bicarbonate leaching also explains why there is a sharper drop in permeability for untreated samples leached with sodium carbonate-bicarbonate compared with the drop in permeability for untreated samples leached with sulfuric acid. This has also been reflected in actual in situ leaching experience.

Further evidence of the mechanism by which clay stabilizers reduce permeability losses was provided by a clay-swelling test on a sodium montmorillonite clay. In vial 1 (fig. 7) clay was exposed to acid leach solution. In vial 2 clay was

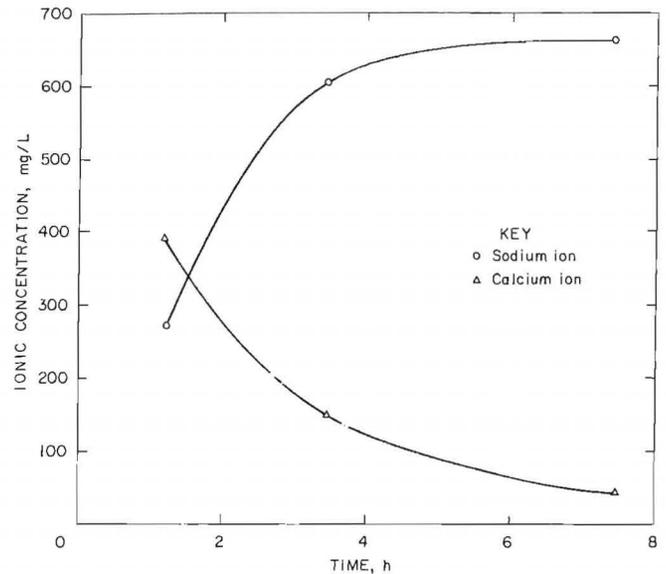


FIGURE 6. - Ionic concentration in effluent.

exposed to acid leach solution and 2 pct diluent, while in vial 3 clay was exposed to acid leach solution, 2 pct diluent, and 1 pct clay stabilizer. Results of these tests (fig. 7) demonstrate that the clay stabilizer reduced swelling in the clay. Untreated clay has swelled the most, while clay pretreated with stabilizer swelled very little. This characteristic of clay stabilizers is important in retarding clay swelling when a sodium leach is used or when sodium montmorillonite is present in the ore.

ZETA POTENTIAL MEASUREMENTS

Zeta potential measurements were made on clays subjected to various treatments to provide additional clues regarding the mechanisms responsible for the clay stabilizer's effect on the clay particles.

Electrophoretic mobility of finely divided, solid particles in aqueous suspension can be measured by using a microelectrophoresis instrument. Electrophoretic mobility is the rate of particle motion in an electric field. This motion is brought about by the interaction of the electrostatic charge at the particle-medium interface with an imposed electric field. Electrostatic particle charge is expressed as zeta potential in units of millivolts.

