



## Kinetics study on separation of cadmium from tellurium in acidic solution media using ion-exchange resins

Wenming Wang, Vasilis Fthenakis\*

National Photovoltaic Environmental Health and Safety Research Center, Brookhaven National Laboratory, Upton, NY 11973, USA

Received 9 November 2004; received in revised form 18 February 2005; accepted 26 February 2005

### Abstract

The feasibility of using ion-exchange resins to separate cadmium from tellurium in acidic solutions of the two metals was investigated. We studied the competitive adsorption of cadmium and tellurium in such resins under varying acid strengths and contact time. We found that low sulfuric acid strength (i.e., 0.5 M) was most effective in removing cadmium from solutions. Different ion-exchange resins were tested for their affinity for cadmium and tellurium ions. In the selected systems, the ion-exchange rate of cadmium was rapid in the first 20 min, and reached equilibrium within 2 h. The Lagergren first-order model described the kinetic data with high coefficient of determination and correlation values. At room temperatures the ion-exchange for cadmium onto the resin followed the Freundlich isotherm model. The maximum removal of cadmium obtained from batch studies using resin A was 91%. Column studies with the same resin showed the removal of cadmium of 99.99% or higher.

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**Keywords:** Cadmium; Tellurium; Waste management; Ion-exchange; Recycling; Photovoltaics

### 1. Introduction

Cadmium (Cd) and tellurium (Te) are the major materials used in manufacturing cadmium telluride (CdTe) modules for photovoltaic (PV) cells. However, the content of these two metals in the PV module's glass is extremely low, around 0.06% for each, according to our intensive leaching tests. Cadmium is a potentially hazardous metal and tellurium is a rare one; thus, both need to be treated and recycled. This demands prudent scrap-material management practices throughout the PV modules' life cycle to avoid environmental contamination and health risks, and to comply with stringent regulations on cadmium discharges to the environment. Previous studies were limited to leaching with acidic solutions and extraction of cadmium and tellurium into the liquid phase [1–7]. None of the previous studies succeeded in completely separating Cd from Te. The concentrations of tellurium and cadmium in the leachate were ~1000–1100 ppm of each

element. Then, multiple steps (including leaching, neutralization, precipitation, filtration/separation, and re-dissolving) were used to separate and recover both from solutions. Yet, the efficiency of separating cadmium from tellurium, and subsequent recovery were not satisfactorily high. The best separation was obtained from Bohland et al. who recovered about 80% of Te at 99.7% purity in lab-scale experiments [2]. Apparently, these methods were not sufficiently effective in recovering the metals from low-concentration waste solutions. We investigated alternative processes that have the potential to completely separate cadmium from tellurium in acidic solutions. Ion-exchange technology offers a viable alternative for treating such waste streams. By using an ion-exchange resin, either all metal-ions can be removed from a solution, or one specific metal ion can be selectively removed, thus, achieving their separation. By carefully choosing the type of ion-exchange resin, the heavy metal ions can be completely separated and removed from the waste solutions to meet stringent environmental regulations. Several researchers studied adsorption as a means to remove cadmium from aqueous solutions [8–24]. The tested adsorbents

\* Corresponding author. Tel.: +1 631 344 2830; fax: +1 631 344 4486.  
E-mail address: vmf@bnl.gov (V. Fthenakis).

58 included activated carbon, bone char, peat, lignite, vermiculite, chitin, zeolite, and treated pinus pinaster bark. These  
59 studies focused on the adsorption of cadmium from low-concentration aqueous solutions; none of them describes the  
60 potential for separating cadmium from tellurium in acidic solutions. In the present work, we explored the feasibility of  
61 separating cadmium from tellurium in sulfuric acid solutions using different ion-exchange resins. Our study focuses on the  
62 adsorption kinetics and the effectiveness of separation.  
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## 67 2. Materials and methodology

### 68 2.1. Tellurium–cadmium containing solutions

69 Solutions containing both tellurium and cadmium were prepared by dissolving known amounts of high purity  
70 (99.99%) CdTe powder in solutions of sulfuric acid and hydrogen peroxide of known volume and strength. The solu-  
71 tions were prepared using de-ionized water. They then were passed through a filter with a pore size of 0.70  $\mu\text{m}$  to ensure  
72 that they were free of suspended particulates. The concentrations of tellurium and cadmium were determined using a  
73 Varian Liberty 100 inductively coupled plasma (ICP) Emission Spectrometer. Frequent calibrations showed that the pre-  
74 cision of the ICP measurements were  $\pm 1.0\%$  for cadmium, and  $\pm 3.0\%$  for tellurium.  
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### 81 2.2. Ion-exchange resins

82 Several resins were tested and two were selected for further evaluation. Before using them, the resins were soaked in  
83 deionized water for 24 h and then were rinsed several times also with deionized water.  
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### 86 2.3. Batch studies

