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THE PUSH-PULL TEST

A METHOD OF EVALUATING FORMATION ADSORPTION PARAMETERS FOR PREDICTING THE ENVIRONMENTAL EFFECTS ON IN-SITU COAL GASIFICATION AND URANIUM RECOVERY

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ABSTRACT

The push-pull test, which is a simple injection and pumping sequence of groundwater spiked with solutes of interest, is presented as a method of determining the adsorption characteristics of a formation. Adsorption properties are necessary to predict restoration from both in-situ coal gasification and in-situ uranium extraction.

The major problems in applying laboratory measurements to the field concern scaling the effect of particle size and obtaining representative samples. Laboratory measurements are conducted on gram to kilogram scale samples, whereas the push-pull test evaluates a sample weighing approximately 130 to 1,000 metric tons, depending on volume injected and porosity. The problems in translating laboratory results to the field appear to be less severe for sedimentary uranium bodies than for coal. Laboratory measurements are useful in delineating ranges in adsorption properties and in planning the field experiment.

The adsorption behavior of a formation can often be described by a linear Langmuir-type isotherm in which the significant parameters are the cation exchange capacity (C) and an exchange constant which can be derived from the distribution coefficient measured at

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low concentration (k_d). Laboratory procedures for their measurement on coal and uranium are presented.

Two field push-pull tests were conducted on uranium formations in Wyoming. Adsorption properties estimated from these tests on the basis of a simple cell model were compared to the laboratory values. In the first case, excellent agreement was observed between the values estimated from the field test and the values measured in the laboratory . In the second case, the value for k_d determined in the laboratory was five times higher than the field value.

It is recommended that push-pull tests be conducted on coal formations being considered for in-situ gasification in view of the great uncertainty in extrapolating laboratory adsorption properties in the field.

1.0 INTRODUCTION

The largest single issue confronting in-situ processes at present is restoration of groundwater. Two restoration modes are possible - induced and natural restoration. Induced restoration is brought about by using engineering knowledge together with various combinations of pumping, injecting, and surface processing with or without chemical additives. Natural restoration relies upon the slower but sure processes of nature such as groundwater flow, dispersion, and sorption phenomena to reduce post mining concentrations to acceptable levels. Furthermore, natural restoration may also be used in conjunction with induced restoration.

To predict the outcome of either method, it is essential to have a knowledge of the adsorption and absorption properties of the medium. Adsorption of ions from solution can usually be regarded as an ion exchange process involving exchange of surface ions with ions in solution. Absorption involves an exchange of fluid between main permeability paths and regions of lower permeability. In coal,

absorption would result from fluid migrating from the main fracture system into the smaller fractures within the matrix. Absorption occurs in uranium sands due to fluid exchanging with lower permeability sands and clays through advection.

Adsorption at present appears to be the dominant mechanism affecting solute transport. The field results we will present from in-situ uranium can be explained entirely on the basis of adsorption. In addition, limited field tests in coal reported by Dalton and Campbell (1978) were satisfactorily explained on the basis of adsorption theory.

Absorption cannot be ruled out as an important mechanism in large-scale fluid migration. However, owing to a lack of data in support of absorption at present, we will address only the evaluation of formation adsorption properties.

To evaluate the adsorption characteristics of a formation, two approaches are possible - laboratory and field. Considerable discussion has been raised in the past concerning the merits of the two approaches. It is our contention that laboratory measurements when properly conducted are useful to identify the range of possible values. However, some uncertainties will always remain. Among these are selection of a representative sample. In the laboratory approach, samples are extracted from their natural environment. Sample removal may generate new surface area which would otherwise be unavailable to the fluid. Existing surfaces can be altered from handling and crushing or exposure to the atmosphere. In this respect, oxidation and particle size effects are particularly pronounced in coal (Dalton and Campbell, 1978; Drever, Murphy, and McKee, 1980).

Does Knowledge of the properties of a small sample on the order of grams allow extrapolation to large-scale behavior? Dalton and Campbell were able to obtain satisfactory agreement regarding postburn behavior from laboratory data. In their work, they were presumably concerned with small particle sizes both in the laboratory and field situations. However, contaminants will leach from the burn zone into the larger-scale fractures. Laboratory tests do not tell us how much of the surface area will be exposed. Will adsorption behavior in-situ be different from the laboratory? Do freshly broken surfaces resulting from handling and crushing behave differently from the naturally occurring surfaces exposed in fractures? Scaling from small laboratory-sized particles on the order of millimeters to larger blocks delineated by fractures on the scale of meters is not straightforward (Drever, Murphy, and McKee, 1980).

These considerations have led us to the use of the push-pull test to evaluate formation adsorption properties and to confirm predictions based on laboratory studies. The push-pull test is a relatively simple concept. Figure 1 shows a vertical cross section of test arrangement. An easily erected pool or bladder is prepared on site. Water from the well is filtered and pumped into the bladder. Appropriate amounts of the species to be studied are mixed into the bladder together with formation water. The solution is then injected into the formation and allowed to reside for a few days. Figure 2 shows the affected area in plan view. The next step is to lower a pump into the well to recover the solution and measure its resulting concentration as a function of volume produced. Typically, 15,000 to 20,000 liters of solution are injected, with approximately 10 times this amount being recovered on pumping.

