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NOVEL APPROACHES FOR THE RECLAMATION AND REUSE OF POWER PLANT EFFLUENTS

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Preface

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program, managed by the Energy Commission, annually awards up to \$62 million to conduct the most promising public interest energy research by partnering with Research, Development, and Demonstration (RD&D) organizations, including individuals, businesses, utilities, and public or private research institutions.

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What follows is the final report for the Novel Approaches for the Reclaim and Reuse of Boiler Blowdown Streams project, contract Number #500-02-004, MRA #015-008, conducted by the Chemical Engineering Department of the University of Southern California. The report is entitled *Novel Approaches for the Reclamation and Reuse of Power Plant Effluents*. The project contributes to the Energy-Related Environmental Research program.

For more information on the PIER Program, please visit the Energy Commission's Web site at <http://www.energy.ca.gov/pier> or contact the Energy Commission at 916-654-4628.

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Abstract

This project tested the utilization of anionic clay sorbents—specifically, layered double hydroxides (LDH)—for reclaiming and reusing arsenic- and selenium-impacted power plant wastewater streams. Based upon our characterization of boiler blowdown and cooling water effluents from local power plants, we generated model effluent streams containing As and Se in the concentration range of 20 to 200 ppb. Batch and flow experiments showed LDH adsorbents to be very effective in removing As and Se from such effluents. Calcined LDH showed higher adsorption capacity and efficiency than uncalcined LDH for both As and Se; equilibrium for the 20-ppb solutions was obtained within the first two hours of adsorption. Adsorption increased with increasing temperature, indicating an overall endothermic process. The starting solution pH did not significantly influence the adsorption of As and Se on calcined LDH, as long as it was higher than 4. Several solutions were shown capable of regenerating the spent adsorbents. Desorption of As and Se from the spent LDH depended on the type of ion species and their concentration in the desorbing solutions. The calcined LDH materials developed under this project show promise for treating utility effluents so they can be reused in the power plant, thus enabling significant water savings.

Keywords: Layered double hydroxides, Hydrotalcites, Arsenic, Selenium, Adsorption, Anionic clays, Sorbents

Executive Summary

Introduction

U.S. electric utilities are heavy users of water. As demand for electricity increases with the growing population and the economy, so will power plants' need for cooling water. As a result, the electric power industry in California is likely to find itself in direct competition for new sources of water with other growing sectors of the economy.

Reclaiming and reusing the water from power plants can reduce the pressure to find new sources of cooling water. Moreover, reclamation and reuse of utility cooling water – if done properly – could help alleviate concerns about the environmental fate of metals such as arsenic (As) and selenium (Se) that are found in many power plant effluents.

Power plants discharge high volumes of “too clean to clean” effluents – i.e., wastewaters with very dilute concentrations of metals or other contaminants that are currently unregulated and therefore do not require removal prior to discharge. However, such effluents would need to be “cleaned” before they could be reused in the power plant. This would require highly efficient treatment techniques, particularly for the removal of trace-level metals. Such techniques would not only enable effluent reuse, but could help control the environmental fate of trace contaminants.

This project focused on the use of novel anionic microporous clay sorbents as treatment agents for reclaiming and reusing power plant effluents. The specific sorbents tested were layered double hydroxides (LDH) previously synthesized by our group.

Project Objectives

The project addressed the following objectives:

- To sample and analyze boiler blowdown¹ and other wastewaters from selected local power plants
- To study the removal of As and Se from model effluents on anionic clay materials, namely calcined and uncalcined layered double hydroxides
- To develop second-generation products via product characterization and optimization, if the existing adsorbents did not exhibit good performance (i.e., equally good or higher adsorption capacities and faster uptake rates than what is already reported in the technical literature)
- To investigate the safe disposal of spent adsorbents

¹ Periodically, water must be removed from a boiler to control buildup of precipitates and scale and to reduce the concentration of other contaminants. The process for removing the water is referred to as boiler blowdown, and the waters themselves are the boiler blowdown effluents, or simply “boiler blowdown.”

Results

- As and Se were found present in power plant discharges, usually in small concentrations up to 50 ppb.
- Model effluent streams were prepared containing As and Se. LDH clays were tested for their ability to remove the metals from these solutions both in batch and flow experiments. The LDH adsorbents were shown to be very effective in removing As and Se from such solutions (i.e., exhibiting equally good or higher adsorption capacities and faster uptake rates than what is already reported in the technical literature).

For example, in our study, the one-day adsorption capacity of As on uncalcined and calcined LDH was found to be 1344 and 7692 $\mu\text{g As (V)}/\text{g}$, respectively, for an initial As concentration of 20–200 ppb. For the adsorption of trace ppb levels of arsenic from aqueous solutions, adsorption capacities reported in the literature for ferrihydrite are around 300 $\mu\text{g As (V)}/\text{g}$ (Thirunavukkarasu et al. 2001), while adsorption capacities on iron oxide-coated sand (IOCS) at pH 7.6 are around 45 $\mu\text{g As}/\text{g}$ (Thirunavukkarasu et al. 2003).

- Because the existing adsorbents proved highly effective in the removal of metals from model effluent streams, no further effort was made to develop additional adsorbents.
- A variety of treatments were shown capable of regenerating the LDH adsorbents, i.e., removing the As and Se from the surface of the LDH so the adsorbents could be reused. Solutions containing HPO_4^{2-} were particularly effective in desorbing (removing) both As (V) and Se (IV). Toxicity Characteristic Leaching Procedure (TCLP) tests on these LDH materials showed those adsorbents to be safe for disposal (As at 0.32 ppm and Se at 0.18 ppm).

Conclusions and Recommendations

The adsorbent materials prepared and tested in this project show good promise for the removal of trace levels of As and Se from model power plant effluents. Our recommendation is that they be tested with real effluents in a field study to establish their long-term viability in real-life applications.

The LDH adsorbents are inexpensive, and thus regeneration is not as critical as with other adsorbent materials. Nonetheless, regeneration is often desirable, and a key aspect of any future study should be to find efficient ways to regenerate the LDH without generating large quantities of spent desorption solutions, as these must eventually be disposed of. This will be less of a challenge for the large-capacity LDH materials used on dilute waste streams such as boiler blowdown, compared to other industrial processes (such as conventional chemical precipitation) treating heavily polluted streams or using adsorbents with inferior adsorption capacities. Environmentally sound and cost-effective disposal methods for spent solutions will contribute to the viability of sorbent technology, thereby promoting reclamation and reuse of utility wastewaters.

Benefits to California

Anionic clay sorbents such as layered double hydroxides offer key economic and environmental benefits:

- They would conserve fresh water by enabling treatment and reuse of utility wastewaters.
- They would reduce the concentration of trace metals, such as As and Se, discharged in high-volume power plant effluents. Instead, the metals would be concentrated in lower-volume wastes (spent sorbent and desorption solutions), which would be easier to treat and control. Consequently, LDH sorbents would enable utilities to meet stricter discharge regulations, should trace metal limits become more stringent.

1.0 Introduction

1.1 Background and Overview

The electric power industry consumes an enormous amount of water for steam generation and cooling. Indeed, electric utilities are among the largest water users in the United States, on par with farm irrigation in terms of water needs. As demand for electricity increases with a growing population and economy, so will the need for water. As a result, the electric power industry is likely to find itself in direct competition for new sources of water with other growing sectors of the economy. In the future, utilities may have to look for alternative sources of cooling water, such as “gray” water and underground water, other than today’s conventional seawater or freshwater supplies.

In addition to uncertainty over future water supply, there is concern over utility wastewaters – specifically, the environmental fate of metals such as the mercury (Hg), arsenic (As), and selenium (Se) found in many utility effluents, which negatively impact their disposal. As a result, power plant discharges are likely to come under increased scrutiny as future water regulations become more stringent.

The ability to reclaim and reuse spent (discharged) water would address both concerns. Reuse of utility effluents would reduce the pressure to find additional sources of conventional cooling water, while reducing the volumes of discharges.

Most utility wastewater streams (including, but not limited to, flue gas scrubber wastewater, boiler blowdown water, and other plant-wide discharges) fall under the category of high-volume, “too clean to clean” effluents – that is, their concentration of contaminants is too dilute to warrant treatment under existing regulations (Steinberger and Stein 2004). Nonetheless, these low contaminant levels would prevent effluent reuse in the power plant. To allow reuse, highly efficient treatment techniques are required, particularly for the removal of trace-level metals.