87 Batch studies of sulfuric acid strength, kinetics studies, and batch equilibrium isotherm studies were carried out in the  
88 same manner. In each type of studies, we prepared metal solutions containing tellurium and cadmium and transferred them  
89 into 250 mL wide-mouth polypropylene test bottles with screw closure caps using a FINNPIPETTE pipette (accurate  
90 to  $\pm 0.3\%$  with a precision of 0.2%). Each bottle contained a known volume of the solution. A known amount of resin  
91 was then added into each bottle. Afterwards, the bottles were shaken continuously at 100 rpm on an INNOVA 2100 plat-  
92 form shaker manufactured by New Brunswick Scientific Co. Inc. At certain intervals of contact time, the solution sam-  
93 ples were withdrawn and filtered through 0.70  $\mu\text{m}$  filters. The tellurium and cadmium concentrations of the filtered liquid  
94 samples were measured with an ICP emission spectrometer. The experiments were conducted in duplicate, and mean val-  
95 ues were used in analyzing the data.  
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105 The quantities of cadmium and tellurium adsorbed onto the resins at equilibrium ( $q_e$ , mg/g) were calculated using the

mass balance equation:

$$q_e = (C_0 - C_e)V/M$$

where  $C_0$  and  $C_e$  are the initial concentration and equilibrium concentration of metals (mg/L), respectively,  $V$  the volume of solution (L), and  $M$  is the resin mass (g).

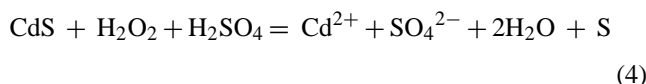
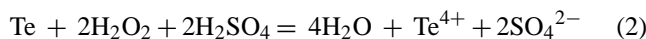
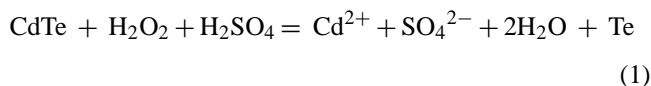
### 2.4. Column studies

The potential of commercial separation was studied using laboratory-scale ion-exchange columns. These columns are made by graduated Perspex of 34 mm inner diameter and 150 mm height. The Perspex column was equipped with a bottom filtration device to prevent the escape of fine resin beads during processing. In general, several ion-exchange resins may be used to remove positively charged heavy metals ions in aqueous solution media. We selected two different resins for evaluation, based on cost, range of operating pH, and adsorption capacity. In each column test, the ion-exchange resin was first soaked in deionized water for at least 12 h to ensure that the resin was fully swelled prior to use. The column was then loaded with 100 mL of the swelled resin. The influent solution was prepared by the dissolution of CdTe powder with sulfuric acid and hydrogen peroxide. The matrix solution was 0.5 M  $\text{H}_2\text{SO}_4$  with approximately 1100 ppm of tellurium and 1000 ppm of cadmium. The prepared influent solution, containing both cadmium and tellurium, was passed downward through the column at a fixed flow rate. A total of  $\sim 2.0$ – $4.0$  L of influent solution was used in each column study. The downstream effluent was collected at different fractions with each fraction measuring about one bed volume (100 mL). The flow rate of the solution was kept at 3–6 bed volumes per hour (BV/h), which was equivalent to 300–600 mL/h. Samples of solution were taken from each fraction of the effluent and were analyzed using ICP for cadmium and tellurium.

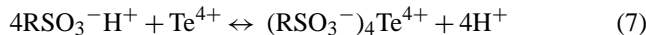
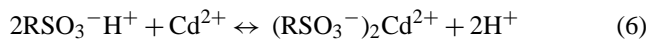
## 3. Chemistry of leaching and ion exchange

Thermodynamic information on tellurium [25] and cadmium [27,28] showed the following: Cadmium is soluble in acid media, and insoluble in neutral and strongly alkaline media; tellurium(IV) is sparingly soluble in acid media, insoluble in neutral media, and soluble in alkaline media; tellurium(VI) is soluble in acid media, and insoluble in alkaline media. Other studies showed that telluride can be readily oxidized with hydrogen peroxide in acid media [1,2,25,26]. In preparing the initial tellurium–cadmium-containing solutions from the raw CdTe powder, a leaching procedure was employed. During leaching, in the presence of sulfuric acid and hydrogen peroxide, the Cd and Te are extracted and solubilized into the liquid phase based on the following

reactions:



In sulfuric acid, essentially all of the dissolved cadmium is expected to exist predominantly as the uncomplexed  $\text{Cd}^{2+}$ , whereas tellurium(IV) may exist in the form of  $\text{Te}^{4+}$  and  $\text{TeO}(\text{OH})^+$  depending on the solution's acidity. The more acidic the solution is, the more likely tellurium(IV) is in the form of  $\text{Te}^{4+}$ . Tellurium(VI) would be in the form of  $\text{H}_6\text{TeO}_6$  in acidic media because  $\text{H}_6\text{TeO}_6$  is a weak acid. Should any tellurium(VI) ions exist in acid media, they would be negatively charged. Therefore, it is unlikely that free  $\text{Te}^{6+}$  exists in the solution. In the present experiments, the only possible ions existing in sulfuric acid solution were  $\text{Cd}^{2+}$ ,  $\text{H}^+$ ,  $\text{Te}^{4+}$ , and  $\text{TeO}(\text{OH})^+$ . On adding the ion-exchange resin A into the solution, the following reversible adsorption reactions are possible:



According to these reactions, low acidity will favor forward reactions whereas high acidity will favor backward reactions. Although all these listed adsorption reactions might take place, their extent (completeness) for specific ion species is very different due to the different affinity and selectivity of the resin to positively charged ions, which is the base for the separation of ions in the solution.