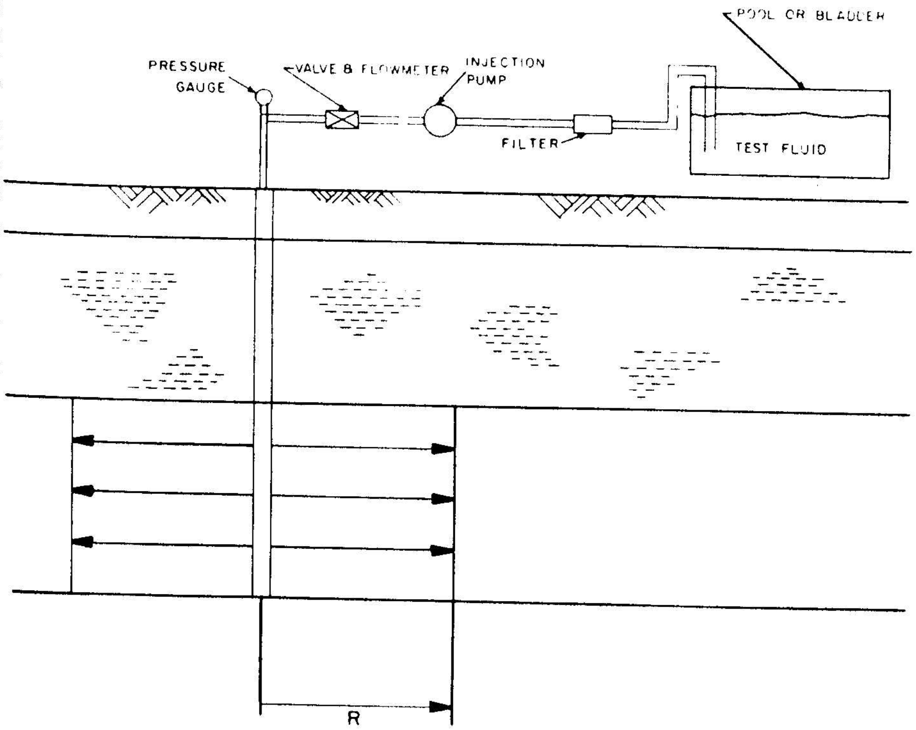

Fig. 1. Layout of push-pull test.

If we are testing a sedimentary ore body with a porosity of 28%, the push-pull method would test approximately 130 metric tons of ore. In the case of coal with a fracture porosity on the order

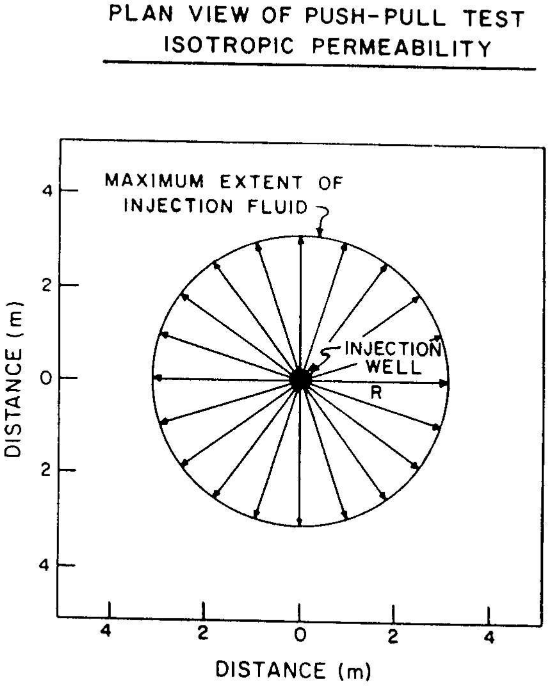

Fig. 2. Plan view of the push-pull test, assuming isotropic permeability.

of a few percent, approximately 1,000 metric tons of coal would be exposed to solution. The test also possesses an additional advantage in that it is relatively easy to obtain the necessary permits.

From the recovered solution concentration as a function of volume pumped, adsorption parameters can be obtained. This information, together with dispersion coefficients, can be used to predict the fate of a plume migrating downstream. Furthermore, the time and pore volumes required to restore a uranium ore body after mining can be estimated. The theory for determining the adsorption

parameters which are required for predicting restoration behavior is given in the following section.

2.0 ION EXCHANGE THEORY

Ion exchange involving two monovalent cations can be described by a mass-action equation (Garrels and Christ, 1965; Hill, et al, 1978)

$$\left(\frac{a_1}{a_2}\right) \text{solid} = K_{ex} \left(\frac{a_1}{a_2}\right) \text{liquid} \qquad (2.1)$$

where a represents an activity and K_{ex} is the thermodynamic exchange constant and 1 and 2 refer to the two ions. Since activity coefficients of ions on a solid exchanger are not well known, it is common to rewrite equation (2.1). This is accomplished by substituting mole fractions for activities in the solid phase and concentrations for activities in solution. Equation (2.1) then becomes

$$\frac{X_1}{X_2} = K'_{ex} \frac{M_1}{M_2} \qquad (2.2)$$

where X represents the mole fractions on the solid and M the concentrations in solution in equivalents/kg. K'_{ex} , the exchange constant, now includes all activity corrections for both solid phase and solution. It will no longer be a true constant, but will vary with X_1 and X_2. However, the variation appears to be within the error or our experimental measurements of K'_{ex}. Since electroneutrality must be satisfied for exchange sites, we have

$$X_1 + X_2 = 1.$$

The concentration of the adsorbed species, Y, is given by

$$Y_1 = CX_1 \qquad Y_2 = CX_2,\ Y_1 + Y_2 = C \tag{2.3}$$

where C is the cation exchange capacity of the solid in meq/kg. For the same reason, the sum of M_1 and M_2 must be a constant

