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Ion Exchange Performance of Commercial Crystalline Silicotitanates for Cesium Removal

R. Braun, T.J. Dangieri, D.J. Fennelly, J.D. Sherman,
W.C. Schwerin, R.R. Willis
UOP
Des Plaines, IL 60017

N.E. Brown, J.E. Miller
Sandia National Laboratories
Albuquerque, NM 87185

R.G. Anthony, C. V. Philip
Texas A&M University
College Station, TX 77843

L.A. Bray, G.N. Brown
Battelle Pacific Northwest National Laboratories
Richland, WA 99352

D.D. Lee
Oak Ridge National Laboratories
Lockheed Martin Energy Systems Inc.
Oak Ridge, TN 37831

T.T. Borek, W. J. Connors
West Valley Nuclear Services Co, Inc.
West Valley, NY 14171

Additional Technical Contributors:

A.S. Behan, R.W. Fisher, N. Greenlay, F.G. Portenstein,
T.M. Reynolds, W. Zamechek
UOP

E.A. Klavetter, J.L. Krumhansl, J.E. Reich, S.G. Thoma, D.E. Trudell
Sandia National Laboratories

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ABSTRACT

A new class of inorganic ion exchangers called crystalline silicotitanates (CST), invented by researchers at Sandia National Laboratories and Texas A&M University, has been commercialized in a joint Sandia-UOP effort. The original developmental materials exhibited high selectivity for the ion exchange of cesium, strontium, and several other radionuclides from highly alkaline solutions containing molar concentrations of Na^+. The materials also showed excellent chemical and radiation stability. Together, the high selectivity and stability of the CSTs made them excellent candidates for treatment of solutions such as the Hanford tank supernates and other DOE radwastes.

Sandia National Laboratories and UOP have teamed under a Cooperative Research and Development Agreement (CRADA) to develop CSTs in the powdered form and in an engineered form suitable for column ion exchange use. A continuous-flow, column ion exchange process is expected to be used to remove Cs and other radionuclides from the Hanford supernatant. The powder material invented by the Sandia and Texas A&M team consists of submicron-size particles. It is not designed for column ion exchange but may be used in other applications.

IONSIV® IE-910 CST powder has been manufactured by UOP in commercial quantities and tested under a wide range of conditions. Cesium distribution coefficients (Kd) of up to 1,000 mL/g are measured in DSSF-5 simulant, a Hanford waste that is 5M in Na, and 0.5M in K and has high concentrations of OH^-, NO^-_3, NO^-_2, and other ionic species. The engineered form of IONSIV® IE-911 CST has been prepared by UOP under commercial manufacturing conditions and tested for cesium Kd in batch and kinetic tests. Tests with Hanford DSSF-5 and related simulants resulted in a 50% breakthrough of Cs of about 550 column volumes (CV) at a flow rate of 3.75 CV/hr. A column test on IONSIV® IE-911 using an ORNL Melton Valley Tank W-27 simulant also resulted in a 50% breakthrough of 500 CV at a flow rate of 3 CV/hr. Column tests on INEL groundwater simulant with a flow rate of 10 CV/hr showed no Cs breakthrough to 4500 CV and excellent performance for removing Sr.

The experimental results have been integrated with an effort at Texas A&M University to model the CST's equilibrium and kinetic behavior. For the IONSIV® IE-910 exchanger, the removal of Cs and Sr from solution can be estimated to within about 10% for a variety of solutions ranging from 2M acid to 6 M hydroxide. The model also predicts the effect of high concentrations of potassium, sodium, and rubidium on the selectivity for Cs. Kinetic models have been developed that accurately estimate the breakthrough curve through the 50% breakthrough point for IONSIV® IE-911 as conditions are varied.

Data are also presented confirming the excellent stability of the commercial CSTs over a broad pH range and the high radiation stability of IONSIV® IE-910 and IE-911 exchangers. In addition, data are provided that demonstrate the high physical strength and attrition resistance of IONSIV® IE-911, critical properties for column ion exchange applications.

INTRODUCTION

A new class of inorganic ion exchangers, invented by researchers at Texas A&M University and Sandia National Laboratories, has been successfully commercialized by UOP. The materials, crystalline silicotitanates (CSTs), demonstrate high cesium distribution coefficients in acidic, alkaline, and neutral, solutions despite the presence of high concentrations of competitive ions such as Na^+ and K^+ [1,2]. The affinity for Sr^{++} in neutral and alkaline wastes is also found to be high [2]. The CST is stable in Hanford tank waste simulants for long time periods and to exposure to at least 10^9 rads [2].

UOP and Sandia teamed under a Cooperative Research and Development Agreement (CRADA) to develop commercial CST materials. UOP commercially-synthesized IONSIV® IE-910 CST powder demonstrates high capacity and selectivity for Cs^+ and Sr^{++} over a wide range of pH conditions and competitive ion concentrations. In simulated and actual waste tests, Cs^+ distribution coefficients are high over a pH range of 0 to 14 in the presence of varying concentrations of Na^+ and K^+. Distribution coefficients for Sr^{++} are also high at neutral and alkaline pH. The chemical stability of the IONSIV IE-910 exchanger is also demonstrated at pH from 0-14, and no effect on performance is noted after radiation exposure to 10^9 rads.

The UOP-Sandia CRADA was targeted toward the development of a commercial engineered form of the CST (beads, pellets, or granules) to meet the requirements anticipated for the removal of Cs, Sr, and other radionuclides from the Hanford alkaline tank waste supernates. These requirements included high selectivity and capacity for Cs^+ and Sr^{++} from highly alkaline, high-sodium waste solutions, that have good radiation and chemical stability. The column ion exchange process likely to be used at Hanford for radionuclide removal also requires an ion exchanger that can be easily loaded and unloaded from the columns and that provides rapid ion exchange kinetics with acceptably low pressure drop and good mechanical strength characteristics. A final critical requirement was that the ion exchanger needed to be compatible with final waste forms, such as borosilicate glass, that are likely to be used at Hanford. An ion exchanger meeting all the above requirements has the potential to offer significant waste-treatment cost savings. Because other DOE sites also have a need for radionuclide removal, the product developed under the CRADA was to be as broadly applicable as possible. Work is presented that shows that UOP IONSIV IE-911 ion exchanger has met these criteria in a wide range of test conditions.

Application Conditions: High pH, High Salt, Low Cs

The principal target use for the CST ion exchanger is in the remediation of liquid wastes containing radioactive Cs from DOE operations. UOP has developed this material into commercial products: the CST powder is IONSIV IE-910 ion exchanger, and the engineered form is the IONSIV IE-911 ion exchanger.

The primary waste-treatment application is at Hanford, Washington, where 177 tanks containing highly radioactive waste are currently stored. Most of the gamma radiation results from ^{137}Cs. A significant amount of radiation is also due to the presence of ^{90}Sr. The liquid portion of this waste has a wide range of compositions, but all of it can be characterized as high pH (typically pH 11.5 to 2 M OH^-) with high dissolved salt concentrations and a low molar concentration of Cs. The concentrated salt solution contains several cationic metals (mostly sodium and potassium), which compete with Cs for ion exchange sites and can affect both the selectivity and the ultimate capacity of the exchanger for cesium. The waste also contains significant concentrations of anions including NO^-_3, NO^-_2 and $Al(OH)^-_4$.