## 4. Results and discussion

### 4.1. Batch acid strength studies

We investigated the effect of acid strength on the resin's adsorption capacity by using solutions containing 1060 ppm of Cd and 1240 ppm of Te in sulfuric acid strengths of 0.5, 1–5 M. We mixed 100 mL of resin with 2, 5, and 10 g of resin A for a total contact time of 24 h, which was sufficiently long for the system to reach equilibrium.

As seen from the reversible adsorption reactions (6)–(8), the concentration of  $\text{H}^+$ , or, in other words, the strength of

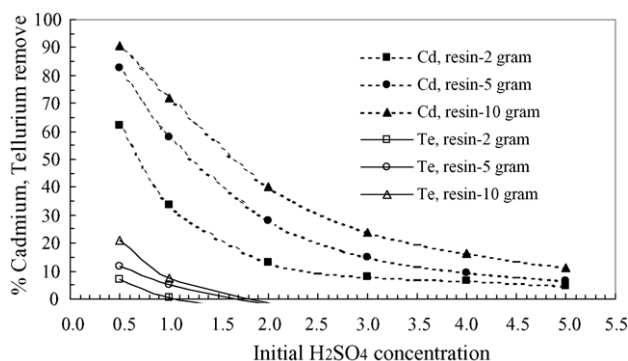


Fig. 1. Effect of  $\text{H}_2\text{SO}_4$  concentration on cadmium adsorption by resin A (initial metal concentrations: Cd, 1060 ppm; Te, 1240 ppm; solution, 100 mL).

sulfuric acid, plays an important role in adsorption. As the concentration of  $\text{H}^+$  increases, the positively charged metal ions compete to a lesser degree for exchange on the resin. Fig. 1 shows the dependence of the adsorption of tellurium and cadmium on the strength of the sulfuric acid. A very low percentage of cadmium was removed at high  $\text{H}_2\text{SO}_4$  concentration. For instance, at an initial 5 M  $\text{H}_2\text{SO}_4$  concentration, less than 10% of the cadmium, and no tellurium was adsorbed. The low adsorption may be explained by the competition between  $\text{H}^+$  and metallic ions. With decreasing  $\text{H}_2\text{SO}_4$  strength in the initial solution, more cadmium was exchanged to the resin phase. A dramatic increase occurred in cadmium removal when the initial  $\text{H}_2\text{SO}_4$  was lowed to 0.5 M. For example, approximately 91% of cadmium was removed when 10 g of resin was added to an initial 0.5 M  $\text{H}_2\text{SO}_4$  solution. During the ion-exchange process, cadmium ions compete with tellurium, but the resin has a much higher affinity for cadmium than tellurium. This distinction allows the separation and removal of cadmium from tellurium in sulfuric acid solution. As shown in Fig. 1, no tellurium was adsorbed at initial  $\text{H}_2\text{SO}_4$  concentrations of 2.0 M and above. Yet, at that concentration, still as much as 40% of cadmium was removed from the solution. Overall, whatever the initial  $\text{H}_2\text{SO}_4$  concentration was, many more cadmium ions were adsorbed on the resin than were tellurium. This suggests that by carefully controlling the acidity of the solution, cadmium can be selectively adsorbed in the resin leaving tellurium in the liquid phase. By selecting an appropriate strength of acid, 0.5 M in our studies, the effluent liquid phase can be virtually free of cadmium while tellurium retained in solution and cadmium ions adsorbed on the resin. Elution of the resin will generate concentrated cadmium solution, from which cadmium can be recovered. Investigations on Cd and Te recovery are in progress.

The manufacturer's suggested operating pH range for resin A is an all inclusive 0–14. For effectively removing cadmium in the tellurium–cadmium–resin systems we studied, low acidity is preferable. However, according to our studies on the leaching behavior of CdTe containing PV glass

waste, a low acid concentration would have the following consequences: (1) incomplete extraction of tellurium and cadmium; (2) precipitation of  $\text{TeO}_2$  from the leachate when the  $\text{H}_2\text{SO}_4$  concentration was below 0.5 M. Accordingly, the goal of removing both tellurium and cadmium from PV glass waste would not be met. Investigations on the adsorption of cadmium and tellurium at concentrations below 0.5 M  $\text{H}_2\text{SO}_4$  were beyond the scope of present studies.

Our studies also demonstrate that the amount of resin affects the percentage of cadmium removed. Fig. 1 shows that to remove more than 90% of 1060 ppm of cadmium from 100 mL solution with 0.5 M sulfuric acid, a minimum of 10 g of resin A is required at equilibrium. In comparison, only 83% and 62% of cadmium was removed when the amount of the resin was 5 and 2 g, respectively. As expected, the equilibrium concentrations of cadmium and tellurium in the liquid phase decrease with the increase in the amount of resin because the number of active  $\text{H}^+$  sites increases. However, this effect is not linear in high  $\text{H}_2\text{SO}_4$  concentration solutions. As shown in Fig. 1, in 5.0 M  $\text{H}_2\text{SO}_4$ , the efficiency of cadmium removal was 11%, 7%, and 5% when the resin level was 10, 5, and 2 g, respectively.