$$M_1 + M_2 = G \tag{2.4}$$

where G is the total concentration of cations in solution. Using equations (2.3) and (2.4), the mole fraction and concentration of species 2 can be eliminated from equation (2.2) to obtain

$$\frac{Y_1}{C-Y_1} = K'_{ex} \frac{M_1}{G-M_1} \ . \tag{2.5}$$

Although laboratory measured values of K'_{ex} can be found in the literature for various pairs of ions on various minerals (for example, Gilbert and Van Bladel, 1970), we do not believe these values are of much use in predicting the behavior of a real-world aquifer. The minerals in the aquifer (and, hence, their K'_{ex} values) are likely to be different from those on which measurements were made. Furthermore, it is difficult to extrapolate from simple two-ion systems to the complicated chemistry of a groundwater system in which several ions are competing for exchange sites. Our approach has been to measure, in the laboratory, the exchange properties of each aquifer-groundwater system in which we were interested and to predict the results of the push-pull test on the basis of these results. If the laboratory prediction and field data do not agree, exchange parameters can be estimated from the field data. The procedure will be discussed in a subsequent section. A typical example showing the adsorption characteristics of ammonium ion from a sedimentary uranium property is given in Figure 3. We will use the ammonium ion as an example in our present work since it is a problem cation in in-situ uranium processes as well as an unavoidable by-product of coal gasification (Hill, et al, 1978 and Campbell, Pellizzari, Santor, 1978).

The adsorption curve in Figure 3 is characterized by two numbers - the cation exchange capacity, C, and the exchange constant, K'_{ex}. The exchange constant is related to the distribution coefficient at low concentration, k_d, by the equation

$$k_d = K'_{ex} \frac{C}{G} \ ; \tag{2.6}$$

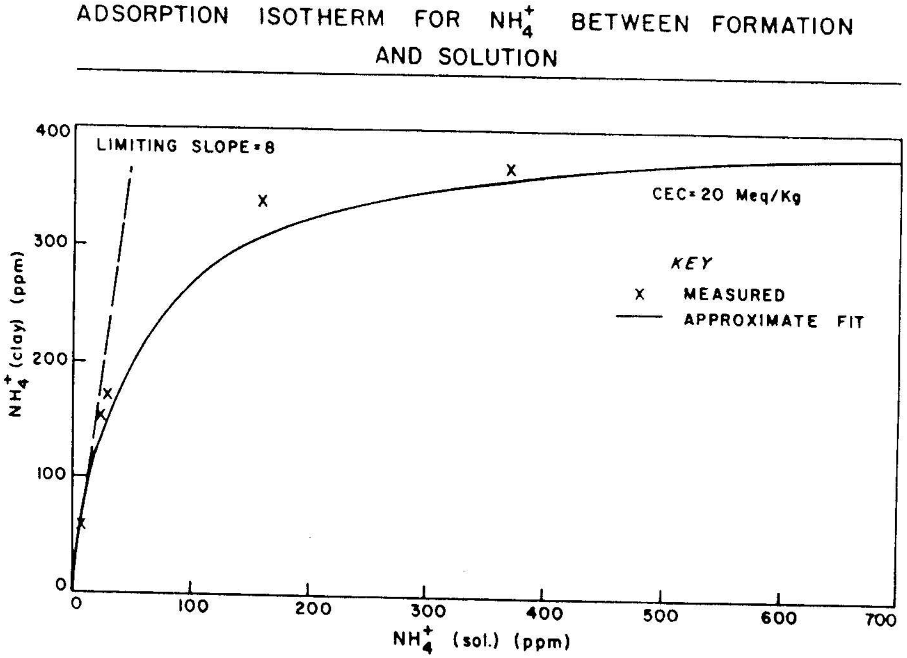

Fig. 3. Typical adsorption curve showing relationship between ammonium adsorbed on sediment and ammonium in solution. Solution was an artificial groundwater, Na+ = 173 ppm, Ca^{2+} = 122 ppm, K^+ = 10 ppm, Mg^{2+} = 14 ppm.

k_d is equal to the limiting slope of the exchange curve at low concentrations (the dashed line on Figure 3). Although k_d is used rather than K'_{ex} in subsequent discussions as an adsorption parameter, it should be emphasized that the model is applicable over the whole concentration range described by the Langmuir-type adsorption isotherm (equation 2.5).

Rewriting equation (2.5) in terms of k_d and C, we obtain

$$\frac{Y_1}{1-Y_1/C} = k_d \frac{M_1}{1-M_1/G} \,. \qquad (2.7)$$

In this equation, the cation exchange capacity, C, and the distribution coefficient for dilute concentrations are the unknowns. G in equation (2.7) represents the total concentration (in meq/gm) of cations in the groundwater which is a known quantity. Our approach is equivalent to treating the sum of all cations which are not of species 1 as a single monovalent cation M^+. This approach cannot be rigorously justified on theoretical grounds, but can be regarded as a convenient approximation. In theory, when the principal ion competing with a monovalent ion such as NH_4^+ is divalent, for example Ca^{++}, equation (2.5) should have the form

$$\frac{Y^2_{NH_4}}{C-Y_{NH_4}} = K'_{ex} \frac{[NH_4]^2}{G-[NH_4^+]} \qquad (2.8)$$

where square brackets denote concentration. We have measured adsorption curves such as Figure 3 using groundwater in which the molar Na/Ca ratio varied from 2.5 to 26. In all cases, a simple linear equation (equation 2.5 or 2.7) fitted the data as well as, or better than, an equation with squared terms (equation 2.8) or and equation with an exponent between 1 and 2.