So far, very little emphasis has been placed on reusing such discharges. The focus of this project is the utilization of anionic microporous clay sorbents for reclaiming and reusing utility wastewaters – in particular, selenium- and arsenic-contaminated effluents, which have received only scant attention. Novel materials and concepts are dictated by the technical challenge of reclaiming these “too clean to clean” effluents, whose contaminant levels are expected to be in the trace (ppb) level. Membrane technology and conventional precipitation approaches are not capable of dealing economically with such waste streams. Commercially available adsorbents suffer from selectivity problems towards such metal contaminants, particularly in the presence of background contaminants, and especially when these target contaminants are at trace concentration levels.

1.2 Project Objectives

The project addressed four objectives:

- To sample and analyze boiler blowdown effluents and other wastewaters from local power stations. The goal here was to establish “typical” contaminant profiles of such discharges.
- To perform preliminary reclaim/reuse studies using a number of “surrogate” effluent streams and focusing on anionic clay materials, namely calcined and uncalcined layered

double hydroxides (LDH). The goal of this task was to establish a preliminary treatability database for the layered double hydroxides and to investigate the suitability of these adsorbents for a given stream application.

- If the existing material properties were deemed to be insufficient (i.e., inferior to conventional adsorbents as reported in the literature), to undertake further developmental R&D activities.
- To investigate the safe disposal of spent LDH adsorbents.

2.0 Project Approach

2.1 Objective 1: Characterize Power Plant Effluents

To characterize a “typical” effluent stream, we established a database of information from various sources:

- Our own measurements of effluents obtained from two local power plants: (1) boiler blowdown from AES Corporation’s Redondo Beach generating station in Redondo Beach, California, and (2) boiler blowdown and cooling water from Harbor Cogeneration Company’s Wilmington plant in Wilmington, California. On these samples, we performed a comprehensive composition analysis in order to identify soluble As and Se as well as other metals present. All metals were profiled by inductively coupled plasma mass spectrometry (ICP-MS, Perkin-Elmer ELAN-9000) following the methodology of EPA method 200.8 and the EPA method 1638. These methods do not determine the oxidation state of the metals, and thus we did not distinguish between As (III) and As (V) or Se (IV) and Se (VI).
- A report by the Southern California Coastal Water Research Project for the year 2000, which contained effluent data from 13 power stations located on the Southern California Coast (Steinberger and Stein 2004).
- Discussions with various contacts at the Los Angeles Department of Water and Power (LADWP), the Southern California Coastal Water Research Project (SCCWRP), and the Los Angeles Regional Water Quality Control Board.

All the various sources indicated the presence of As and Se in power plant discharges, usually in small concentrations up to 50 ppb. Based on these findings, we created “model” effluent streams containing from 20–200 ppb of As and Se to study the removal of metals using these anionic clay materials.

2.2 Objective 2: Test LDH Performance on Model Effluent

Using the “typical” profiles obtained for Objective 1, we generated model effluent streams representing the maximum, minimum, and average levels of As and Se contaminants and pH range. The water samples were then treated in batch and flow experiments using LDH.

All the adsorption experiments used a magnesium-aluminum-carbonate-LDH (Mg-Al-CO₃-LDH), with a Mg/Al mole ratio of 2.9. The Mg-Al-CO₃-LDH was prepared by our group.

All tests were run on both calcined (heat treated) and uncalcined (untreated) LDH. Calcination—subjecting a material to high heat to remove water, carbon dioxide, and other volatile compounds—generally yields a higher surface area for adsorption. If a given LDH is calcined and put in contact with an anion-containing water, it rapidly rehydrates and adsorbs the anions, thus reconstructing its original structure; this is known as the “memory effect.” Therefore, we investigated the performance differences between calcined and uncalcined LDH.

The LDH materials were characterized via Fourier transform infrared (FT-IR) spectroscopy using a FT-IR Mattson Genesis II spectrophotometer with the samples diluted in KBr disks. The specific surface area of the LDH materials was determined by the single-point Brunnauer, Emmett, and Teller (BET) method.

2.2.1 Batch experiments

The goals of the batch experiments were as follows:

- To establish the adsorption isotherms as a function of pH and temperature for both As and Se in the concentration range of interest. The effect of As and Se oxidation state on adsorption was studied as well.
- To study the adsorption kinetics of As and Se on both calcined and uncalcined LDH, as such kinetics are important for estimating adsorbent service life and for optimal adsorbent design.
- To determine the potential capacity reduction due to competition by background ions, such as CO_3^{2-} , SO_4^{2-} , NO_3^- , and HPO_4^{2-} .
- To study the desorption properties of the LDH adsorbents.

The adsorbents were prepared by co-precipitation, following a method proposed by Jules et al. (2002). The calcined Mg-Al-LDH was obtained by heating the original (uncalcined) LDH in a muffle furnace at 773 K (930°F) for four hours in an air atmosphere with heating and cooling rates of 2 K per minute.

Batch adsorption studies were performed at various temperatures in order to obtain the equilibrium adsorption isotherms. Aqueous solutions of As (V) and Se (IV) of a predetermined concentration ranging from 20 ppb to 200 ppb were prepared by diluting the 1000-ppm ICP-MS standard solutions. The initial pH of these solutions ranged from 4.2 to 5.4. No pH adjustment was carried out in order to avoid any possible interference of foreign anions during the adsorption process.

For these experiments, a constant mass of the LDH was added to a 13-ml snap-seal polyethylene bottle, which was then filled with a 10-ml aqueous solution of As or Se of a given concentration. The bottles containing the LDH suspension and the As- and Se-containing solutions were kept closed for the whole period of the adsorption experiment. They were placed in a reciprocal shaking water-bath (Precision Model 25) and were shaken at 150 rpm (rotations per minute) for 24 hours in order for adsorption on the LDH to reach equilibrium. The mixture in each bottle was then centrifuged immediately, and the As and Se concentrations in the supernatant solutions were determined by ICP-MS (Perkin-Elmer ELAN-9000).

For the experiments measuring the adsorption kinetics, the solutions were prepared by adding 90 mg of LDH to 750 ml of 20-ppb As or Se solutions in a 1-liter screw-top bottle. During the experiments, the mixture was shaken at 150 rpm at a predetermined temperature, and at selected time intervals 4-ml samples were extracted and centrifuged, and their As or Se concentrations were determined by ICP-MS.

To investigate the effect of competing ions, the LDH sorbents were accurately weighed and added to 10 ml of 20-ppb As or Se solutions containing additional competing ions, such as NO_3^- , CO_3^{2-} , SO_4^{2-} , and HPO_4^{2-} in various concentrations; these were prepared using NaNO_3 , Na_2CO_3 , Na_2SO_4 , and K_2HPO_4 , respectively. The samples were shaken for 24 hours and centrifuged; the concentrations of As or Se still remaining in solution were then determined.

Desorption experiments investigated the effects of using different desorption solutions containing various anions with concentrations ranging from 100 ppb to 1000 ppm. Initially, 10 ml of 20-ppb As or Se solutions were equilibrated with the calcined LDH, as described above. After centrifuging, 4 ml of the equilibrated solution were removed for the ICP-MS analysis and were replaced with 4 ml of the solution containing other anions (e.g., NO_3^- , CO_3^{2-} , SO_4^{2-} , HPO_4^{2-}); the resulting solution was then shaken for an additional two hours and centrifuged again. Four milliliters of the supernatant solution were then again replaced by 4 ml of the solution containing the other anions, and the process was repeated; the overall desorption experiment consisted of five such dilution cycles.

The ICP-MS detection limit was found to be 0.043 $\mu\text{g}/\text{l}$ for arsenic and 0.172 $\mu\text{g}/\text{l}$ for selenium using the EPA 200.8 method. Experimental errors were checked randomly for some of the experiments. The experimental errors were all within $\pm 3\%$. We repeated many of the experiments on the adsorption and desorption kinetics, isotherms, and the effect of pH. All of them showed good repeatability. Analysis of duplicate experiments found the variability to be within $\pm 8\%$.

2.2.2 Flow experiments

The goals of the flow experiment were as follows:

- To identify the optimum conditions for column operation. To determine the adsorption capacity under flow conditions, and to compare it with the capacity estimated from the adsorption isotherms determined from the batch studies.
- To help validate a mathematical model to predict the breakthrough pattern of the column at various operating conditions and design parameters, thereby facilitating the design of a full-scale adsorption system.

For the flow experiments, fixed-bed columns with an internal diameter of 0.7 cm and a height of 4 cm were used. Once the LDH was packed inside the columns, the columns were fully filled with deionized water, which was left there for 24 hours to “wet” the column. The metal ion-containing solutions were then pumped vertically downwards through the column. Samples from the solution exiting the column were taken at predetermined time intervals and were analyzed using ICP-MS.