#### 4.2. Batch kinetic studies

The batch kinetic studies were conducted with the metal solutions containing initial concentrations of Cd 1090 ppm and Te 1270 ppm in 0.5 M sulfuric acid media. The amounts of resin A used were 5, 10, and 20 g, respectively. In each experiment, a total of 240 mL metal solution was used. The solution samples were withdrawn at contact times of 10, 20, 30, 40, 60, 80, 100, 120, and 720 min.

Fig. 2(a) and (b) plot the ion-exchange kinetics for separating cadmium from tellurium with different amounts of resin A at an initial  $\text{H}_2\text{SO}_4$  concentration of 0.5 M.

It is clear from Fig. 2(a) and (b), that significant and rapid adsorption of cadmium took place within first 20 min, beyond which, there was only a marginal increase in adsorption. Within 2 h, the concentrations of cadmium in the solutions reached a steady state, indicating that the ion-exchange reac-

tions reached equilibrium. The adsorption equilibrium of tellurium was well established within less than 20 min. We confirmed that both the Cd and Te concentrations remained constant, by continuing sampling and analysis up for up to 12 h.

As discussed earlier, tellurium exists in the forms of Te(IV) and Te(VI) in sulfuric acid solutions. The only possible ions of tellurium in acidic media are Te(IV) since Te(VI) cannot be positively charged. Moreover, by using  $\text{H}_2\text{O}_2$  in the leaching process, a large fraction of tellurium was oxidized to Te(VI). Consequently, only a small amount, if any, of positively charged Te(IV) may exist in the studied solutions. When in contact with resin A, positively charged Te(IV) ions, if any, would compete with cadmium ions. Evidently, the resin has a much higher affinity for cadmium, so unsurprisingly, the removal percentage of cadmium was much higher than that of tellurium. The two metals were completely separated in our column studies.

The mechanism of ion-exchange involves diffusion through a liquid film around the resin particle, and diffusion within the particle. The former is the rate-controlling mechanism at low concentrations, and the latter at high concentrations. However, in both cases, the size of the resin particles also is a determining factor.

We investigated the kinetics of cadmium and tellurium adsorptions for resin A at its optimum 0.5 M  $\text{H}_2\text{SO}_4$  concentration at short intervals over 12 h. We expected that the kinetic studies would help in evaluating which classical models were suitable for assessing cadmium and tellurium adsorption. Fig. 3 shows the kinetics of cadmium adsorption on the resin.

Several mathematical models have been used to describe the adsorption kinetics of resin–solution systems. The most popular and frequently used models are Lagergren's first order model [29,30] and Ho's pseudo second-order model [31].

The Lagergren's first order reaction model is expressed as follows [29,30]:

$$\ln(q_e - q_t) = \ln(q_e) - K_L t \quad (9)$$

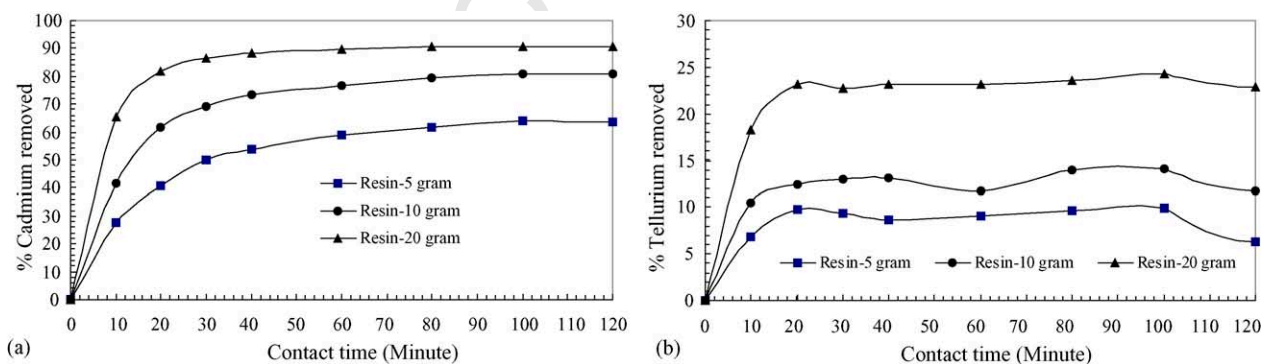


Fig. 2. (a) Cadmium removal percentage vs. time at initial  $\text{H}_2\text{SO}_4$  concentration of 0.5 M (initial metal concentrations: Cd, 1090 ppm; Te, 1270 ppm; solution, 240 mL); (b) tellurium removal percentage vs. time at initial  $\text{H}_2\text{SO}_4$  concentration of 0.5 M (initial metal concentrations: Cd, 1090 ppm; Te, 1270 ppm; solution, 240 mL).

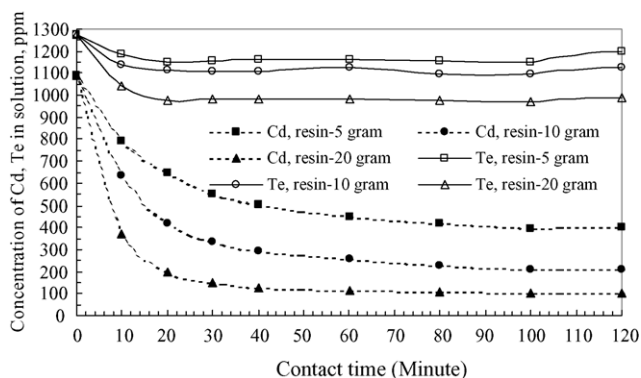


Fig. 3. Plots of Cd concentration vs. contact time at 0.5 M H<sub>2</sub>SO<sub>4</sub> media (initial metal concentrations: Cd, 1090 ppm; Te, 1270 ppm; solution, 240 mL).