As we remarked in the introduction, there are two approaches in determining the necessary constants C and k_d. They are laboratory and field tests, the simplest field test being the push-pull test. Before discussing the theory of the push-pull test, we will first present the laboratory measurement techniques we have employed.

3.0 LABORATORY MEASUREMENTS OF ADSORPTION PARAMETERS

Adsorption measurements on granular sediments associated with uranium ore bodies are slightly different from those for coal. We, therefore, discuss them under separate headings.

3.1 Uranium Core Samples

As previously mentioned, we will use the ammonium ion to illustrate the procedure.

Measurements are made on core material from the aquifer. Samples are taken from permeable lithologies which will be in contact with lixiviant during mining. It is important to exclude impermeable shale units, as these will not be in effective contact with the lixiviant. The core samples are lightly ground where necessary to disaggregate the sample. Next, the material is saturated with NH_4^+ by treatment with 1M NH_4CO_3 solution and then cleaned of excess ammonium salts by repeating washing with distilled water, using centrifugation followed by membrane filtration to retain solid phases. If the samples contain much gypsum or calcite, it may be necessary to dissolve them out prior to saturation with NH_4^+, since they can interfere with the exchange measurements. The cation exchange capacity (CEC) is them measured on one split of the sample by modification of the method of Busenberg and Clemency (1973). For measurement of K'_{ex} and k_d, approximately six splits of ammonium-saturated sample are equilibrated with different volumes of groundwater, and then the ammonium concentration in solution and on the sediment is measured. The graph of NH_4^+ adsorbed on the sediment versus NH_4^+ in solution (Figure 3) is generally linear at low NH_4^+ concentrations, and k_d is calculated from the slope of the linear portion. We have observed limiting slopes or distribution coefficients in the range of 2 to 10. Cation exchange capacities have ranged from 0.2 - 7 meq/100 g. In general, fairly good agreement has been obtained between laboratory data and push-pull tests. Two examples were permitted to be released in this article. One (Figure 4) showed excellent agreement between laboratory and field results, the other (Figure 6) poor agreement, hence, demonstrating the necessity of comparing field results to laboratory projections.

3.2 Coal Samples

Our laboratory experiments with coal have been limited to examining the distribution of low concentrations of lead, cadmium, mercury, and selenium (Drever, Murphy, McKee, 1980). These were in the nitrate form with the exception of selenium which was copper selenate. All elements were in the +2 valence state with the exception of selenium which was +6. For these elements, we are always working in the low concentration range where the distribution coefficient is approximately constant. This is the limiting slope region in Figure 3.

Cores from granular sediments in the previous case readily disaggregate to a definite size distribution. Beyond this point, considerable effort is required to reduce the grain size further. Coal, on the other hand, is characterized by fractures on various scales. The choice of particle size is somewhat arbitrary and limited by convenience and available equipment. Currently, the approach has been to begin with sub-millimeter particles and progress to the centimeter size scale in order to study the effects of various particle sizes.

Adsorption characteristics were studied by preparing an 8% weight suspension of a limited range of particle sizes in a groundwater sample. The groundwater sample was prepared in the laboratory from its previously determined composition. Aliquots of a standard solution of a given trace element were added to the suspension. After equilibration, an aliquot of solution is removed from the suspension and analyzed for the element of interest. The suspensions were continuously stirred throughout the experiment. As a control, 100 ml of groundwater was treated and analyzed in exactly the same manner as the coal suspension. The concentration of adsorbed metal can be calculated from the difference between the concentration in the control and coal experiments. This concentration can be used to calculate a distribution coefficient for each element between coal and groundwater.

Some difficulties were encountered with insoluble carbonates of lead and cadmium forming. Considerable scatter was also observed. Nevertheless, certain trends were noted for sub-millimeter scale particles. Lead and cadmium were strongly adsorbed ($k_d \sim 100$). Mercury exhibited a k_d of about 40, while selenium was not adsorbed. The dependence of k_d decreases approximately linearly with increasing particle size (Drever, Murphy, and McKee, 1980). This was in agreement with our expectations for k_d to be proportional to the specific surface area which has the dimensions of 1/length. Time dependent problems were noted.

In view of these problems and the uncertainty of projecting the coal results to the field, we are advocating the use of the push-pull test. This will, hopefully, provide a guide and scale-up procedure in translating laboratory results in the field.

4.0 INTERPRETING THE PUSH-PULL TEST

The results of a push-pull test can be satisfactorily explained on the basis of a simple ion exchange model that assumes no mixing or dispersion (plug flow). The volume injected from the surface holding pool is termed a pore volume. In the examples given below, the pore volume was divided into 10 cells (the number is arbitrary, depending on the amount of resolution required; results based on 20 cells are almost indistinguishable from those based on 10 cells). As each increment of solution to fill a cell volume is injected (or extracted in the "pull" part of the test), the solution in each cell is displaced into the next cell. Within each cell, concentrations are assumed to be uniform. Equilibrium is assumed to be reversible and rapid compared to the rate of water movement.