2.3 Objective 3: Develop Better Adsorbents

Because the existing adsorbents proved highly effective in removing metals from model effluent streams, no further effort was made to develop additional adsorbents.

2.4 Objective 4: Investigate Sorbent Disposal

Sierra Analytical Labs, Inc., performed a TCLP test on our spent adsorbents to investigate sorbent disposal.

3.0 Results

3.1 Objective 1: Characterize Power Plant Effluents

The concentration of soluble As and Se as well as other metals present in the two local power-plant discharges are shown in Table 1. The pH of these samples was neutral. For our measurement, the 99% confidence interval for the As and Se with a concentration of around 20 ppb, with 10 sequential measurements, is 20.54 ± 0.15 for As and 21.12 ± 0.09 for Se, respectively. Our analysis and the report from (SCCWPR) (Steinberger and Stein 2004) indicated the presence of As and Se in power plant discharges, usually in small concentrations up to 50 ppb. Based on these findings model effluent streams containing from 20-200 ppb of As and Se were generated to study the removal of metals using these anionic clay materials.

Table 1. Constituent concentration in waste streams discharged by power generating stations (ppb)

Grouping Level	Units	Redondo Beach Blowdown*	Harbor Cogeneration Blowdown/Cooling Water*	Alamitos Blowdown/Cooling Water**
Arsenic	µg/l	0.04	22.8	<20
Cadmium	µg/l	ND***	0.091	<3
Chromium	µg/l	0.071	3.37	5.1
Copper	µg/l	0.291	26.982	2.4
Lead	µg/l	0.042	ND	<7
Nickel	µg/l	ND	8.129	<15
Selenium	µg/l	0.022	ND	<50
Silver	µg/l	ND	0.081	<2
Zinc	µg/l	ND	2.345	19

* Measured in this study

** Alamitos power plant data from Steinberger and Stein 2004

*** ND = not detected

3.2 Objective 2: Test LDH Performance on Model Effluent

The following sections summarize our key technical findings.

3.2.1 Characterization of calcined and uncalcined LDH

The FT-IR spectra of the calcined and uncalcined LDH in the room environment are shown in Figure 1. The broad absorption peak in the uncalcined LDH spectra (see Figure 1a) between 3600 and 3300 cm^{-1} is due to the vibration of structural OH^- groups from the brucite-like layers. The peaks around 1655 and 3038 cm^{-1} are due to the interlayer water molecules. The peaks around 1377, 874, and 685 cm^{-1} are due to the carbonate ions. FT-IR spectra of calcined LDH suggest that most of the interlayer water bands have disappeared, but some of the carbonate anions are still present after calcination (e.g., bands at around 1389 cm^{-1} in Figure 1b). These may also be due, however, to the carbonate species adsorbed when the LDH sample is cooling in the atmosphere during the calcination.

The specific surface areas of uncalcined and calcined LDH were determined by the single-point Brunauer, Emmett, and Teller (BET), and were found to be 47 and 198 m^2/g , respectively. That the calcined LDH has the higher surface area has also been previously reported by other investigators, and is believed to be due to the additional mesoporous region created by the formation of channels and pores resulting from the removal of water and carbon dioxide (Reichle 1986).

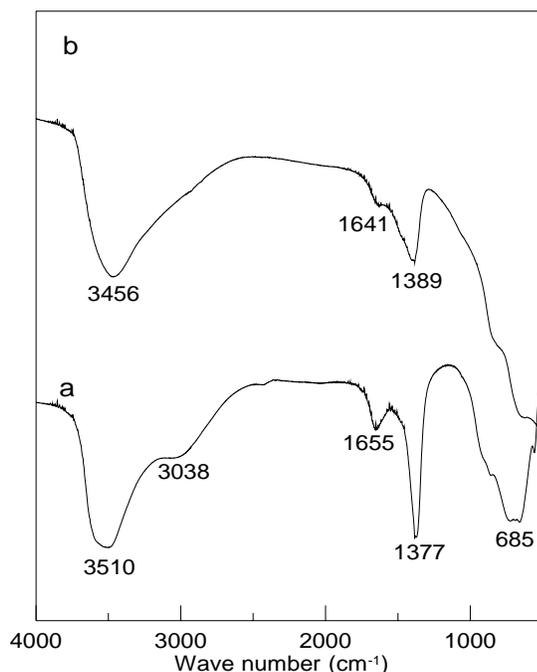


Figure 1. FT-IR spectra of (a) LDH and (b) calcined LDH

In summary, the LDH materials were well characterized by a variety of techniques, including FT-IR and surface area measurements. These structural characterizations provide better insight into the mechanism of how these materials remove metal anions from polluted wastewaters.

3.2.2 Batch experiments

Result 3.2.2.1 As (V) has a greater adsorption affinity than Se (IV) for both calcined and uncalcined LDH. The adsorption capacities of As (V) and Se (IV) are higher on the calcined LDH than on the uncalcined LDH.

Adsorption processes are usually modeled by two types of isotherms, Freundlich and Langmuir. Figure 2 shows the adsorption isotherms generated in the batch experiments together with their fit to the calculated Freundlich adsorption isotherm (in the form $\log(q_e) = \log K + 1/n \log(C_e)$, where q_e is the amount of solute adsorbed at equilibrium, and C_e is the bulk concentration of the solute). The data show a satisfactory fit to the Freundlich isotherm (better than the fit to the Langmuir isotherm equation), with an R^2 greater than 0.97 (R^2 is the coefficient of determination and expresses the amount of common variation between the two variables).

The estimated K [(mg solute/kg adsorbent) \cdot (1/ μ g solute) $^{1/n}$] and n values are shown in Table 2. In the Freundlich isotherm model, K is a measure of the adsorption capacity (larger K indicates a larger overall capacity), whereas the parameter $1/n$ is a measure of the strength of adsorption (larger n indicates higher adsorption affinity). As can be seen in Table 2, As (V) has a larger adsorption capacity than Se (IV) for both the uncalcined and calcined LDH. The isotherms also indicate that the adsorption capacity of As (V) and Se (IV) on the calcined LDH is considerably higher than on the uncalcined LDH. The higher adsorption capacity on calcined LDH is explained by the loss of H_2O and CO_3^{2-} due to calcination, resulting in a higher anion exchange capacity, and the higher surface area resulting from calcination.

In summary, the adsorption isotherm experiments indicate that calcined Mg-Al- CO_3 -LDH is a promising adsorbent for the removal of trace levels of As and Se from aqueous solutions.

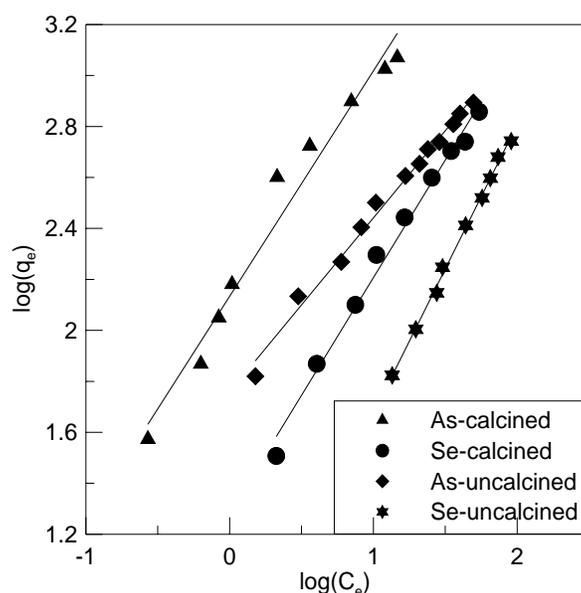


Figure 2. Adsorption isotherms for As (V) and Se (IV) on calcined and uncalcined LDH

Table 2. Freundlich adsorption constants for the adsorption of As and Se on LDHs

	K_1	$1/n$	R^2
As/calcined LDH	136.1	0.884	0.972
Se/calcined LDH	19.22	0.923	0.990
As/uncalcined LDH	57.29	0.683	0.991
Se/uncalcined LDH	3.48	1.133	0.997

Result 3.2.2.2 The adsorption of As (V) and Se (IV) on calcined and uncalcined LDH is endothermic.

The effect of temperature on the adsorption capacity of As (V) on calcined and uncalcined LDH is shown in Figure 3. As can be seen, the amount of As (V) adsorbed increases with increasing temperature both on the calcined and uncalcined LDH, which suggests that the adsorption of As (V) on these two adsorbents is apparently an endothermic process. Se (IV) adsorption on calcined and uncalcined LDH as a function of temperature shows similar trends.