Three typical waste liquids; Double Shell Slurry Feed (DSSF), Neutralized Current Acid Waste (NCAW), and Complexant Concentrate (CC). are highly concentrated sodium salts (mostly nitrate and nitrite) with low concentrations (at the parts per million level) of Cs. The NCAW tends to have a relatively high concentration of ^{137}Cs but comparatively low potassium concentration. The DSSF has relatively high potassium concentration, while CC tends to have more residual organic material, including some original complexing agents combined with their hydrolytic and radiolytic by-products.

The overall objective of the remediation project is to reduce the volume of High Level Waste (HLW) for disposal. The approach to be used is to extract the Cs from the concentrated salt solution by selective ion exchange and, thereby, convert the treated solution to Low-Level Waste (LLW) for easier disposal. The concentrated ^{137}Cs along with the other Cs isotopes would then be vitrified and placed into long-term storage as HLW.

Product Requirements: Capacity/Selectivity, Stability; IE-911

The need to produce a minimum volume of concentrated ^{137}Cs from a dilute Cs solution, in the presence of high concentrations of competing metal cations, sets severe demands on the capacity and selectivity of the ion exchanger chosen. In addition, the ion exchanger needs to operate in the high pH environment without loss of its high capacity and selectivity and physical integrity. Finally, the exchanger needs to operate without loss of performance resulting from the effects of prolonged exposure to high levels of radiation.

These requirements are all taxing. Nevertheless, the CST invented by Sandia and Texas A&M University (TAMU) and commercialized by UOP as the IONSIV IE-910 and IE-911 ion exchangers has these characteristics and can deliver the performance needed to ensure the successful decontamination of the Hanford waste.

A standard method of exchanger evaluation involves determination of the equilibrium distribution coefficient, or Kd value. The Cs Kd is dependent on test conditions such as pH, ion concentration, and relative abundance of competing ions. The Maintenance of a high Kd value in the operating environment is critical to achieving the maximum reduction in waste volume. As will be illustrated later, the IONSIV IE-910 and IE-911 products maintain high Cs Kd values across a broad range of conditions spanning the expected range at Hanford.

The distribution coefficient, Kd, is calculated using the equation:

$$\boxed{Kd=\frac{C_s}{C_l}=\frac{(C_i-C_f)}{C_f}*\frac{V}{(M*F)}}$$

Kd: distribution coefficient
C_s: equilibrium activity in the ion exchanger solid
C_l: equilibrium activity in the liquid
C_i: initial concentration of the ion of interest in the liquid
C_f: final concentration of the ion of interest in the liquid after the period of contact
V: solution volume
M: mass of ion exchanger used, as received basis
F: F-factor = ratio of (mass of dry exchanger) to (mass of as-received exchanger)

Figure 1 shows the effect of pH on the Cs distribution coefficient [3]. The Kd value decreases noticeably as pH becomes increasingly alkaline. However, even at the highest pH, CST maintains a high coefficient. The high selectivity for Cs at low pH enables it to resist acid leaching.

Although the principal focus of the IE-910 and IE-911 development was the selective removal of radioactive Cs, (Figure 2), the CST is also effective for Sr exchange at alkaline pH [3]. This capability was also highlighted in later studies with simulated Hanford ground water, neutral ground water (INEL simulant), Oak Ridge waste, West Valley waste, and also in DSSF actual waste at PNL [4].

The abundance of Na^+ present in the Hanford solutions would be expected to compete with Cs^+ for the ion exchange sites within the CST. Increases in both $[Na^+]$ and Na:Cs ratio are expected to influence the ion exchange selectivity for Cs^+. This effect is illustrated in Figures 3 and 4 for both the IE-910 CST powder and the IE-911 (engineered form) [3]. The actual solutions at Hanford have high Na:Cs ratios and tend to have high molar concentrations of Na^+. An important feature of CST is that it maintains a high selectivity even under these extreme conditions. All of the data in this paper have been obtained with representative simulants at room temperature.

Another significant, or competing, cation present in the Hanford waste is potassium. Potassium would be expected to have an ion exchange affinity more similar to that of Cs and, therefore, a more competitive influence on Cs^+ selectivity (distribution coefficient). This effect is illustrated in Figure 5 for the IE-910 powder [3]. In this comparison, the $[Na^+]$ in the DSSF simulant is at a typical concentration representative of much of the Hanford waste, and the $[Cs^+]$ and $[K^+]$ are varied across the typical ranges expected. As expected, the presence of potassium reduces the Cs Kd values. The effect is most pronounced at low $[K^+]$, but further increases in $[K^+]$ don't appear to have much additional impact on selectivity. As noted previously with the effect of both pH and Na:Cs ratio, the IONSIV ion exchanger maintains a high selectivity in the presence of realistic concentrations of competing potassium that is representative of actual wastes.

Because of the wide range of solution compositions and the competing effects standardized tests were established for use during ion exchanger development: Batch and Column tests. These tests allowed rapid, accurate comparison of relative exchanger selectivities, capacities, and ion exchange kinetics.

Batch Ion Exchange tests were used to evaluate comparative equilibrium Cs Kd values at various times. The test consists of contacting a small amount of ion exchanger (typically about 0.1 g) with a fixed amount of waste simulant (typically about 10 mL), such as DSSF, and then vigorously shaking or swirling the mixture. Experiments are established for several time durations to evaluate the rate of approach to equilibrium. The simulant composition is prepared in the laboratory to be representative of its respective waste type. Results of this testing are expressed as Cs Kd values vs. time. Comparisons between materials can be made using their equilibrium values (data ≥ 24 hr). The Kd values obtained are expressed on an exchanger weight basis (mL solution per gram exchanger). This method can provide a crude estimation of large differences in mass transfer efficiency. However, if small differences in physical properties exist between ion exchanger samples or subtle differences in mass transfer rates occur, then the Column Ion Exchange test is more representative of performance.

Comparisons can be made between materials of widely differing physical properties. For example, if the density of an exchanger is known, then a volumetric distribution coefficient can be estimated. This "Cs-lambda" (units: mL of solution per mL) value is derived by simply multiplying the exchanger density by its respective Cs Kd value. Comparison on this basis can estimate the relative waste-volume reduction achievable by each ion exchanger being evaluated, a key factor for consideration. However, a value for the exchanger density must be representative of its density in the waste solution. Many organic resins change density depending on their degree of hydration and solution pH. The IONSIV IE-911 does not change density with hydration or solution pH.

Performance of IE-910 and IE-911 Ion Exchangers

Several different ion exchangers (Table I) have been under evaluation for this application. Each was tested using the standard Batch Ion Exchange method.

Table I
Ion Exchangers

Product Name	Description
IONSIV IE-910	CST Powder
IONSIV IE-911(-38B)	CST engineered form; 30x60 mesh granular, preliminary development sample
IONSIV IE-911(-08)	CST engineered form; 30x60 mesh spherical, preliminary development sample
IONSIV TIE-96	Commercial inorganic ion exchanger
CS-100	Commercial Phenol-formaldehyde ion exchange resin
R-F (BSC-210)	Resorcinol-formaldehyde ion exchange resin
SuperLig® 644	Macrocyclic ion exchange resin

The results are summarized in Figure 6 [4]. The figure shows Cs-lambda values, which provide a relative volumetric capacity for the ion exchangers listed. The key features to note are the values at 24 to 72 hours, where all materials have achieved equilibrium (note that the Cs-lambda values are shown on a log scale). A comparison of equilibrium Cs-lambda values shows that both IONSIV IE-910 and IE-911 ion exchangers achieve similar high distribution coefficients compared with all of the other candidates evaluated. Comparison of IONSIV IE-911 with the parent IE-910 powder shows that it has a slightly lower value because of the presence of the inert binder acting as a diluent.