The distribution of NH_4^+ between solid and solution in the ith cell after the nth increment of solution has been injected is given by

$$\frac{Y_{i,n}}{C-Y_{i,n}} = K'_{ex}\,\frac{M_{i,n}}{G_{i,n} - M_{i,n}} \qquad (4.1)$$

where the symbols are the same as in equation (2.5) with the subscripts changed to correspond to the cell model. The material balance equation for NH_4^+ is

$$Y_{i,n} - Y_{i,(n-1)} = \frac{\phi}{(1-\phi)\rho}\left(M_{(i-1),(n-1)} - M_{i,n}\right) \qquad (4.2)$$

(ϕ is the porosity and ρ the grain density of the sediment) and for the total cations is

$$G_{i,n} = G_{(i-1),(n-1)}. \qquad (4.3)$$

Equations (4.1), (4.2), and (4.3) are solved simultaneously for each cell for each increment of solution pumped into or out of the well. The predicted concentration of ammonium in water pumped from the well as a function of volume pumped is then compared with field data. Since "plug flow" is assumed, the result does not depend on the assumed geometry (one-dimensional, cylindrical, spherical) of the pore volume underground.

As an example of the procedure, we will discuss two specific push-pull tests conducted on in-situ uranium properties in Wyoming. In both cases, 4,000 gallons (15,000 liters) of water containing 650 ppm ammonia as ammonium carbonate-bicarbonate were injected into a single well. This is the "push" part of the test. Next, 52,500 gallons (200,000 liters) were "pulled" or pumped from the well. The ammonium iron concentration was periodically measured. The same wells employed in the push-pull test were also used to obtain the core and groundwater samples. As mentioned in a previous section, a composite sample was gathered from the permeable core sections. This was done to duplicate the material injected fluid would most likely contact.

4.1 Push-Pull Test #1

Laboratory values for the cation exchange capacity and distribution coefficient or limiting slope were 4 meq/100 g and 3, respectively. Using these values in the model, we obtained the comparison between field data and calculations based on laboratory data shown in Figure 4. A best fit in this instance resulted without the necessity of history matching by adjusting parameters. The fit in Figure 4 was obtained in two stages. In the first pore volume produced, the ion concentration of the stronger ammonium solution was included in the groundwater concentration G of equation (4.1). Thereafter, only the concentration of cations in the natural groundwater was used.

Another interesting feature of the push-pull tests is that the bulk of the ammonia does not attain the full extent shown in Figure 2. The radius (R) given in Figure 2 refers to the distance from the well that non-adsorbed species would propagate. The true situation is shown in Figure 5. In this figure, we note that the bulk of the ammonium ion lies within .25 pore volume of the subsurface material contacted and corresponds to a distance of .5R. This is the major reason the push-pull test has been misinterpreted in many recent tests. As an illustration, consider the number of pore volumes required to restore the groundwater to 10 ppm of ammonia.

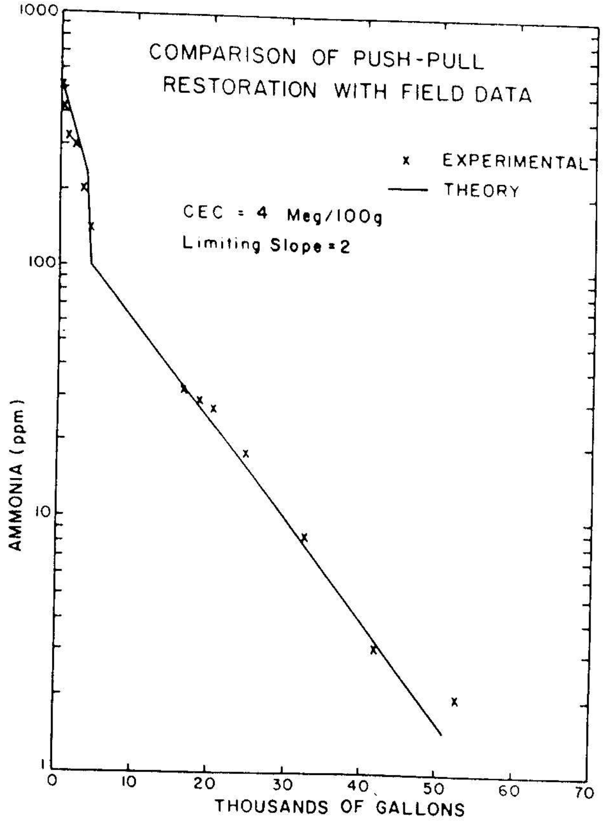

Fig. 4. Push-pull restoration: comparison of field data (crosses) with prediction based on laboratory measurements (CEC = 4 meq/100 g, k_d = 3). Concentration of ammonia injected = 650 ppm.