In summary, the endothermic nature of adsorption enables the direct use of these adsorbents for the treatment of effluent streams at elevated temperatures, since their adsorption capacity was shown to increase with increasing temperature.

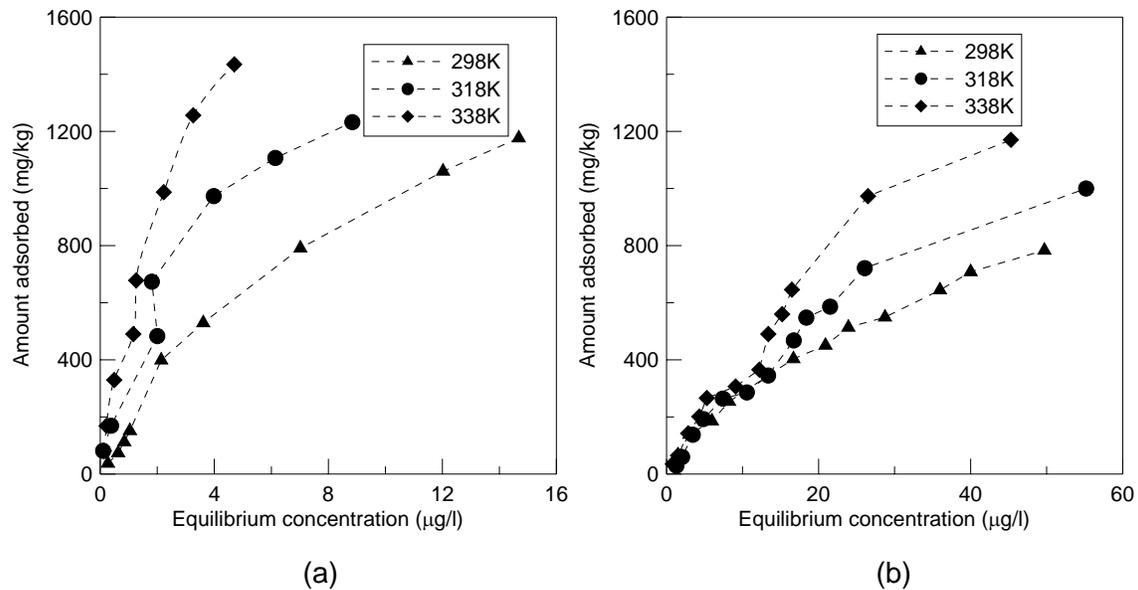


Figure 3. Adsorption of As (V) on (a) calcined and (b) uncalcined LDH as a function of temperature

Result 3.2.2.3 An m^{th} order kinetic rate equation describes the adsorption kinetics of As and Se on calcined and uncalcined LDH.

The adsorption of As (V) and Se (IV) from aqueous solutions on calcined LDH is a relatively fast process (compared to the uncalcined LDH), and equilibrium for the 20-ppb solutions is obtained within the first two hours of adsorption. Se (IV) adsorption on the uncalcined LDH is also a rather fast process and reaches equilibrium within two hours. Adsorption of As (V) on uncalcined LDH is a slow process, however, and reaches equilibrium only after a 24-hour reaction time.

Adsorption kinetics models correlate the solute uptake rate with bulk concentration of the solute to be adsorbed; these models are important in water treatment process design and optimization. To fit the experimental data, we have utilized an m^{th} order kinetic rate equation of the form shown in Equation 1:

$$dq_t / dt = k_1 (q_e - q_t)^m \quad (1)$$

where q_e is the amount of solute adsorbed (mg solute/kg adsorbent) at equilibrium with the corresponding bulk concentration of the solute, q_t the amount of solute adsorbed on the LDH at any time, m is the adsorption rate order, and k_1 is the effective adsorption rate constant. Equation 1 must be coupled with the mass balance equation below for the batch reactor system:

$$V \frac{dC}{dt} = -W \frac{dq_t}{dt} \quad (2)$$

where C is the bulk concentration for the solute ($\mu\text{g/l}$) at time t , V (ml) the volume of the reactor, and W (mg) the amount of the adsorbent present. Equations 1 and 2 must also be coupled with the Freundlich adsorption equilibrium relationship in Equation 3 (see further discussion below).

$$q_e = KC^{1/n} \quad (3)$$

A genetic algorithm which uses selection, crossover, and mutation steps to update the parameter values was utilized to calculate the values of parameters which are consistent with the experimental data.

Figure 4 shows the raw experimental data for As (V) and Se (IV) on calcined and uncalcined LDH in the form of the concentration remaining in the solution versus time, together with the calculated theoretical lines based on the estimated parameter values. The estimated values of the model parameters (k_1 and m), together with the corresponding coefficients of determination (R^2), are shown in Table 3.

In summary, as shown in Figure 4, the empirical exponential rate model provides a satisfactory fit for the adsorption of both As and Se on calcined and uncalcined LDH. Adsorption kinetics seem to be of second order, except for the adsorption of Se (IV) on calcined LDH.

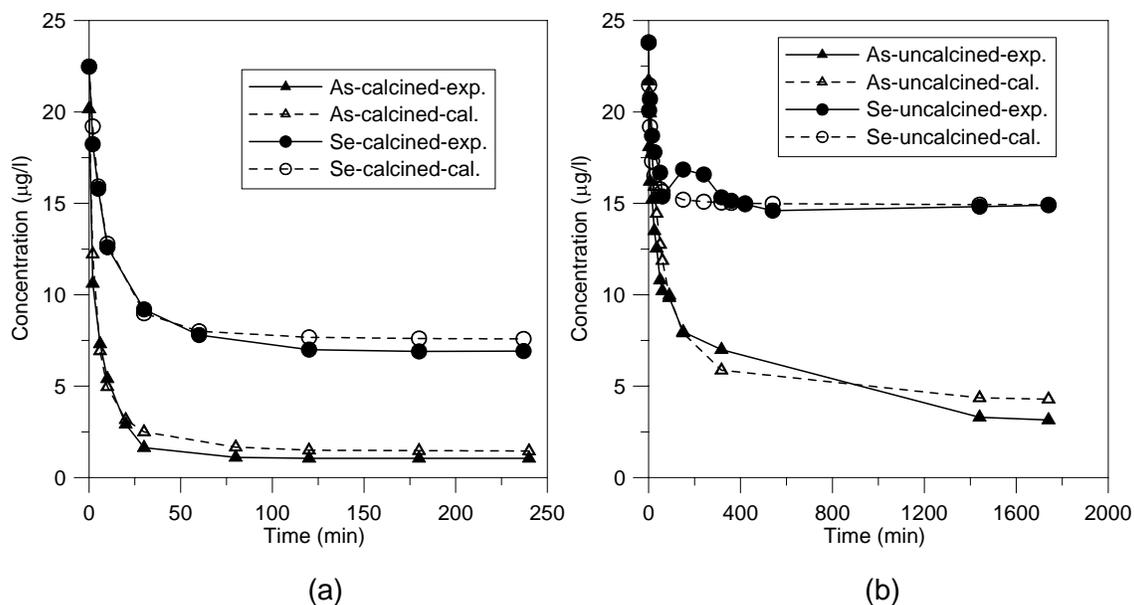


Figure 4. Comparison between the measured and modeled time profiles for adsorption of As and Se on (a) calcined and (b) uncalcined LDH

Table 3. Kinetic parameters for the adsorption experiments

	k_1	m	R^2
As/calcined LDH	1.53 E-5	2.01	0.988
Se/calcined LDH	3.12 E-3	1.49	0.986
As/uncalcined LDH	1.86 E-5	2.01	0.933
Se/uncalcined LDH	4.69 E-4	2.01	0.903

Result 3.2.2.4 The starting solution pH does not significantly influence the adsorption of As and Se on calcined LDH, as long as it is higher than 4. However, As and Se adsorption on uncalcined LDH is more sensitive to variations in the initial pH.

The amounts of As (V) and Se (IV) adsorbed on calcined LDH (Figure 5a) decrease with decreasing pH, for starting solution pH below 4; for pH above 4, the adsorption seems to be pH-independent. The decrease in adsorption with decreasing pH in the low pH range may be due to the dissolution of LDH in the low-pH solutions. This was confirmed by the presence of magnesium (Mg) and aluminum (Al) in the final solution using ICP-MS analysis.