At test times much less than 24 hours, an obvious difference shows in the apparent Cs-lambda value for the IE-910 powder and the IE-911 30x60 mesh material. This apparent difference in performance is almost entirely due to differences in mass transfer efficiency caused by the particle size. The IE-910 powder particles are approximately 0.2 microns in size. The size for the 30x60 mesh IE-911 material is a nominal 250 to 600 microns.

Evaluation of ion exchangers is usually reported on a weight basis (as is the data in this paper). The UOP IE-910 and 911 ion exchangers outperform all of the other candidates. The SuperLig® 644 is the next best performer. However, in the type of column ion exchange system envisioned for Hanford, the low density of the SuperLig is a detriment. This candidate would require additional column volume (therefore, capital cost) because of the low density.

Comparisons of how regenerable organic and nonregenerable inorganic ion exchangers are integrated into radwaste processing are a complex issue. The regeneration of organic ion exchangers will generate large volumes of acidic waste that must be concentrated and processed for vitrification. This waste may require interim storage. Disposal of the resins is another consideration. The present flow sheet calls for the spent organic ion exchanger to be decontaminated and sent to the low level glass plant. There it must be integrated into the redox chemistry of the wastes being fed to the LLW glass melter.

In contrast, the IONSIV IE-910 and 911 CST materials are not designed for regeneration and will permit the design and operation of a much-simpler facility. Studies to-date show that the IE-911 composition is compatible with high-level waste vitrification. This inorganic exchanger also seems compatible with extended lag storage options.

In addition to Batch Ion Exchange evaluations, the second type of test uses a small-scale simulation of the column ion exchange process. This Column Ion Exchange test also uses simulated waste liquids as a feed (actual waste has been used but is less typical). Multiple columns are sometimes used in series to simulate the large-scale process.

Figures 7 and 8 illustrate the performance of a sample of IE-911 exchanger [3,5]. The feed compositions in each of the illustrations are representative of the different waste streams. The figures show the relative effluent Cs^+ concentration for a nominal 10 ppm Cs in the simulant feed plotted against the cumulative amount of feed processed expressed in relative Column Volumes (CV). Exchanger capacity is estimated by observing the point at which the relative effluent concentration reaches 50% of the feed concentration. Assuming that the breakthrough curve is approximately symmetrical, the 50% breakthrough point gives an estimate of the amount of feed solution that can be treated at equilibrium saturation of the exchanger.

In both illustrations, with DSSF or Melton Valley simulants, the example shows that a preliminary development sample of IE-911 exchanger has the capacity to treat more than 500 CV of waste (at 10 ppm Cs) before becoming saturated. Testing at Oak Ridge with actual Melton Valley waste confirmed good, though somewhat lower, performance with 350 CV treated to 50% breakthrough in W-27. Retesting at Sandia National Labs has confirmed that the difference between Melton Valley simulant and actual waste data resulted from a higher sodium concentration and higher pH in the W-27 waste. This performance has been further improved to 660 CV capacity in DSSF with an improved material (Figure 9). This high capacity coupled with high selectivity demonstrates a level of performance sufficient to allow use without regeneration or further concentration. Eliminating the need for regeneration or elution offers significant cost savings in the construction of the large-scale unit.

Figure 7 also includes predictions of column ion exchange performance from the model developed at Texas A&M University [5]. The experimental results closely match the prediction and demonstrate the utility of the model of Zheng , Anthony, et. al..

Samples of IE-911 exchanger have also been evaluated with lower pH West Valley waste and with contaminated ground water. Although still alkaline, both of these applications are at significantly lower pH, than the Hanford type wastes. The lower pH would be expected to further improve the performance of IE-910and IE-911 beyond that already discussed because of the large increase in Cs Kd values that accompany decreases in pH. A test at West Valley with actual waste (pH 11.5) demonstrated more than 400 CV capacity without breakthrough to give a Cs decontamination factor of 10^5-10^6 [3]. Tests with Neutral Ground Water simulant (pH 8 to 9) also demonstrated decontamination factors of more than 500 even though the Cs^+ feed concentration was only 50 ppb.

In addition to the high Cs decontamination factors, significant Sr removal occurred in both the West Valley actual waste and Neutral Ground Water studies. The Neutral Ground Water study saw a slight breakthrough of Sr with a decontamination factor more than 1800. Testing with the actual West Valley waste gave a decontamination factor of 10^4. A modest removal of uranium and plutonium cations, represented by a decontamination factor of about 100, also occurred.

Kinetics and particle size

In addition to selectivity and capacity, a number of other considerations need to be taken into account when designing an ion exchange column. As noted previously, smaller particles give improved mass transfer rates. Therefore, using the smallest practical particle size is to the designer's advantage. However, as average particle size decreases, flow resistance (pressure drop) through a packed bed of particles increases sharply.

The commercial development effort behind the IE-911 exchanger focused on achieving the optimal mass transfer efficiency from the optimal particle size. The 30x60 mesh particle size for the standard IE-911 exchanger represents a balance of ion exchange kinetics and design engineering requirements. Although the 30x60 mesh product represents an engineering optimum, other size ranges, both larger and smaller (for example, 20x50 or 60x100), could be made available on request.

Early in the development of the CST engineered form, researchers recognized that an understanding of the ion exchange kinetics would be useful to optimize the design of the ion exchange plant. An effort was undertaken, under the direction of R.G. Anthony (coinventor of CST) at the Kinetics, Catalysis and Chemical Reaction Engineering Laboratory of Texas A&M University, to model Cs ion exchange. This work was done in parallel with the commercial development of IE-911 exchanger. The model developed by R.G. Anthony, and others, has clearly demonstrated its utility as a predictive tool. It can be used to predict the effects of variations in waste chemistry and column ion exchange design parameters. Readers are referred to published papers by R.G. Anthony for further details [5].

Physical Properties of IE-910 and IE-911 Ion Exchangers

UOP IONSIV IE-95 and IE-96 and TIE-96 ion exchangers are zeolite-based ion exchangers developed, and used successfully, for earlier wastewater and ground water remediation. The IE-911 exchanger was engineered to match the strength and attrition characteristics of these earlier successful products.

Both the IE-910 CST and the inert binder used to make the IE-911 exchanger are highly resistant to chemical attack. Thus, the exchanger can maintain its physical integrity under virtually all pH conditions. Samples of IE-911 have been tested for seven days in contact with extremely high pH DSSF-5 simulant to determine whether there might be a loss of strength typical of the Hanford type wastes, might occur during exposure [3]. Strength after exposure was, by the standard UOP ion exchange attrition test, comparable to material not exposed to DSSF-5. The results were within the acceptable range for successful commercial nuclear ion exchange materials such as IONSIV IE-95 exchanger. Additional long-term tests that include the effects of time and temperature are currently underway.