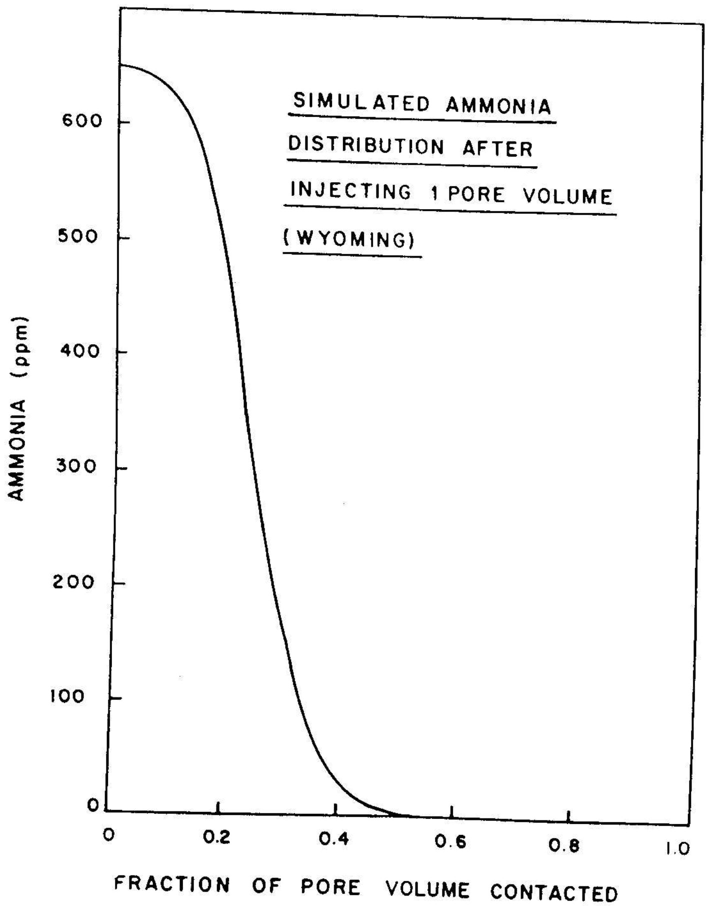

Fig. 5. Calculated distribution of dissolved ammonia after injection of 1 pore volume. Parameters are in Fig. 4.

From Figure 4, a concentration of 10 ppm is attained when 30,000 gallons have been pumped. Superficially, it would appear as if 30,000/4,000 or 7.5 pore volumes are required to lower the concentration to 10 ppm. However, restoration is occurring by sweeping the smaller volume. The number of pore volumes passing through the small volume is, therefore, enhanced by the ratio 1/.25 = 4. The actual number of pore volumes required to restore 10 ppm is then 4 x 7.5 or 30 pore volumes. In an actual well field, the number of pattern pore volumes would be greater owing to the different lengths and arrival times of various flow paths. The path with lower response times would restore sooner than longer flow paths. The longer paths would, therefore, be rate controlling and result in the number of pattern pore volumes larger than 30.

4.2 Push-Pull Test #2

For this case, the cation exchange capacity determined in the laboratory was 4 meq/100 g. The limiting slope was found to be 10. Results calculated from laboratory data as shown in Figure 6 did not compare well with field data, particularly in the low concentration range. To obtain a better match, a series of type curves were prepared by varying the parameters as shown in Figure 7. The best fit was obtained with C = 4 meq/100 g and $k_d = 2$.

It is apparent from the type curves in Figure 7 that k_d can be determined fairly precisely, but, under the conditions of these particular tests, the CEC cannot be determined with any confidence. This is a consequence of the ammonia distribution underground shown in Figure 4. If the CEC is large, the injected ammonia will all be close to the injection site, and one "pore volume" will correspond to many pore volumes of the volume that is actually saturated. If the CEC is small, the injected ammonia will spread out farther, and one "pore volume" will correspond to fewer pore volumes of the volume that is saturated. This pore volume effect almost exactly cancels out the effect of CEC changes on the push-

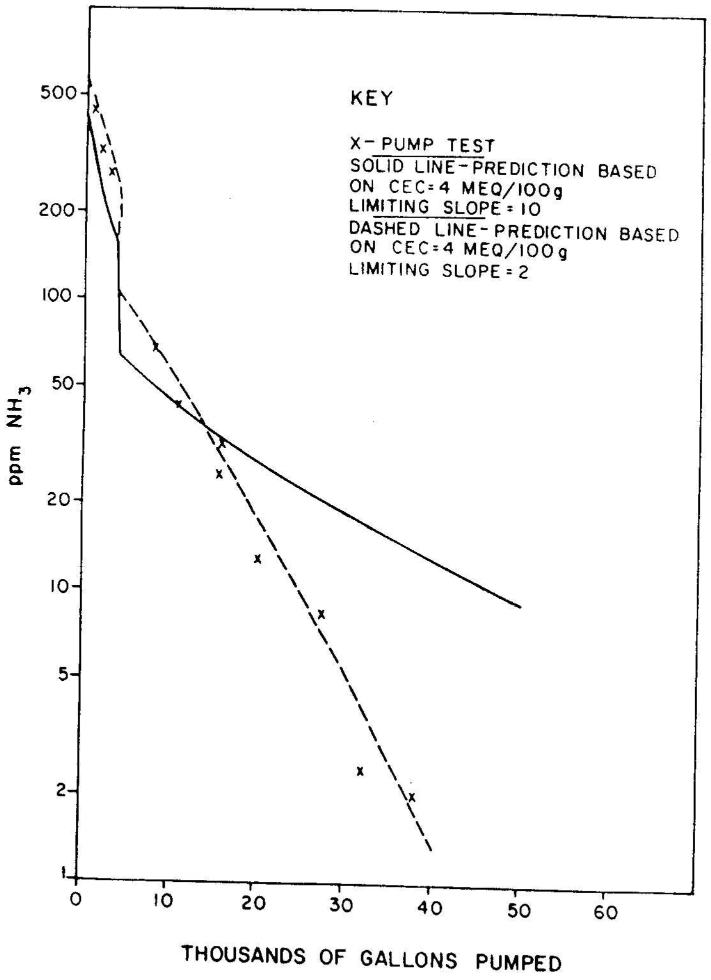

Fig. 6. Push-pull restoration: comparison of field data (crosses) with prediction based on laboratory data (CEC = 4 meq/100 g, k_d = 10; solid line) and "best fit" values (CEC = 4 meq/100 g, k_d = 2; dashed line). Concentration of ammonia injected = 650 ppm.