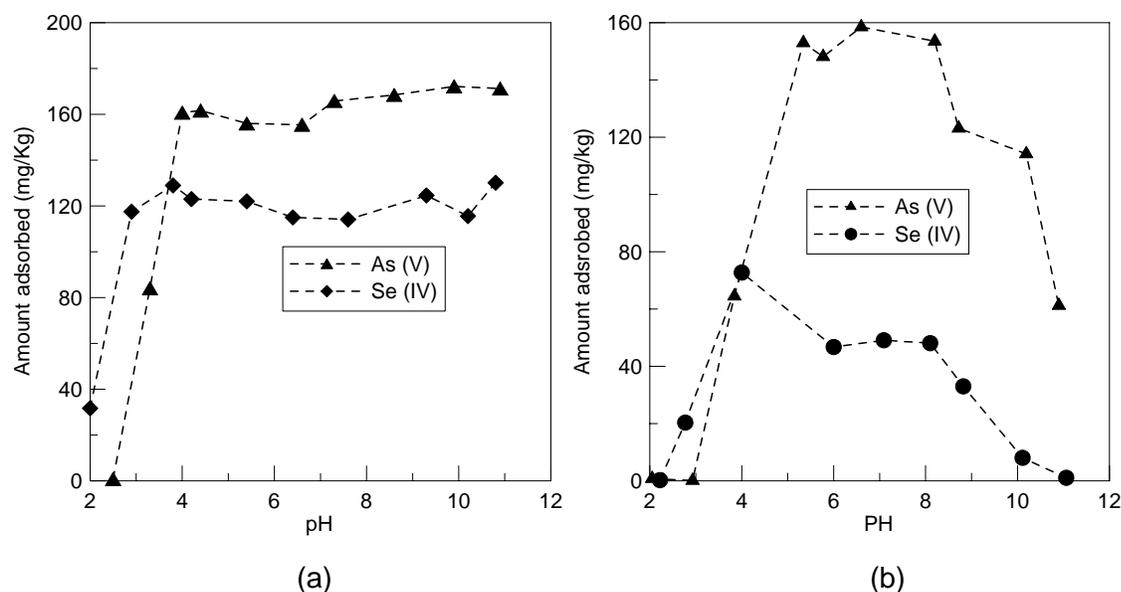


Figure 5. The effects of pH on the uptake of As (V) and Se (IV) in 20-ppb solutions on (a) calcined and (b) uncalcined LDH

The adsorption of As (V) and Se (IV) on uncalcined LDH shows a different behavior with respect to the starting solution pH than the adsorption on the calcined LDH. As Figure 5b indicates, there is a certain range of pH values for which the adsorbed amount is maximized. For As (V), adsorption is fairly high in a starting pH range from 5 to 8. Below pH 5, adsorption decreases sharply with decreasing pH (this again may be due to the dissolution of the LDH structure), and the same is true with increasing pH above 8 (see explanation below). Adsorption of Se (IV) on uncalcined LDH first increases with increasing pH, and reaches its maximum at \sim pH 4. Then, the adsorption decreases and appears to reach a plateau in the pH range of 6 to 8; the adsorption decreases again with increasing pH, above 8.

The effect of pH on adsorption on uncalcined LDH can be explained in the region of high pH by the effect of pH on the point of zero charge (pH_{pzc}), which for the uncalcined LDH was reported to be in the range of 6.8 to 8.9 (Das et al. 2003; Manju 1999). The surface of LDH is negatively charged when $pH > pH_{pzc}$. Therefore, in the higher pH range, the arsenate and selenite anionic species will be repelled by the LDH surface. The negative effect of pH may be further compounded by the increasing competitive effect of OH^- adsorption in the higher pH range. For $pH < pH_{pzc}$, the LDH surface is positively charged, which is normally beneficial for the adsorption of the negatively charged anionic species. On the other hand, as previously noted, very low pH negatively impacts the stability of the LDH structure.

In summary, from the experimental results reported here, we conclude that calcined LDH can be used effectively in a broad pH range (pH above 4).

Result 3.2.2.5 As (III) is more difficult to remove than As (V) with both the calcined and uncalcined LDH. Calcined LDH has a larger adsorption capacity for Se (IV) than Se (VI), whereas Se (VI) adsorption is significantly greater than Se (IV) on uncalcined LDH.

Less As (III) adsorbs from aqueous solutions than As (V) (Figure 6); in fact, uncalcined LDH adsorbs almost no As (III). The difference in the total amounts adsorbed of As (III) and As (V) on the LDH adsorbents may be related to the different species found in solution for these two forms of As with different oxidation state. Arsenate is present as negatively charged ionic species (either H_2AsO_4^- or HAsO_4^{2-}) in a broader range of pH conditions than arsenite, which is mostly found in the non-ionic form H_3AsO_3 (Smedley et al. 2002). The negatively charged As (V) species are expected to be more easily adsorbed by the LDH structure, either through anion exchange for the uncalcined LDH, or by rehydration and incorporation into the calcined LDH, in order to rebuild the initial LDH structure.

For selenium, calcined and uncalcined LDH show different adsorption behavior towards Se (IV) and Se (VI), as shown in Figure 7. On the calcined LDH, Se (IV) is adsorbed in larger amounts than Se (VI), whereas Se (VI) adsorption is greater than Se (IV) on uncalcined LDH. Differences in the adsorption characteristics between Se (IV) and Se (VI) were also previously reported by other investigators. Kuan et al. (1998) reported, for example, selenium adsorption in surface coal-mine soils. The adsorption of Se (VI) was shown to be stronger than that of Se (IV). Saviz et al. (1998) reported that Se (VI) exhibits higher affinity towards the surface of activated alumina, and was, therefore, more easily removed than Se (IV), except for $\text{pH} > 6$.

In summary, As (III) is more difficult to remove. Therefore, one must first oxidize As (III) to As (V) before using LDH for its adsorption. Oxidants such as chlorine, ferric chloride, and potassium permanganate are effective in oxidizing As (III) to As (V).

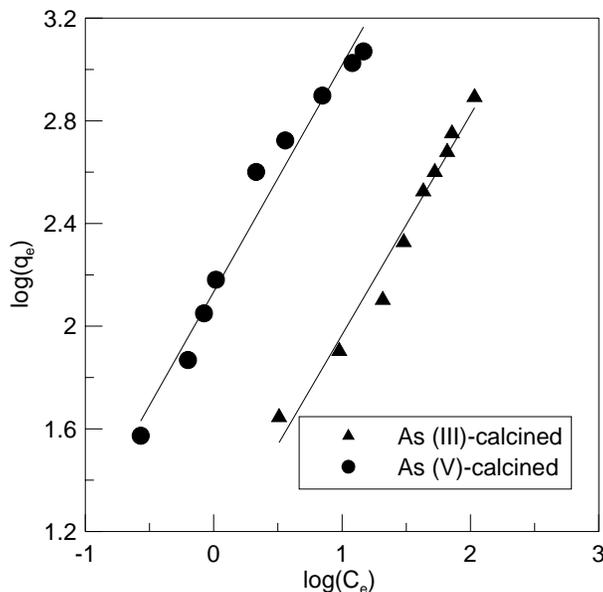


Figure 6. Adsorption isotherms of As (III) and As (V) on calcined LDH

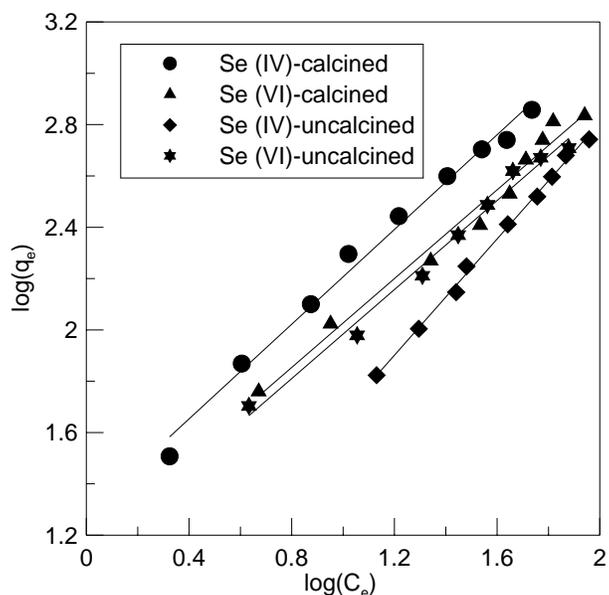


Figure 7. Adsorption isotherms of Se (IV) and Se (VI) on calcined and uncalcined LDH

Result 3.2.2.6 Competing ions have a greater effect on Se (IV) uptake than on As (V) uptake.