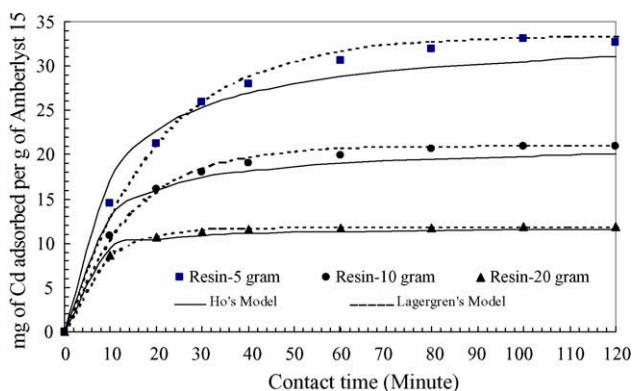


Fig. 4. Lagergren first-order reaction model and Ho's pseudo second-order reaction model plot for adsorption of cadmium on resin A.

314 The above equation can be rearranged as follows:

315  $\ln(1 - q_t/q_e) = -K_L t$  (9a)

316  $q_t = q_e(1 - \exp(-K_L t))$  (9b)

317 where  $K_L$  is the Lagergren's rate constant for adsorption  
 318 ( $\text{min}^{-1}$ ),  $q_e$  the amount of metal ions adsorbed at equilibrium  
 319 (mg/g), and  $q_t$  is the amount of metal ions adsorbed at  
 320 any given time  $t$  (mg/g).

321 Ho developed a pseudo second-order kinetic expression  
 322 for the competitive sorption systems of heavy metal ions by  
 323 sphagnum moss peat [31]. It is expressed as follows:

324  $t/q_t = 1/(2Kq_e^2) + t/q_e$  (10)

325 This can be rearranged to the form:

326  $q_t = (2Kq_e^2 t)/(1 + 2Kq_e t)$  (10a)

327 where  $K$  is the pseudo second-order rate constant for adsorption  
 328 ( $\text{g/mg min}$ ),  $q_e$  the amount of metal ion adsorbed at equilibrium  
 329 (mg/g), and  $q_t$  is the amount of metal ions adsorbed  
 330 at any given time  $t$  (mg/g).

331 The batch kinetic study data for optimum initial H<sub>2</sub>SO<sub>4</sub>  
 332 of 0.5 M was fitted to both models by nonlinear regression  
 333 analysis using the software package ProStat (Version 3) for  
 334 Windows. The analysis indicates that both models adequately  
 335 described the kinetic data at the 95% confidence level. The  
 336 Lagergren first-order model described the kinetic data quite  
 337 well with higher coefficient of determination (COD) and correlation  
 338 ( $R^2$ ) values than Ho's pseudo second-order model.  
 339 Figs. 4 and 5 show the kinetics of cadmium adsorption on

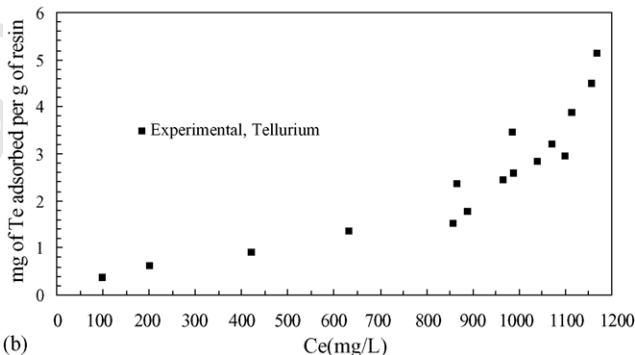
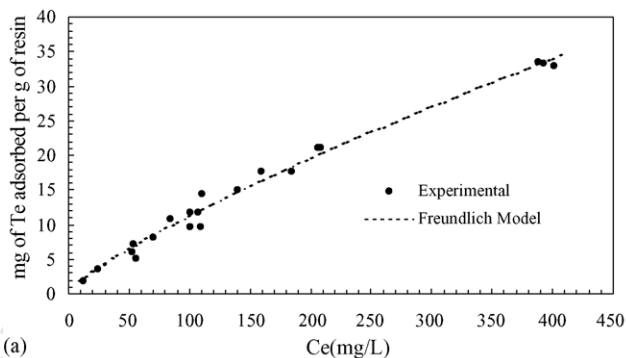


Fig. 5. (a) The Freundlich model plot for ion exchange of Cd on resin A; (b) the equilibrium isotherm of tellurium on resin A.