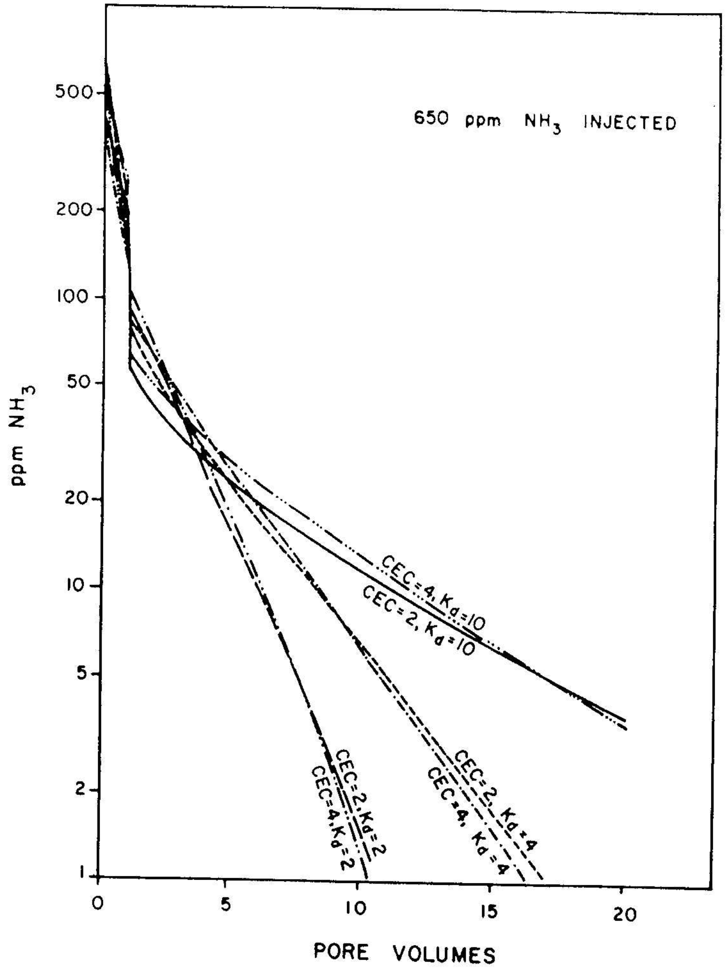

Fig. 7. Predicted recovery curves for push-pull test. Concentration of ammonia injected = 650 ppm, porosity = 0.30, grain density = 2.6 g/cm^3. The discontinuity at 1 pore volume is caused by the change in total ion concentration from the value in the spiked solution to the groundwater value. CEC values are in meq/100 g.

pull recovery curve. In order to determine CEC from the push-pull test, it is necessary to use a high enough concentration of ammonium ion in the injected solution to saturate (or almost saturate) all the sediment contacted by the injected solution. The pore volume effect discussed above no longer operates, and the recovery curve is sensitive to changes in CEC (Figure 8). For problems of trace element migration, as in in-situ coal gasification, it is often not necessary to know the CEC. The important adsorption parameter is k_d.

From these examples, several lessons are apparent. First, they stress the necessity of confirming laboratory predictions in the field. Secondly, they demonstrate that reliable values can only be obtained if the pull or pumping portion of the test is run for approximately 10 pore volumes. If pumping had continued for only two or three pore volumes, we might have concluded that this agreement in Figure 6 was close enough. Thirdly, if it is necessary to measure the in-situ CEC, a high concentration of the adsorbing species must be present in the injected solution. The appropriate concentration is best estimated on the basis of laboratory CEC determination.

5.0 SUMMARY AND CONCLUSIONS

We have addressed the problem of verifying laboratory measurements using the simplest possible field experiment, namely, the push-pull test. A number of reasons were listed as to necessity of field verification. It was concluded that coal adsorption