The background ions – such as carbonate, phosphate, sulfate, and nitrate – present in the wastewater samples might interfere with the operation of LDH adsorbents. Therefore, the effect of these ions on As and Se adsorption was studied.

As shown in Figure 8a, NO_3^- ions have almost no effect on the adsorption of As (V) on the calcined LDH up to a concentration of 1000 ppm (50,000 times higher than the initial concentration of As (V) of 20 ppb). SO_4^{2-} and CO_3^{2-} have a modest effect, causing only 14% and 20% reductions when their concentration is 500 ppm, and 33% and 45% reductions, respectively, when the concentration is 1000 ppm. HPO_4^{2-} appears to be the anion that most adversely impacts adsorption of As (V). When its concentration is 20 ppm, adsorption of As is 34% less than when HPO_4^{2-} is absent from the solution. As (V) adsorption completely stops when the HPO_4^{2-} concentration is higher than 500 ppm. To summarize, the effect of competing anions on adsorption of As (V) decreases in the order $\text{HPO}_4^{2-} > \text{CO}_3^{2-} \sim \text{SO}_4^{2-} > \text{NO}_3^-$.

As shown in Figure 8b, competitive anions have a stronger effect on Se (IV) uptake than on As (V). CO_3^{2-} and HPO_4^{2-} have significant effect on Se uptake, even when their concentrations are only 400 times higher than that of Se. The effect of competing anions on adsorption of Se (IV) decreases in the order $\text{HPO}_4^{2-} > \text{SO}_4^{2-} \sim \text{CO}_3^{2-} > \text{NO}_3^-$. However, in the case of Se, the negative impact of HPO_4^{2-} is not as significantly different from that of carbonate and SO_4^{2-} as in the case of As(V). The differences in behavior between As (V) and Se (IV) on the effect of competitive ions are consistent with the differences in their adsorption affinities (see Table 2) towards the LDH.

In summary, competing anions in solution generally have a minimal effect on As and Se adsorption.

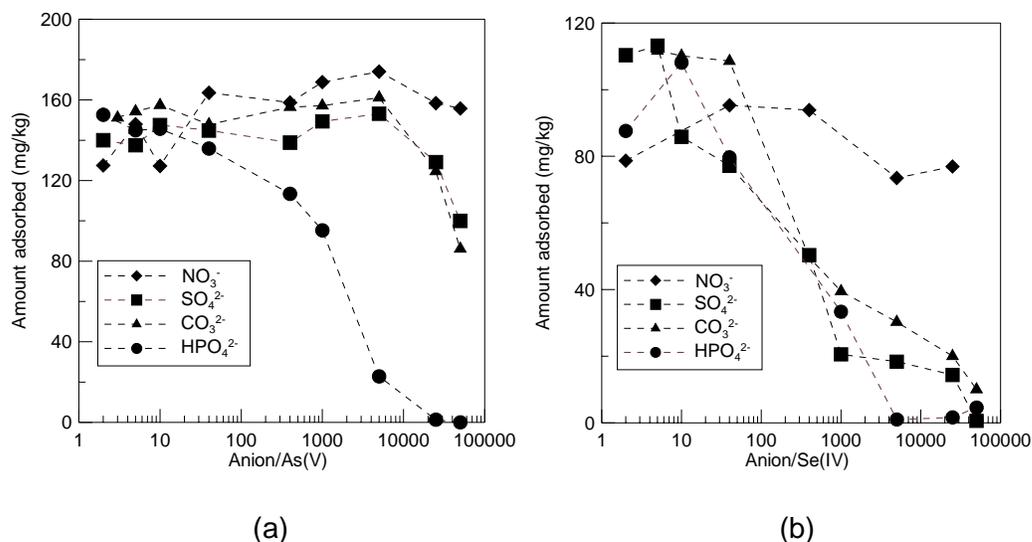


Figure 8. The effect of competitive anions on the uptakes of (a) As (V) and (b) Se (IV) on calcined LDH in 20-ppb solutions

Result 3.2.2.7 The desorption of As (V) and Se (IV) from LDH depends on the type of ion species present in the desorbing solutions, and their concentration.

Figure 9 shows the effect of solutions containing various anions with differing concentrations on the desorption of As (V) from calcined LDH. In the NO_3^- solution, only up to 17% of the adsorbed As (V) is desorbed after five desorption cycles. For the CO_3^{2-} and SO_4^{2-} solutions, when above 10 ppm, the fraction of As (V) that desorbs increases with increasing carbonate and SO_4^{2-} concentration. After five cycles with the 1000 ppm CO_3^{2-} and SO_4^{2-} solutions, for example, 46% and 43% of As (V) are desorbed, respectively. The release of As (V) in HPO_4^{2-} solutions is faster, and more concentration dependent. Almost 84% of As (V) desorbs in the 100-ppm HPO_4^{2-} solution after the five desorption cycles. The desorption results for As (V) in the presence of various anions are consistent with the adsorption behavior in the presence of the same competitive anions.

We have found previously that the effect of various competitive anions on the adsorption of As on calcined LDH decreases in the order $\text{HPO}_4^{2-} > \text{CO}_3^{2-} > \text{SO}_4^{2-} > \text{NO}_3^-$; we noted in the discussion that the reason for such a behavior is most likely the different affinities of the same anions for the LDH, which also follow the same order. As Goswamee et al. (1998) noted, when an anion is better suited stereochemically for inclusion into the interlayer of LDH, it also has a greater ability to cause the release of interlayer anions already present in the LDH.

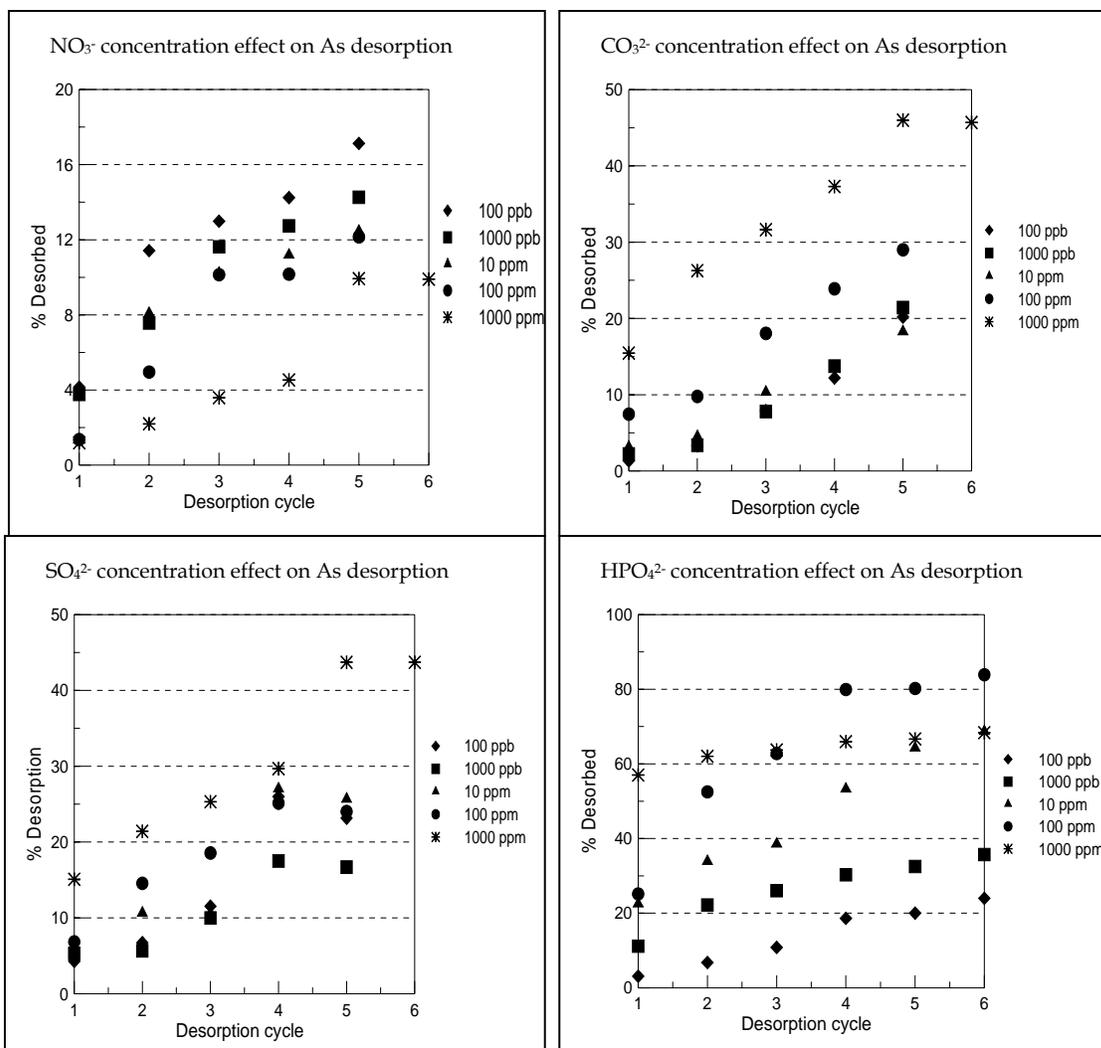


Figure 9. Desorption of As (V) from calcined LDH as a function of anion concentration