Table 1  
 Comparison of two models for cadmium adsorption on resin A

Resin amount (g)	Model type	Model equation	COD	R <sup>2</sup>
5	First-order	$q_t = 33(1 - e^{-0.052t})$	0.997	0.998
	Pseudo second-order	$t/q_t = 1/[2(0.0016)(33^2)] + t/33$	0.973	0.991
10	First-order	$q_t = 21(1 - e^{-0.072t})$	0.998	0.999
	Pseudo second-order	$t/q_t = 1/[2(0.0037)(21^2)] + t/21$	0.977	0.992
20	First-order	$q_t = 12(1 - e^{-0.13t})$	0.999	0.999
	Pseudo second-order	$t/q_t = 1/[2(0.015)(12^2)] + t/12$	0.989	0.996

Table 2  
Initial concentrations of metal solutions

Bottle	Dilution factor (%)	Concentration of metals (ppm)	
		Te	Cd
1	10	117	104
2	20	233	208
3	40	466	416
4	60	699	625
5	80	933	833
6	100	1160	1040

where  $q$  is amount of metal ions adsorbed per unit of weight of resin (mg/g),  $K_f$  an equilibrium constant indicative of adsorption capacity,  $n$  the adsorption equilibrium constant whose reciprocal is indicative of adsorption intensity, and  $C_e$  is the concentration of metal ions in bulk solution at equilibrium (mg/L).

The Langmuir model is mathematically written as follows [33]:

$$q = (q^0 b C_e) / (1 + b C_e) \tag{12}$$

where  $q^0$  is amount of solute adsorbed per unit weight of resin in forming a complete monolayer on the surface (mg/g),  $b$  the constant related to the energy or net enthalpy of adsorption, and  $C_e$  is the concentration of metal ions in bulk solution at equilibrium (mg/L).

The experimental results were analyzed using the software package ProStat (Version 3). We found that the adsorption data obtained were best fitted with the Freundlich isotherm model. The obtained equation is  $q = (0.29)C_e^{1/1.26}$ . The constants obtained with this model were statistically significant at 95% confidence level. The COD is 0.985, and the  $R^2$  is 0.992. Fig. 5(a) shows plots of the Freundlich model as well experimental results for cadmium adsorption on resin A.

The equilibrium isotherm of tellurium was also investigated and the equilibrium plot of the concentrations of the tellurium in solution against the concentrations of the tellurium in the resin is shown in Fig. 5(b). The adsorption of tellurium on the resin did not fit the considered equilibrium isotherm models. This suggests that the tellurium may be adsorbed only physically onto the resin.

The experimental results also showed that, in the present batch study conditions, resin A had an adsorption capacity of 33 mg/g-resin for cadmium and 5 mg/g-resin for tellurium. The equilibrium isotherm studies revealed that the selectivity of resin A to cadmium is much higher than to tellurium. This makes it possible to separate these two metals using ion-exchange resin column.

#### 4.4. Column studies

The column studies were conducted to elucidate the shape of the breakthrough curves of cadmium and tellurium. In the column studies, the effluent solution was collected at different volume fractions and was analyzed by ICP for cadmium and tellurium. The efficiency of adsorbing cadmium and tellurium is presented by breakthrough curves showing concentration ratios  $C/C_0$  as a function of throughput volumes, where  $C$  is the instantaneous concentration of effluents and  $C_0$  is the initial concentration of influent. Fig. 6 shows such curves for tellurium and cadmium from an experiment on resin B. In this test, the nominal resident time of the influent solution in the resin column was 16 min. It is shown that the tellurium breaks through the column almost immediately (at 50 mL, 0.5 bed volumes) after feeding and the column took approximately 800 mL (8 bed volumes) before being completed

resin A for these models. As shown in these figures, Lagergren's first-order model slightly overestimates the kinetics of cadmium adsorption, whereas Ho's pseudo second-order expression slightly underestimates them. However, when additional resin was used (20 g), the prediction of two modules were very close. The equations of the models are shown in Table 1.

Apparently, the cadmium adsorption-rate constants increase significantly as the dosages of resin increase. For the Lagergren model, the calculated first-order reaction constant was 0.052, 0.072, and 0.13 min<sup>-1</sup>, respectively, with 5, 10, and 20 g of resin. These findings are very close to the first-order kinetic rate constants reported by Mathialagan and Viraraghavan of 0.059 min<sup>-1</sup> for cadmium adsorption on vermiculite [8] and 0.055 min<sup>-1</sup> on perlite [23].

#### 4.3. Equilibrium isotherm studies

Subsequent to determining the optimum strength of sulfuric acid and the adsorption equilibrium time, equilibrium isotherm studies were conducted at room temperature (23 ± 1 °C) by varying the initial concentrations of tellurium and cadmium. A fixed 100 mL liquid volume was used in each experiment. Solutions of different Cd and Te concentrations were prepared by diluting a stock of 1040 ppm Cd and 1160 ppm Te in 0.5 M sulfuric acid, with virgin 0.5 M H<sub>2</sub>SO<sub>4</sub> solution. Table 2 lists the concentrations of the prepared solutions. Then, 5 g of resin A were added to 100 mL of each prepared solution and shaken for 24 h, which was sufficient to reach equilibrium. A control solution with 100 mL of 0.5 M sulfuric acid solution, but without the metals, was also mixed and shaken with 5 g of the resin to determine the possibility of leaching of tellurium and cadmium from the resin. Both tellurium and cadmium concentrations were measured at the end of the adsorption.