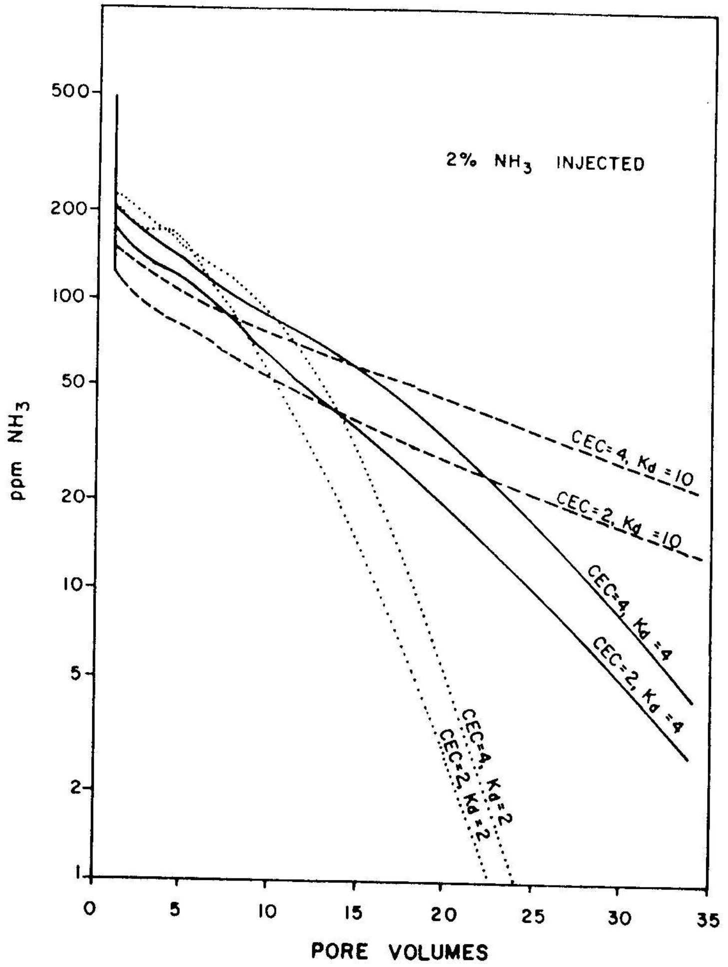

Fig. 8. Predicted recovery curves for push-pull test. Concentration of ammonia injected = 2%, grain density = 2.6 g/cm^3, porosity = 0.30. Concentrations in first pore volume are off scale. CEC values are in meq/100 g.

measurements presented the greatest uncertainty owing to a lack of knowledge concerning the actual in-situ area exposed to fluids.

The laboratory measurement techniques used by us were briefly described for both uranium and coal. Central to our approach is the determination of the adsorption isotherm. This method is superior to column testing where the study is performed with one given inlet concentration thereby obtaining only one point on the entire adsorption curve. We noted that disaggregation of the uranium aquifer sample produced a fairly definite particle size. The good agreement with laboratory and field measured adsorption properties indicated that no significantly additonal surface area was exposed in the disaggregation process. However, the distribution coefficient in the dilute region did not always agree with the field result.

In coal, a trend in the behavior of k_d with particle size was observed. An inverse dependence of adsoprtion properties upon particle size was established. However, it was not clear whether the results could be extrapolated to blocks on the scale of a meter or so. Even then, it would be quite difficult to establish the surface area contacted without adequate field testing. Furthermore, it was uncertain whether the surface behavior of broken pieces was similar to the naturally exposed surface area adjacent to high permeability paths in-situ. For these reasons, we were led to the push-pull test to verify results and to aid in scaling laboratory to field results.

Concerning the push-pull test, we listed two examples from

our work on in-situ uranium properties. No examples were available from coal properties. The two cases listed were from Wyoming. In the first case, excellent agreement was obtained between field and laboratory values. The agreement in the second case was rather poor with the distribution coefficient, k_d, displaying a large discrepancy. We noted that improper interpretation of the push-pull test would lead to a severe underestimate of the number of pore volumes required to restore the formation. This was due to the bulk of a strongly adsorbed solute remaining close to the well in a volume V_a which is significantly less than volume injected V_1. The number of pore volumes transmitted through V_a is larger by ratio

$$(V/V_1)V_a$$

where V is the volume of fluid pumped to reduce the concentration to the level of interest.

We conclude that the push-pull test is a viable technique for comparing laboratory to field adsorption values. Furthermore, the type curve method can be used in the absence of laboratory values to obtain in-situ formation values.

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REFERENCES

Busenberg, E., Clemency, C. V., Determination of the Cation Exchange Capacity of Clays and Soils using an Ammonia Electrode, Clays and Clay Minerals, v. 21, pp. 213-217 (1973).

Campbell, J. H., Pellizzari, E., Santor, S., Results of a Groundwater Quality Study Near an Underground Coal Gasification Experiment (Hoe Creek 1), Lawrence Livermore Laboratory Rept. No. UCRL-52405 (1978).

Dalton, V. A., Campbell, Laboratory Measurements of Groundwater Leaching and Transport of Pollutants Produced during Underground Coal Gasification, In-Situ, 2(4), 295-328 (1978).

Drever, J. I., Murphy, J., McKee, C. R., Adsorption of Lead, Cadmium, Mercury, Selenium and Phenol by Coal. To be published (1980).

Garrels, R. M., Christ, C. L., Solutions Minerals and Equilibria, Freeman, Cooper & Co., San Francisco, CA (1965).

Gilbert, M., Van Bladel, Thermodynamics and Thermochemistry of the Exchange Reaction between NH_4^+ and Mn^{2+} in a Montmorillonite Clay, J. Soil Sci., 21, pp. 38-49 (1970).

Hill, A. D., Walsh, M. P., Breland, W. M., Silverberg, I. H., Humenick, M. J., Schecter, R. S., Restoration of Uranium In-situ Leaching Site, Soc. Pet. Eng. Paper No. 7534 (1978).

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RELATIVE MERITS OF ALTERNATE LINKING TECHNIQUES FOR UNDERGROUND COAL GASIFICATION AND THEIR SYSTEM DESIGN IMPLICATIONS

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ABSTRACT

A technical-economic analysis is made of the comparative merits of three linking techniques for underground coal gasification: countercurrent combustion, directional drilling, and electrolinking. None of these techniques emerges as being superior to the others for all applications, but rather each has its own specific set of physical parameters (coal conditions) that make it superior to the others under certain conditions. The system design implications are discussed, and a novel approach to underground gasification of thin coal seams is presented.

INTRODUCTION

To carry out an underground coal-gasification process, it is first necessary to increase the permeability of the coal in a very specific manner.[1] Channels of permeability are established in the coal seam to permit the high-volume gas flow that is required for the gasification process. Three linking techniques have the greatest promise for the commercialization of the gasification process: countercurrent combustion, directional drilling, and electrolinking. Hydrofracking and pneumatic fracturing are eliminated from consideration here, because it is the author's assessment that

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