The Cs loaded CST powder could not be significantly eluted using 3M nitric or 3M formic acids. Neither could Cs-CST be eluted with 8M NH_4NO_3, 2M $Ca(NO_3)_2$, 1.5M $Pb(NO_3)_2$ or 2M $Mg(NO_3)_2$ [4]. This experience correlates with the extremely high distribution coefficient observed at low pH. This property, combined with its high capacity, makes IE-910 powder and IE-911 exchanger an ideal, single-use materials. Their inorganic composition makes them compatible with direct vitrification.

The CST has also been evaluated to determine the effects of thermal exposure. Dry heating of Cs-loaded CST to several hundred degrees should not cause any loss in the retention of Cs. The CST shows no loss in performance or structural integrity during exposure to ambient temperatures in alkaline solution. However, temperatures should be maintained at less than 60° C when CST is exposed to concentrated acids or extremely alkaline solutions for extended times. Long-term exposure to concentrated nitric acid ($\geq$ 6M) results in leaching of some Ti [4].

The IE-910 and IE-911 materials have rigid inorganic structures that resist significant swelling or shrinkage with changes in temperature, pH, and ion exchange levels. This resistance to physical changes sets it apart from the organic ion exchange resins. Organic ion exchange materials shrink and swell with variations in pH, temperature, and salt concentration. These variations cause deterioration in organic IX beads, that leads to flow maldistribution, bed plugging, and other problems. The bulk density of IE-911 exchanger is approximately 1 g/cc (62.4 lb/ft^3). Typical water contents determined by loss on ignition (LOI) are about 12 wt-% for the IE-910 powder and about 20 w-t% for the IE-911 engineered-form exchanger.

Samples of IE-910 powder have also been exposed to high levels of radiation (10^9 Rads) in various solutions and showed no loss of structure or performance. This resistance to performance degradation was not seen for the organic ion exchange resins. [6,7]. Testing of the IE-911 engineered-form exchanger, is currently in progress.

SUMMARY

Commercial-grade CSTs in the powdered form (IONSIV® IE-910) and the engineered form (IONSIV® IE-911) have been developed and manufactured by UOP. Both materials have been tested under a wide range of conditions in simulants and actual waste solutions. The IE-910 and IE-911 materials exhibit the high radionuclide selectivity and capacity and the chemical and radiation stability of the CST developed by Sandia and Texas A&M. A comparison of equilibrium cesium lambda values shows that both IONSIV® IE-910 and IE-911 materials achieve high distribution coefficients compared with all of the other candidates evaluated. In addition, the IONSIV® IE-911 ion exchanger exhibits physical strength and attrition resistance equivalent to the best inorganic ion exchangers manufactured by UOP..

The commercial CST products are not intended for regeneration. Thus, the design of a cost-effective, safe, and reliable cesium ion exchange process does not require the capital or operating expenses of a regeneration system. The commercial CST products are also compatible with the batch ion exchange processes or with backfill barrier applications not involving a column ion exchange process. The cesium radionuclide-exchanged CST appears to meet the requirements for long-term storage and for incorporation into final waste form, such as glass and concrete. IONSIV® IE-910 and IE-911 ion exchangers provide high capacity, high selectivity, high decontamination factors, physical strength, and resistance to chemical and radiolytic attack. These properties make the IONSIV® IE-910 and IE-911 products ideal for treating a wide range of wastes across the U.S. DOE complex and in commercial applications.

CONTACT FOR INFORMATION AND SAMPLES

Dennis J. Fennelly
UOP
307 Fellowship Road, Suite 207
Mt. Laurel, New Jersey 08054
Telephone: 609-727-9400
FAX: 609-727-9545

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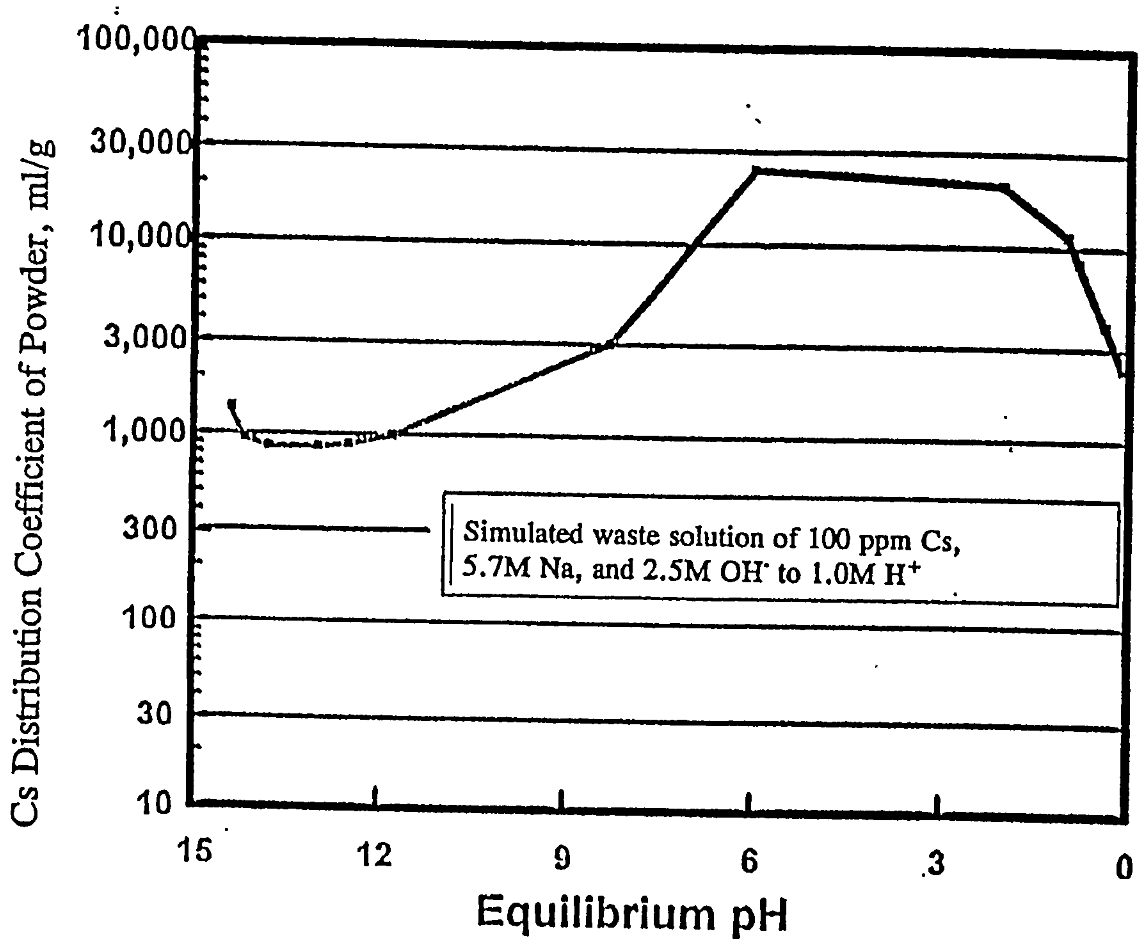
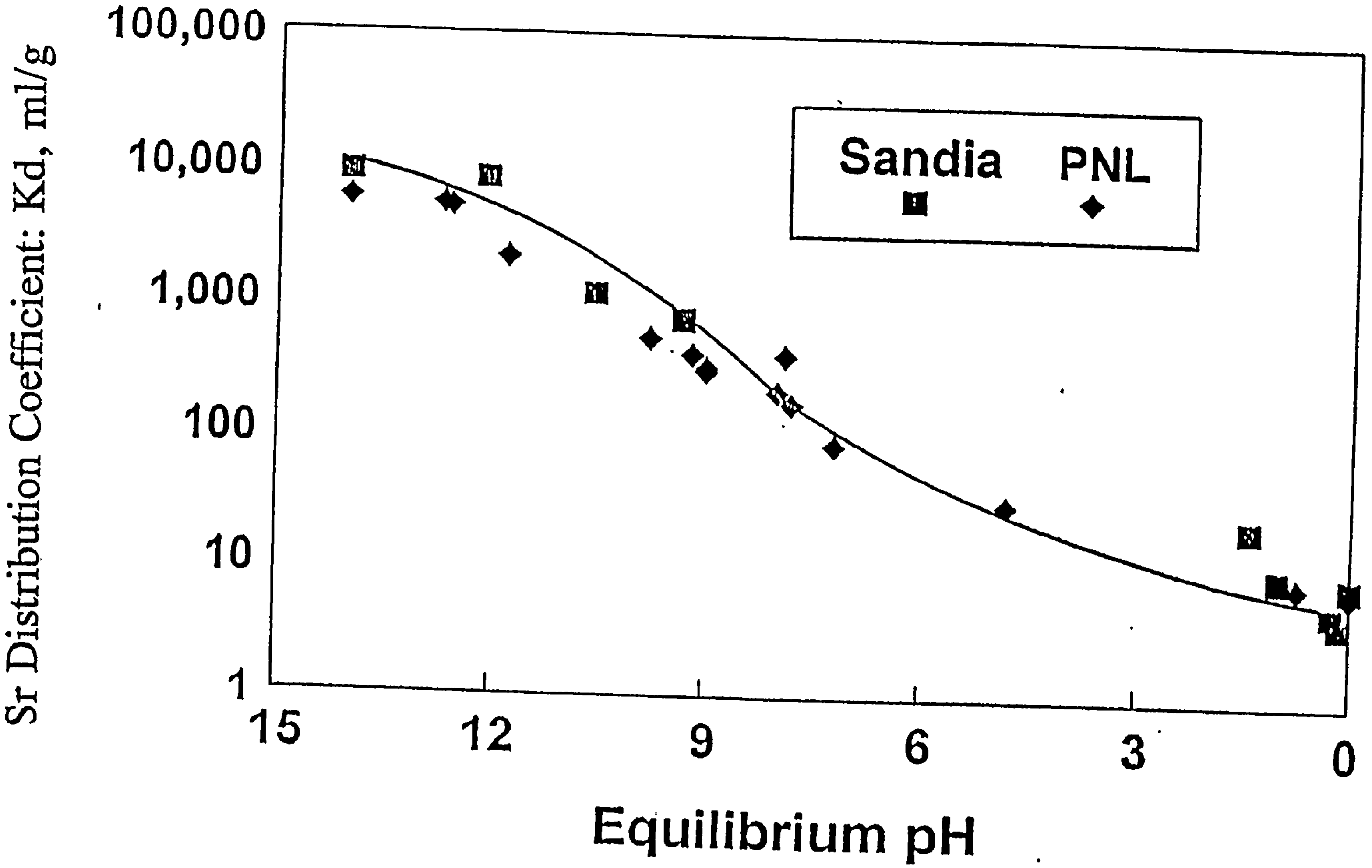