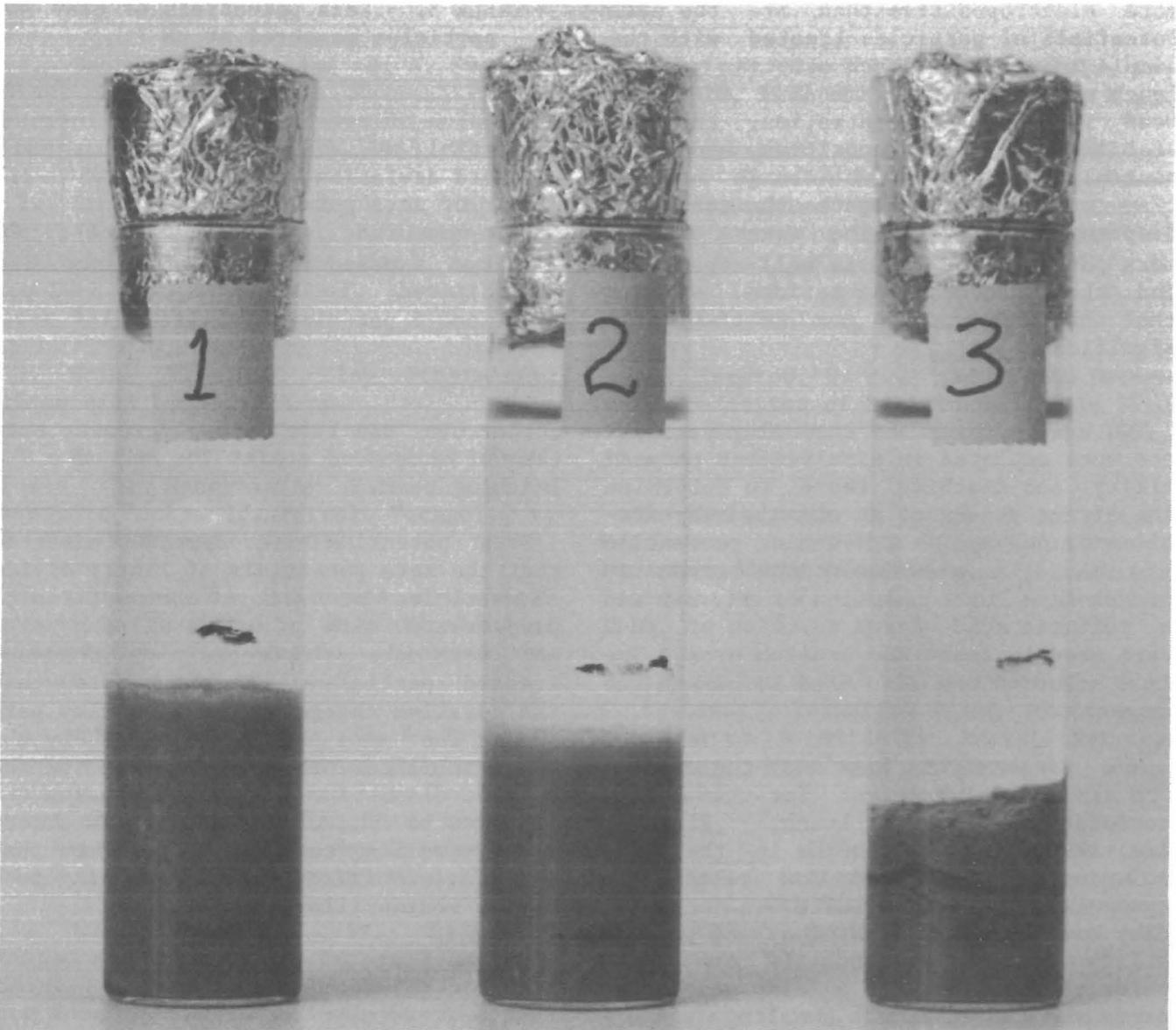


FIGURE 7. - Sodium montmorillonite clay swelling test at 22 h of exposure to liquids of three types.

Zeta potential measurements were made on finely divided clay particles that were exposed to three different liquids. Samples of sodium montmorillonite clay each weighing 2 g were blended into 1-L samples of (1) leach solution alone, (2) leach solution with 2 pct ammonium chloride, and (3) leach solution with 2 pct ammonium chloride and 1 pct clay

stabilizer. Each of the samples was mixed and sheared for 5 min in a blender prior to the measurement of zeta potentials of the suspended fine clay particles.

Test results shown in table 3 indicate the zeta potentials of the fine clay particles treated with the stabilizer are

more electropositive than are the zeta potentials of particles treated with the simple ions of the leach solution or the leach solution with ammonium chloride. Used in proper concentration, the clay stabilizer is electropositive enough to neutralize the negative charge on fine clay particles and negate the resultant dispersive forces. The means of the zeta potential values are well separated, and the standard deviations indicate that the differences are statistically significant.

SUMMARY AND CONCLUSIONS

Two uranium ores and one clayey copper ore were employed in simultaneous permeability and leaching tests to determine the effectiveness of an organic clay-stabilizing polymer in preventing permeability loss. An alkaline sodium carbonate-bicarbonate leach solution of pH 8.5 and a sulfuric acid leach solution of pH 2 were used to leach the uranium ores. The acid solution was also used to leach the copper ore.

The permeability loss in the uranium ore sample was greatest for the sodium carbonate-bicarbonate leach. Effluent analyses proved that sodium in the leach solution is exchanged for calcium in the clays. This results in increased clay swelling and dispersion and permeability loss. Treating the ore sample prior to leaching with a clay stabilizer decreases the attendant swelling and migration of the clays and reduces the permeability loss. The permeability of clay-stabilizer-treated ore was five times higher than that of untreated ore at the end of the 12-h leach test period.

Although the permeability loss in the uranium ore sample was less for the sulfuric acid leach than for the basic leach, permeability of treated ore was still twice that of untreated ore at the end of sulfuric acid leaching tests of 12-h and 14-day durations.

Acid leaching tests on a clayey copper ore indicated that clay-stabilizer pretreatment could also reduce the permeability loss in acid leaching of porphyry copper ores. Permeability of treated

TABLE 3. - Zeta potentials of clay particles measured at pH 7

| Sample ¹ | 1 | 2 | 3 |
|---|------|------|------|
| Mean value of zeta potential, mV..... | 18.1 | 10.0 | 41.8 |
| Standard deviation, mV. | 3.9 | 5.5 | 2.7 |
| Number of zeta potentials measured..... | 20 | 20 | 20 |

¹Clays exposed to leach solution: 1--no additives; 2--2 pct NH₄Cl; 3--2 pct NH₄Cl and 1 pct clay stabilizer.

copper ore was five times greater than that of untreated ore at the end of a 9-h leaching test.

Zeta potential measurements indicated that the zeta potentials of finely divided particles of sodium montmorillonite clay treated with clay-stabilizing polymer were more electropositive than untreated particles. This suggests that the negative charge on the fine clay particles was more than neutralized by the clay stabilizer, thereby negating the resultant dispersive forces and causing the clays to be flocculated and nondispersed. A clay-swelling test also confirmed that the clay stabilizer reduced swelling in a sodium montmorillonite clay.

On the basis of the laboratory results of this investigation, it is concluded that pretreatment of clayey ores with a clay stabilizer will reduce clay swelling and dispersion and thus reduce permeability losses. Some retardation in metal extraction was observed when a pretreated uranium ore was leached. This possible disadvantage in using clay stabilizers could be minimized if the stabilizer were used to treat only the small volume of ore within the zone of high fluid velocity around the injection well. In this case the reduction in metal extraction would be minimized, while the savings accrued by reducing well maintenance costs and ensuring adequate movement of leach solution into the ore formation would be significant. Field testing of clay stabilizers is needed to prove this hypothesis.

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