The ion-exchange equilibrium for metal ions can be conveniently analyzed by the ion-exchange isotherm, which is an equilibrium plot of the concentration of the exchanging ion in solution against the concentration of the same ion in the solid exchanger at constant temperature [20]. Two nonlinear mathematical models are widely used in describing ion-exchange isotherms: Freundlich's model and Langmuir's model.

The Freundlich's model is often written as [32]:

$$q = K_f C_e^{1/n} \tag{11}$$

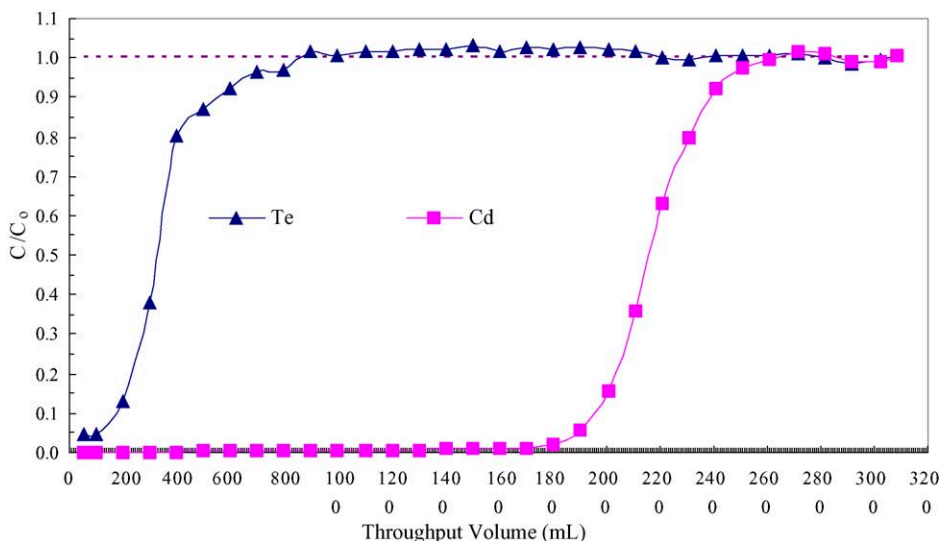


Fig. 6. Removal of Cd from Cd- and Te-containing solution using resin B; volume, 100 mL. Influent concentrations: Te, 1160 ppm; Cd, 980 ppm; solution flow rate: 500 mL/h.

434 exhausted with tellurium. On the other hand, the cadmium  
 435 was adsorbed for a substantial period of time, not achieving  
 436 breakthrough until 1800 mL, and reached exhaustion after  
 437 2600 mL of throughput volume. Separation of cadmium from  
 438 tellurium was fairly complete, as shown by the ICP analysis  
 439 of the effluent fractions. In each of the effluent fractions which  
 440 were collected prior to 1600 mL, the cadmium concentration  
 441 was below 10 ppm showing that at least 99% of cadmium was  
 442 removed by the resin, whereas tellurium was retained in the  
 443 solution.

444 The steep increase in the concentrations of Cd and Te met-  
 445 als in the effluent fractions indicates that a relatively small  
 446 volume of solution would cause the column to reach com-  
 447 plete exhaustion of the resin from the breakthrough point,

448 or, in another words, very short mass transfer zone (MTZ).  
 449 Mass balance calculations show that 2.1 g of cadmium were  
 450 exchanged to 100 mL of swollen resin.

451 The column study results with resin A are plotted in Fig. 7.

452 In this test, the nominal resident time of influent solution  
 453 in the resin column was 27 min. The same trend is observed  
 454 except that the breakthrough of cadmium did not occur until  
 455 2200 mL of influent was passed through the column. When  
 456 a total of 3200 mL of influent solution was passed through  
 457 the resin column, 2.7 g of cadmium were removed from solu-  
 458 tion. In the first 1800 mL of collected effluent, the cadmium  
 459 removal percentage was always 99.9% or better.