Crystalline Silicotitanates Exhibit
High Cs Distribution Coefficients

Figure 1

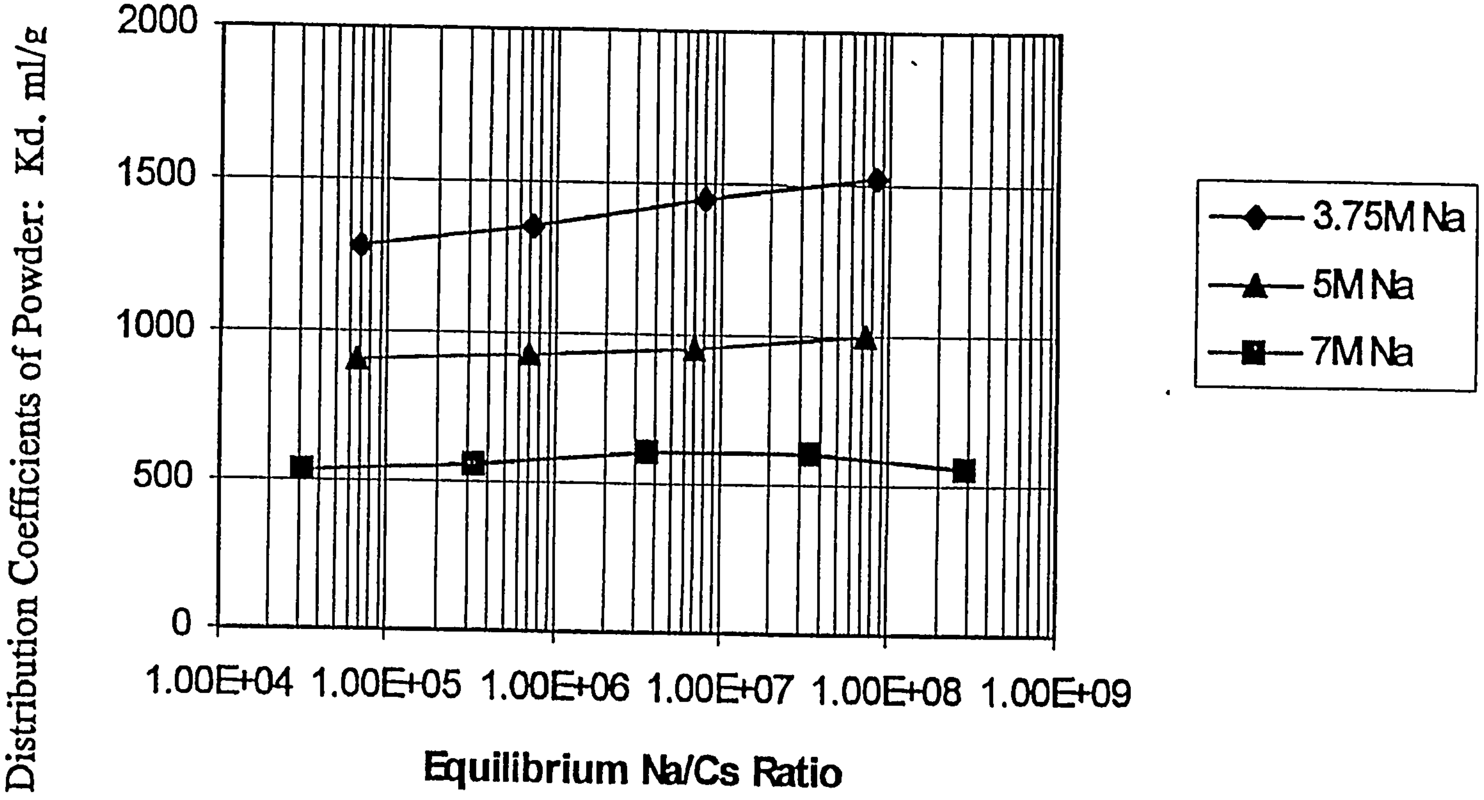
Sandia National Labs (Ref. 3)