Desorption of Se as a function of various anions and concentrations is shown in Figure 10. Both the desorption rate and the fraction of Se (IV) that is desorbed from the calcined LDH are higher than in the case of As (V). This behavior is consistent with the lower sorption affinity of Se towards the calcined LDH, since the lower the affinity of a given metal is to the calcined LDH, the easier it is for the same metal to be released in the solution. In general, the release rates and the fraction of Se metal removed in HPO₄²⁻, SO₄²⁻, and CO₃²⁻ solutions increase with an increase in their concentrations. The maximum amount of desorption of Se is found in the 1000-ppm SO₄²⁻ solution, for which 100% of adsorbed Se is desorbed.

In summary, a number of different solutions were shown capable of regenerating the spent adsorbents; this provides a good potential for adsorbent reuse and recycling.

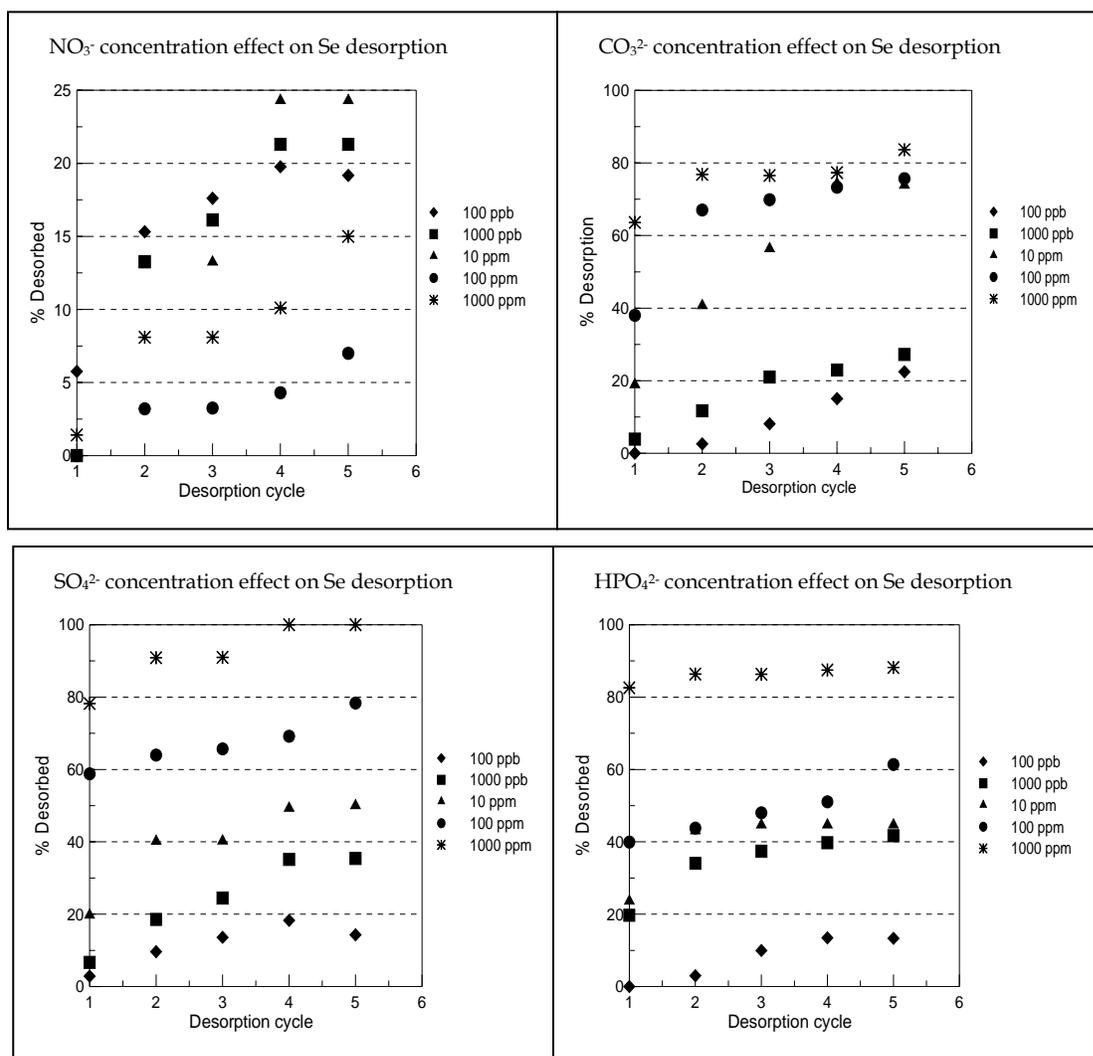


Figure 10. Desorption of Se (IV) from calcined LDH as a function of different anions and concentrations

3.2.3 Flow experiments

Result 3.2.3.1 We have developed a model for packed-bed flow adsorption columns, and have validated it by both batch and flow experiments.

The design of industrial adsorption columns requires substantial quantities of information. Typically, all such design information is gathered in an extensive series of pilot plant experiments that are time-consuming and expensive. As part of this project, we have developed a model that is applicable to the design of such industrial systems and is being validated by bench-scale experiments. This model will be utilized in the design of a full-scale column to study the effect of the various operating parameters. These parameters include linear flow rate,

feed concentration, pH, and temperature. With variation of these parameters, the optimum conditions for the column operation can be predicted. This model allows one to successfully study the column dynamics and breakthrough curves for a specific set of operating conditions.

In the model, mass transport in the adsorbent particles is described by the following unsteady state equation:

$$\frac{\partial q}{\partial t} = \frac{D}{r^2} \frac{\partial}{\partial r} \left(r^2 \frac{\partial q}{\partial r} \right) \quad (4)$$

where q (g metal/g adsorbent) is the local metal concentration at r (the radial distance measured from the center of a particle). Equation (4) must be solved with appropriate initial and boundary conditions:

$$q = 0, \quad 0 \leq r \leq R, t=0, \quad (5)$$

$$\frac{\partial q}{\partial r} = 0, \quad r=0 \quad (6)$$

$$\rho D \left. \frac{\partial q}{\partial r} \right|_{r=R} = k_f (C - C_s) \quad r=R \quad (7)$$

where ρ (g/cm³) is the adsorbent density, K_f (cm/s) the mass transfer coefficient, C (g/l) the concentration of the metal in the liquid, and C_s the metal concentration at the particle interface. Adsorption equilibrium prevails at the interface, and

$$q = q_s = KC_s^{1/n} \quad \text{at } r = R \quad (8)$$

The average concentration throughout the adsorbent particle is defined as

$$\bar{q} = \frac{3}{R^3} \int_0^R q r^2 dr \quad (9)$$

The mass balance in a packed tube reactor for non-dispersive conditions is described as

$$u \frac{\partial C}{\partial z} + \varepsilon \frac{\partial C}{\partial t} + (1 - \varepsilon) \frac{\partial \bar{q}}{\partial t} \cdot \rho = 0 \quad (10)$$

where u (cm/s) is the average superficial (i.e., calculated in terms of the cross-sectional area of the column) velocity of the flowing fluid, t (s) is the time, z (cm) the axial distance coordinate, and ε the void fraction in the bed (in practice, of interest is the number of bed volumes that can be treated before adsorbent saturation is reached; this can be conveniently calculated from the model by multiplying the volumetric flow rate by the time needed to reach saturation and by dividing by the bed volume).

Initial and boundary conditions can be described as

$$C = 0, \text{ at } t=0; \quad (11)$$

$$\bar{q} = 0, \text{ at } t=0; \quad (12)$$

$$C = C_0, \text{ at } z=0; \quad (13)$$

In the model the D and K values are obtained from the batch experiments described in Section 3.2.2, and literature formulas are used to calculate K_f . In the bench-scale column experiments, we studied the effect of initial As and Se concentration and the effect of flow rate on breakthrough.