460 When two ion-exchange columns were arranged in series,  
 461 the removal of cadmium increased to 99.99% or better

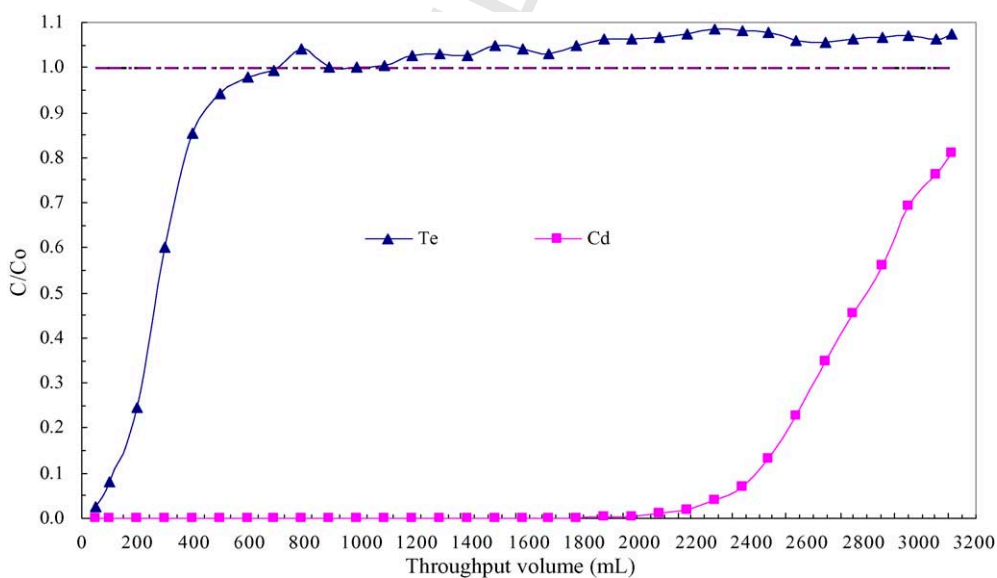


Fig. 7. Removal of Cd from Cd- and Te-containing solution using resin A; volume, 100 mL. Influent concentrations: Te, 1120 ppm; Cd, 942 ppm; solution flow rate: 300 mL/h.

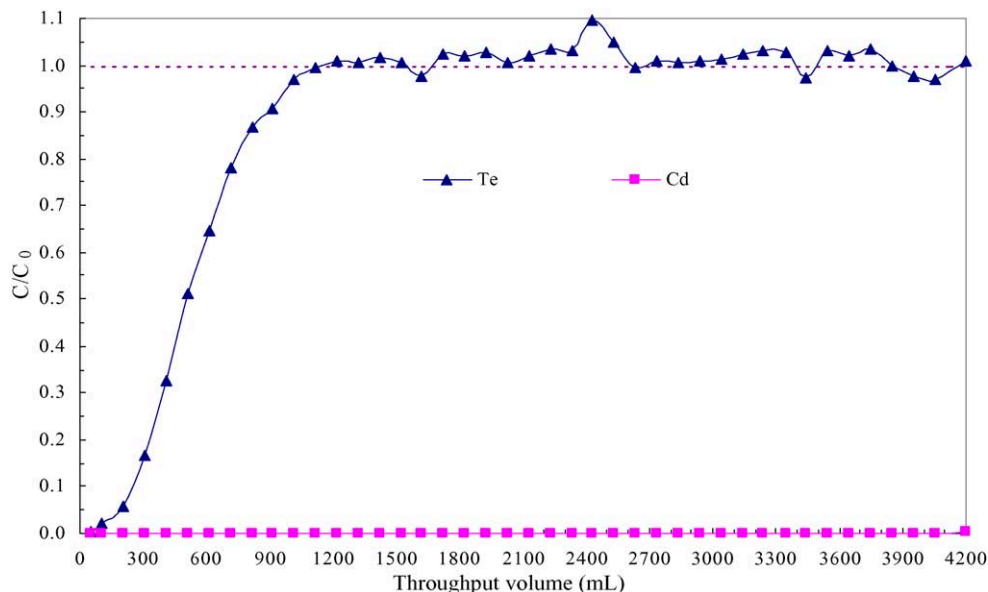


Fig. 8. Removal of Cd from Cd- and Te-containing solution using resin A; two columns in series (100 mL each). Influent concentrations: Te, 1150 ppm; Cd, 989 ppm; solution flow rate: 750 mL/h.

(Fig. 8), although we increased the flow rate and, subsequently, decreased the nominal resident time to 22 min. The flow rate of the influent solution was controlled at 750 mL/h and a total of 4200 mL of influent solution was passed through the two columns. The cadmium concentrations in the first 3400 mL of the effluent solution fractions were often below the detection limit of ICP (i.e., <1.5 ppb). In the whole range of 0–3800 mL, the highest measured Cd concentration was 0.5 ppm and the average concentration was 0.04 ppm; in the range 0–3300 mL, the average concentration was 0.02 ppm corresponding to a 99.998% removal of Cd. Overall, the solution fractions collected before breakthrough were basically free of cadmium, and therefore, high purity tellurium could be recovered subsequent to this separation.

## 5. Conclusion

The feasibility of removing and separating cadmium from tellurium in acidic media was studied using two ion-exchange resins. The following conclusions were drawn from the present studies:

- Significant and rapid adsorption took place within 20 min on both resins.
- Batch studies with resin A showed that approximately 91% of the cadmium was removed, while 21% tellurium was also adsorbed onto the resin.
- A kinetic study at 0.5 M H<sub>2</sub>SO<sub>4</sub> showed that equilibrium for cadmium adsorption on resin A was attained within 2 h.
- The Lagergren first-order model described the kinetic data quite well, with higher coefficient of determination (COD) and correlation ( $R^2$ ) values than Ho's model.

- The equilibrium isotherm analysis of the experimental data showed that the ion exchange for cadmium onto the resin follows the Freundlich isotherm.
- Column studies revealed that both resins A and B were effective in removing cadmium from tellurium. However, resin A showed the least leakage of cadmium in our tests.
- Column studies with two columns in series, showed a removal of cadmium higher than 99.99%, whereas 90–96% of the tellurium remained in the solution. It is expected that very high tellurium recovery (e.g., 99.99%) can be achieved in recirculating systems.
- Ion exchange was found to be an effective method for separating cadmium from tellurium in sulfuric acid media.

## Acknowledgement

This work was funded by the Solar Technologies Program, Conservation and Renewable Energy, United States Department of Energy under contract DE-AEC02-76CH000016.

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