Sr Distribution Coefficient for CST Powder

Figure 2

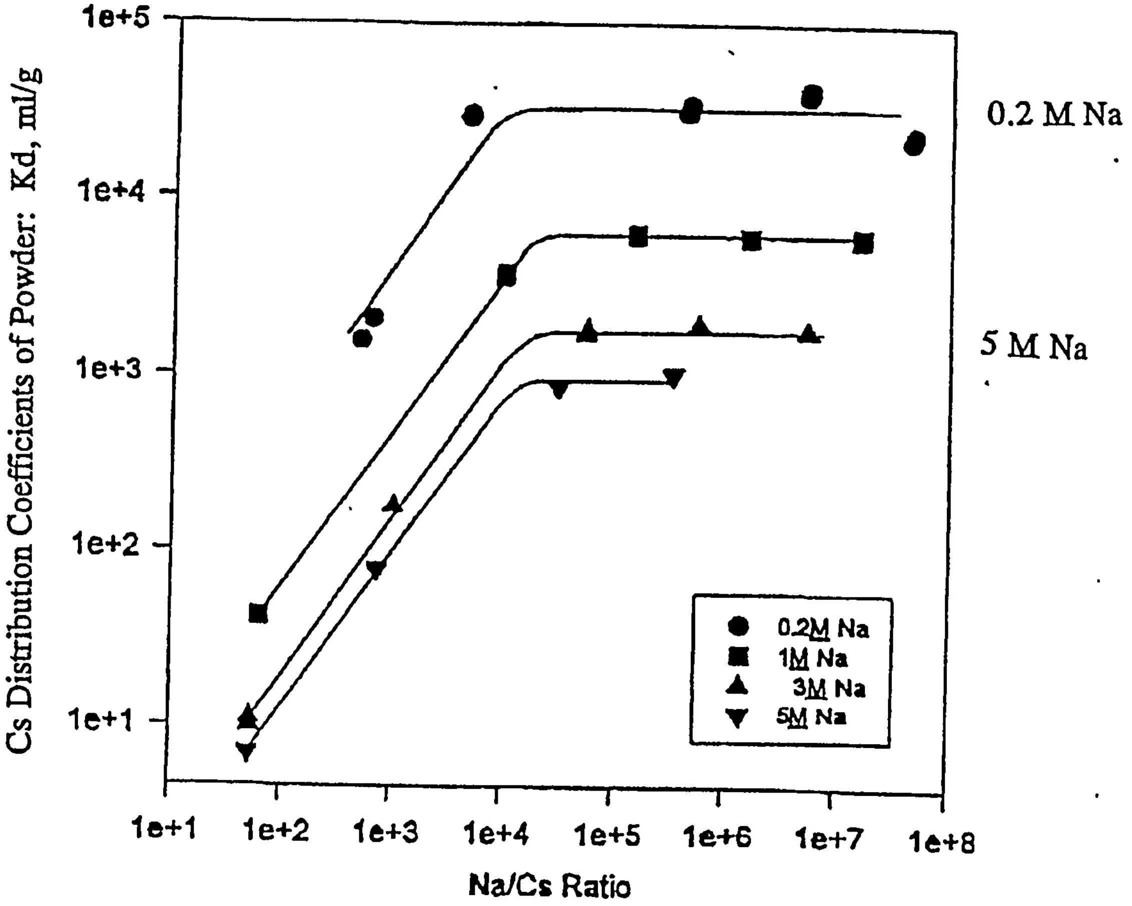
Sandia National Labs & Batelle PNL (Ref. 3)



High Cesium Distribution Coefficients
Over Range of Sodium Concentrations
In DSSF-5 Simulants

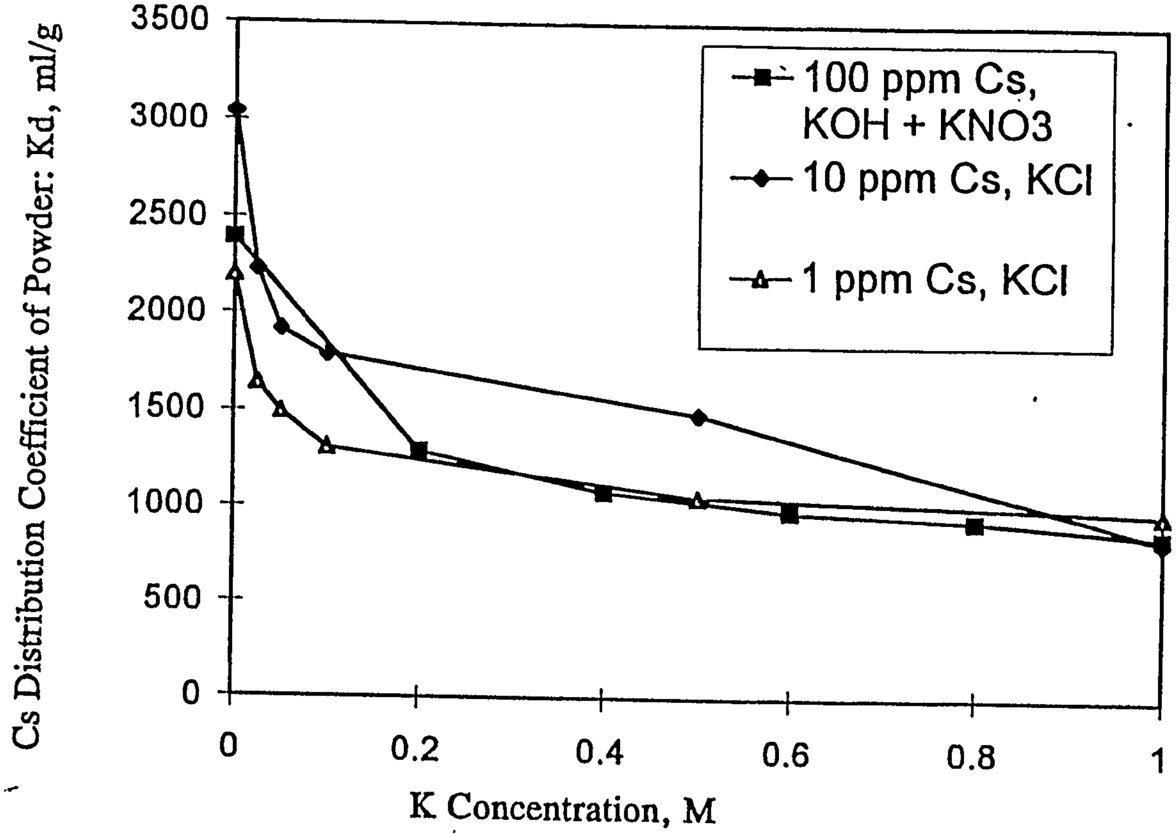
Figure 3

Sandia National Labs (Ref. 3)