Our column model is successful in predicting the breakthrough points of As and Se adsorption at various operating conditions. As such, this model is useful for the design of industrial adsorption columns.

3.3 Objective 3: Develop Better Sorbents

As stated earlier, there was no need for additional R&D to improve the adsorbent materials, as the LDH clays proved quite effective in their adsorptive and desorptive (regeneration) characteristics.

3.4 Objective 4: Investigate Sorbent Disposal

The spent adsorbent was characterized by the TCLP test. The results for As and Se are 0.32 ppm and 0.18 ppm, respectively. These are lower than the EPA limit of 5 ppm for As and 1 ppm for Se, indicating that the adsorbent is safe for disposal. However, there is a possibility that the TCLP may not accurately predict leaching for LDH adsorbents. Our conversations with Alcoa personnel indicated that Alcoa Inc. had performed the TCLP on similar adsorbents and found that the LDH materials interfered with the standard TCLP procedure. Field testing would thus be needed to conclusively demonstrate disposal safety over time.

4.0 Conclusions and Recommendations

4.1 Conclusions

As and Se are present in power plant effluents in small concentrations, less than 50 ppb, which are, however, in some instances 5–10 times higher than U.S. drinking water limits starting in 2006. We established “typical” contaminant profiles of such discharges and created “surrogate” effluent streams. We studied the adsorption of As and Se from these model effluents on calcined and uncalcined layered double hydroxides, and were able to conclude that the calcined materials tested in this project are very efficient adsorbents for these metals and show good promise for the removal of trace levels of As and Se from these model power plant effluents.

4.2 Recommendations

As a next step, the calcined materials should be tested with real effluents in a field study (this is a study we would like to undertake in collaboration with one of our local utilities, pending availability of funding). Such field testing is vital to establish the long-term viability of LDH adsorbents in real-life applications and also for verifying their safe disposal.

We observed (via ICP-MS) some Al or Mg in our modeled effluent streams at low or high pH (though it is still not clear whether it was due to attrition and carryover of fines or true dissolution). To the best of our knowledge, these pH levels are unlikely to be encountered in

typical power plant effluents. However, there is definitely a need for additional studies, as leachate in landfills has been known, on occasion, to be highly acidic (Meunier et al. 2002). The acid environment could cause the LDH to be dissolved by the leachate over time, resulting in increased concentrations of As and Se.

LDH materials are inexpensive, and thus sorbent regeneration is not as economically critical as with some other sorbents. Yet LDH regeneration is easily accomplished. A key aspect of any future study should be to find efficient and cost-effective ways to regenerate the LDH without generating large quantities of spent desorption solutions, as these must eventually be disposed of. This will be less of a challenge for the large-capacity LDH materials used on dilute waste streams such as boiler blowdown, compared to other industrial processes (such as conventional chemical precipitation) treating heavily polluted streams or using adsorbents with inferior adsorption capacities. Environmentally sound and cost-effective disposal of spent solutions is an important aspect of the viability of sorbent technology to enable reclamation and reuse of utility wastewaters.

Future work must also analyze the cost-effectiveness of using LDH materials; such a study can be conducted in collaboration with an adsorbent materials manufacturer.

4.3 Benefits to California

Anionic clay sorbents such as layered double hydroxides offer key economic and environmental benefits:

- They would conserve fresh water by enabling treatment and reuse of utility wastewaters.
- They would reduce the concentration of trace metals, such as As and Se, discharged in high-volume power plant effluents. Instead, the metals would be concentrated in lower-volume wastes (spent sorbents and desorption solutions), which would be easier to treat and control. Thus, LDH sorbents could enable utilities to meet stricter discharge regulations, should trace metal limits become more stringent.

5.0 References

- Das, D. P., Das, J., and Parida, K. "Physicochemical Characterization and Adsorption Behavior of Calcined Zn/Al Hydrotalcite-like Compound (HTLs) towards Removal of Fluoride from Aqueous Solution." *J. Colloid Inter. Sci.* 2003, 261, 213.
- Goswamee, R. L., Sengupta, P., Bhattacharyya, K. G., and Dutta, D. K. "Adsorption of Cr (VI) in Layered Double Hydroxides." *Appl. Clay Sci.* 1998, 13, 21.
- Kuan, W.-H., Lo, S.-L., Wang, M. K., and Lin, C.-F. "Removal of Se (IV) and Se (VI) from Water by Aluminum-Oxide-Coated Sand." *Wat. Res.* 1998, 32 (3), 915.
- Manju, G. N., Gigi, M. C., and Anirudhan, T. S. "Hydrotalcite as Adsorbent for the Removal of Chromium (VI) from Aqueous Media: Equilibrium Studies." *Ind. J. Chem. Technol.* 1999, 6, 134.

- Meunier, N., Blais, J. F., and Tiyagi, R. D. "Selection of Natural Sorbent to Remove Toxic Metals from Acid Leachate Produced During Soil Decontamination." *Hydrometallurgy*, 2002, 67, 19.
- Reichle, W. T. "Synthesis of Anionic Clay-Minerals (Mixed Metal-Hydroxides, Hydrotalcite)." *Solid State Ionics* 1986, 22 (1), 135.
- Roelofs, J. C., Jeroen, A., van Bokhoven, J., van Dillen, A. J., Geus, J. W., and de Jong, K. P. "The Thermal Decomposition of Mg-Al Hydrotalcites: Effects of Interlayer Anions and Characteristics of the Final Structure." *Chem. Eur. J.* 2002, 8 (24), 5571.
- Saviz, M., and David, C. "Application of Activated Alumina for the Removal of Selenium from Water." *Proceedings 15th Technical Seminar on Chemical Spills*, Edmonton, Alberta, June 8-9, 1998.
- Smedley, P. L., and Kinniburgh, D. G. "A Review of the Source, Behavior and Distribution of Arsenite in Natural Waters." *Appl. Geochem.* 2002, 17, 517.
- Steinberger, A., and Stein, E. D. "Characteristics of Effluents from Power Plant Generating Stations in the Southern California Bight in 2000" in S. Weisberg and D. Elmore (eds.), *Southern California Coastal Water Research Project Annual Report 2004*, Westminster, California.
- Thirunavukkarasu, O. S., Viraraghavan, T., and Subramanian, K. S. "Arsenic Removal from Drinking Water Using Iron Oxide-Coated Sand." *Water Air Soil Pol.*, 2003, 142, 95.
- Thirunavukkarasu, O. S., Viraraghavan, T., and Subramanian, K. S. "Removal of Arsenic in Drinking Water by Iron Oxide-Coated Sand and Ferrihydrite-Batch Studies." *Water Qual. Res. J. Can.* 2001, 36, 55.

6.0 Glossary

adsorption	Adhesion of a thin layer of one substance (gas, liquid, or solute) to the surface of a liquid or solid
adsorbent	A substance, usually solid, to which another substance adheres (see also sorbent)
Al	Aluminum
As	Arsenic
As (III)	Arsenite
As (V)	Arsenate
BET	Brunauer, Emmett, and Teller method of determining specific surface area

calcined LDH	Layered double hydroxide that has been heated at high temperature to drive off water and volatile compounds, thereby enhancing its adsorptive properties
CO ₃ ²⁻	Carbonate
CIEE	California Institute of Energy Efficiency
desorption	Removal of an adsorbed substance from the surface of the sorbent
effluent	Wastewater (boiler blowdown is one type of utility effluent)
EPA	U.S. Environmental Protection Agency
FT-IR	Fourier transform infrared spectroscopy
H ₂ O	Water
Hg	Mercury
HPO ₄ ²⁻	Phosphate (phosphoric acid and other types of phosphate, depending on pH level)
hydrotalcite	Aluminium-magnesium-hydroxycarbonate
ICP-MS	Inductively coupled plasma mass spectrometry
isotherm	A line describing adsorption for constant-temperature conditions
LADWP	Los Angeles Department of Water and Power
LDH	Layered double hydroxide
Mg	Magnesium
NO ₃ ⁻	Nitrate
ppb	Parts per billion
ppm	Parts per million
Se	Selenium
Se (IV)	Selenite
Se (VI)	Selenate
SO ₄ ²⁻	Sulfate
solute	A dissolved substance
sorbent	A substance that sorbs another substance; i.e., that takes it up by either adsorption or absorption
TCLP	Toxicity characteristic leaching procedure, a test to determine the mobility of contaminants in liquid or solid wastes

PIER	Public Interest Energy Research (a program of the California Energy Commission)
RWB	Regional Water Board
SCCWPR	Southern California Coastal Water Research Project