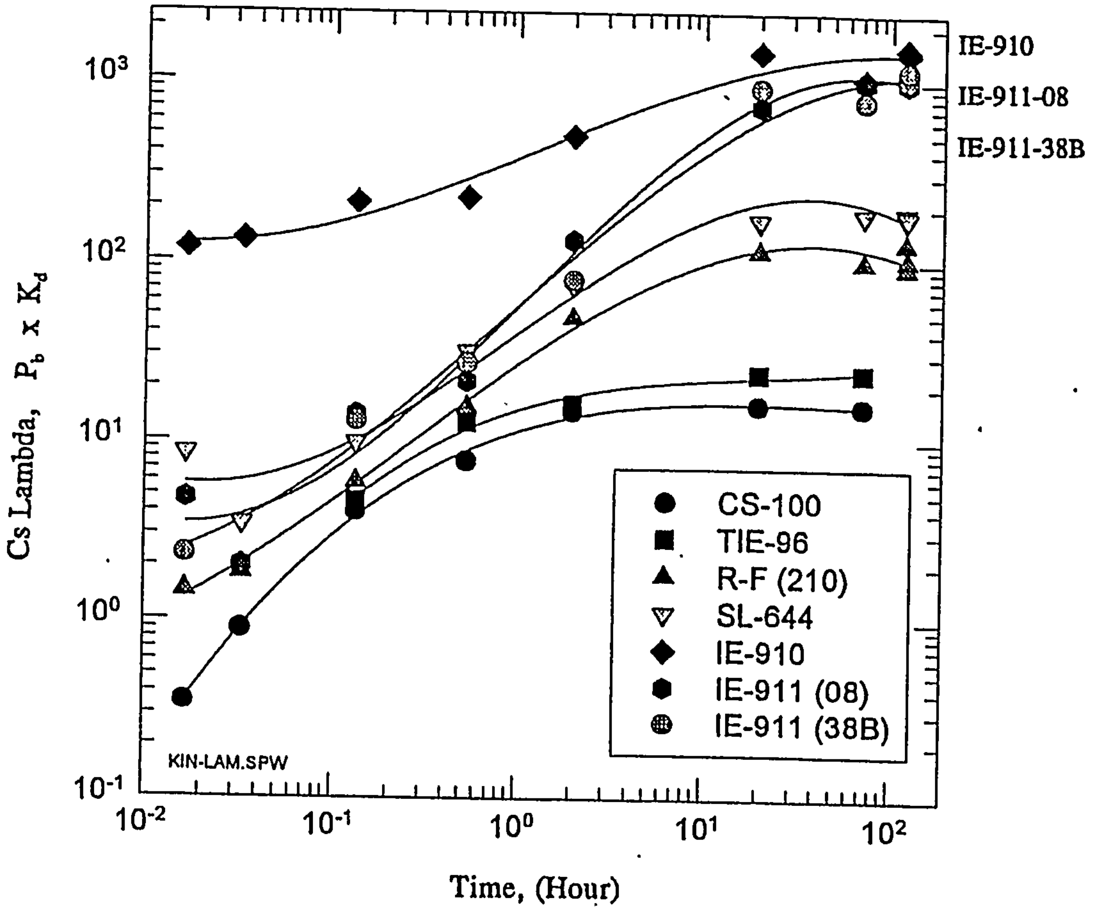
IE-911 Cs Distribution Coefficients
in 101-AW Simulant

Figure 4 Sandia National Labs (Ref.3)



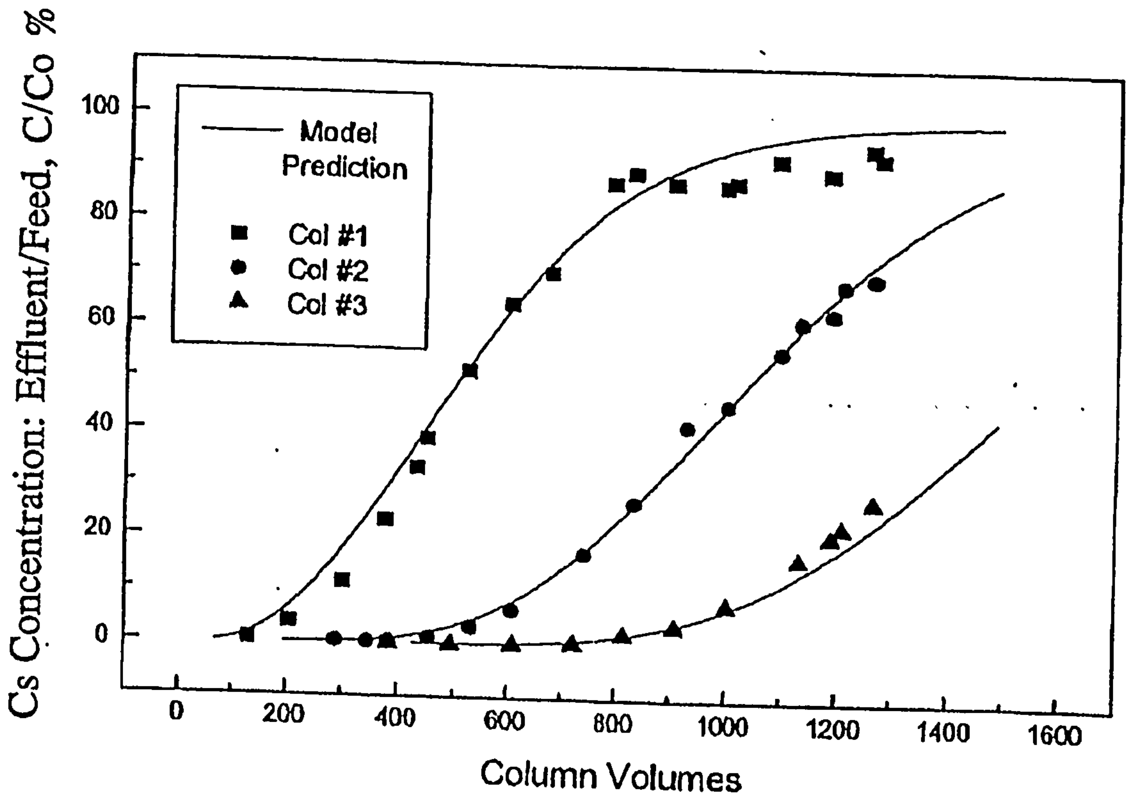
Cesium Distribution Coefficient
in DSSF-5 Simulant
with Varying Potasium Concentration

Figure 5 Sandia National Labs (Ref. 3)



Batch Cs Kinetic Data in 70% 101-AW
Simulant For UOP IONSIV® IE 911
and Competing Exchangers

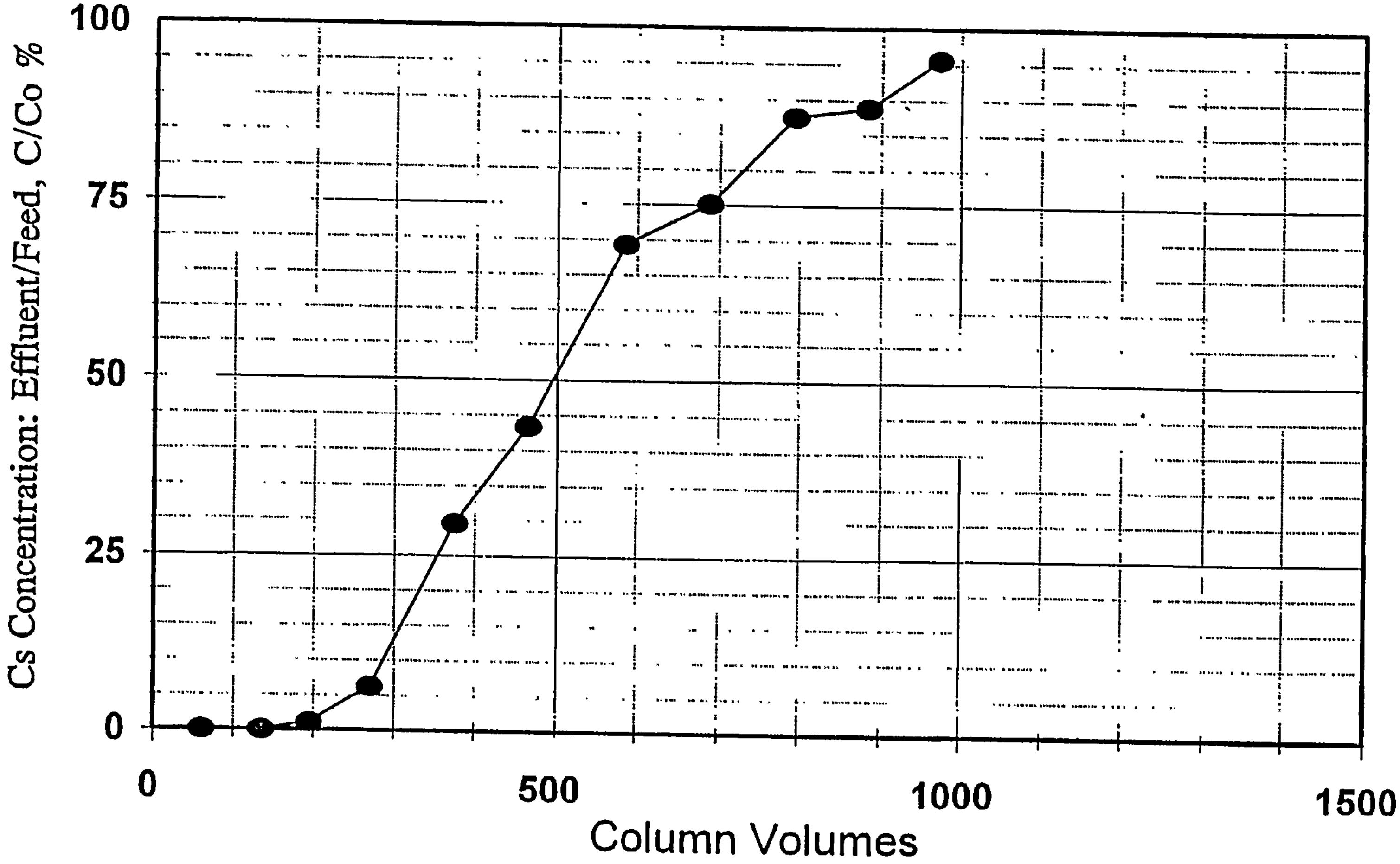
Figure 6 Battelle PNL (Ref. 4)



Series Cs Ion Exchange Column Testing Experimental & Predicted
IONSIV® IE-911 Sample 7398-38B in DSSF-5 Simulant

Figure 7

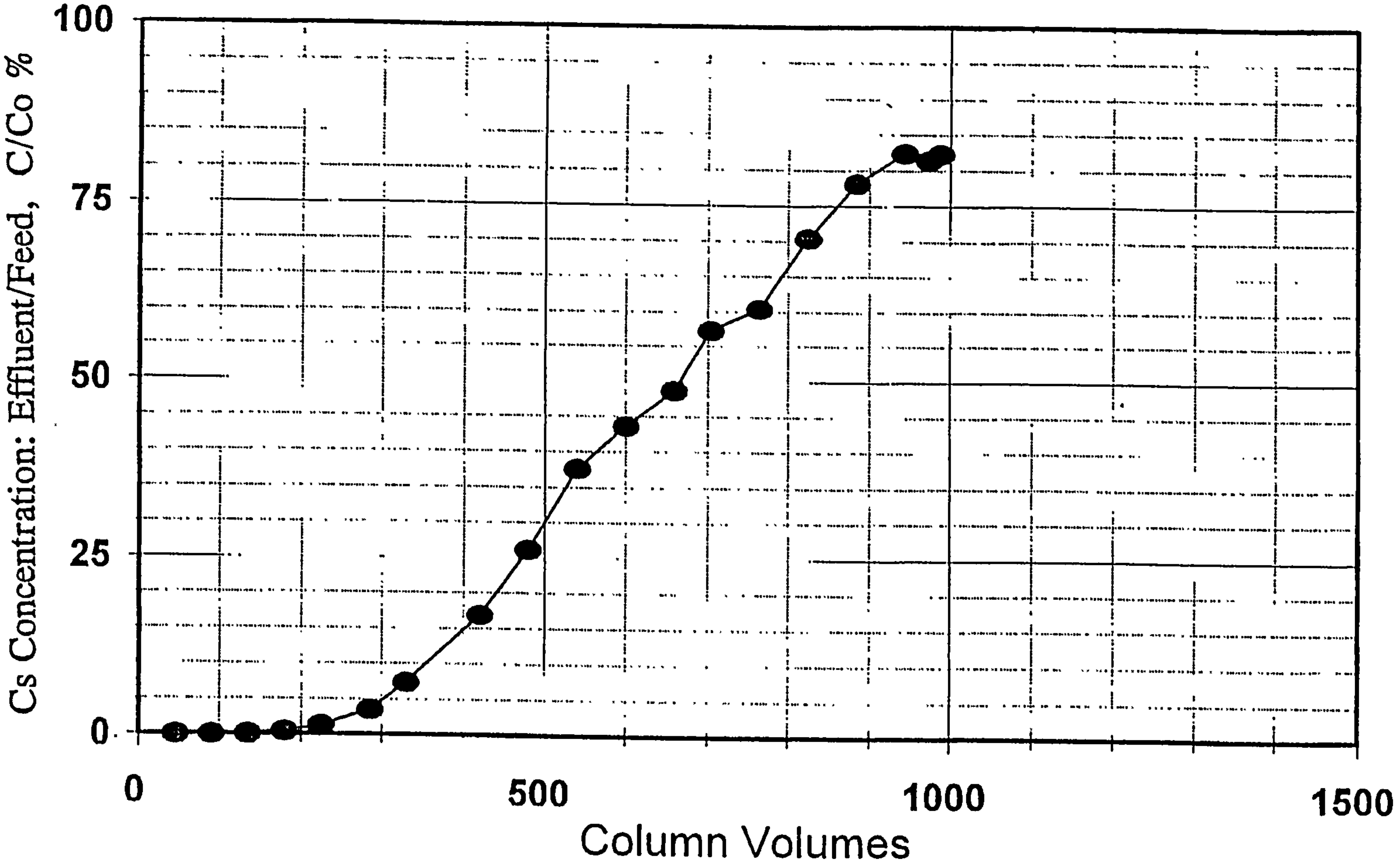
UOP, Sandia & Texas A&M (Ref. 3,5)



Cs Ion Exchange Column Testing in Melton Valley Waste Simulant
IONSIV® IE-911 Sample 7398-38B

Figure 8

UOP & Sandia National Labs (Ref. 3)



Cs Ion Exchange Column Testing
IONSIV® IE-911 Sample 7398-94A in DSSF-5 Simulant

Figure 9

UOP & Sandia National Labs