

CCB LEACHING SUMMARY: SURVEY OF METHODS AND RESULTS¹

Ann G. Kim
National Energy Technology Laboratory
U.S. Department of Energy
Pittsburgh, Pennsylvania

Abstract

The utilization of coal combustion by-products (CCB) as bulk fill and as mine backfill has raised questions about the potential contamination of surface and groundwater. A number of studies have addressed the release of various metal ions from CCB, but correlation of results has been difficult due to the multiplicity of methods and the variety of leachant solutions. Differences in the type of samples and sample size also have complicated the discussion. Leaching is related to the solubility of a specific compound and can be influenced by pH, temperature, complexation, and oxidation/reduction potential. A recent survey identified more than 100 leaching methods to remove soluble components from a solid matrix, including regulatory methods, standard methods, and those developed for a particular application. Regulatory tests and standard methods are not necessarily appropriate for leaching tests intended to simulate natural processes. Data obtained by different laboratories using standard or regulatory tests may be comparable (within an order of magnitude). Studies performed with different leaching methods do not necessarily produce comparable data, although researchers using different methods may arrive at similar conclusions. In the leaching studies surveyed, the disparity in leaching conditions, the duration of leaching, and the different samples make direct comparisons of results very difficult. However, many studies reached these general conclusions:

- C than calcium, less than 50 percent of an element in CCB is labile, even in long-term tests;
- C except for oxyanions, the solubility of cations in CCB increases with a decrease in pH;
- C the alkalinity of the ash will affect its leachability; and
- C the distribution of an element in solid phases (crystalline, amorphous, surface coating) may control its solubility.

Introduction

During the past 50 years, the use of coal to generate electricity has increased substantially, as has the generation of coal combustion by-products (CCB). In EPA's recent regulatory determination, it was acknowledged that CCBs are a nonhazardous materials and that increased utilization of these materials should be encouraged. However, environmental concerns about CCBs focused on the potential release of trace elements to surface and groundwater, particularly when the material is used as mine backfill. Estimating the release of metals from CCBs has been studied using a variety of methods, samples, and leachant solutions. Any attempt to integrate the results of disparate test protocols requires some discussion of leaching, the fundamentals, and the various methods. The results of CCB leaching studies can then be reviewed to determine if the results can be correlated to general conclusions.

Leaching Methods

The leaching behavior of all types of materials is related to several critical factors, including specific element solubility and availability or release potential. Solubility can be influenced by pH, complexation by inorganic species or dissolved organic matter, and reducing properties. A recent survey of the literature identified more than 100 leaching methods to remove soluble components from a solid matrix (Hesbach and Lamey, 2001). Several of these are regulatory methods, mandated to characterize materials; others are approved by organizations for establishing compliance to particular specifications. Many were developed for application to municipal solid waste or industrial wastes prior to use or disposal. Some are intended to mimic natural conditions while the intent of others is to obtain information about the nature of the extractable material within a particular solid. The methods vary in

¹A more detailed discussion of the subjects discussed in this paper are included in "Fluid Extraction of Heavy Metals from Coal Ash," a dissertation submitted to the University of Pittsburgh in partial fulfillment of the degree of Doctor of Philosophy, April 2002.

the amount and particle size of leached sample, the type and volume of leachant solution(s), the leachant delivery method, and time. Most procedures are performed at ambient temperature, although a few decrease the time required to solubilize components by increasing the temperature. Although some methods have been developed for a specific type of material, most leaching methods have been applied to a variety of materials. The parameters for these methods are compared in Table 1.

Although there is a wide variety, leaching methods can be categorized in a number of ways. The first deals with whether the leaching fluid is a single addition (static extraction tests) or is renewed (dynamic tests). Methods are also characterized as (1) batch leaching, in which the sample is placed in a given volume of leachant solution; (2) flow through (column) systems; or (3) flow around systems for monolithic samples. Results are generally reported as a concentration, sometimes as the concentration in the leachant solution (mg/L) or as the concentration in the solid (mg/kg). In many methods, the liquid to solid ratio (L/S) is used to quantify the volume of leachant and the amount of solid sample, usually as mL/g or L/kg.

Summaries of many of the more commonly used leaching methods are given by Sorini (1997) and Wilson (1995). The International Ash Working Group (IAWG) based in Europe has done extensive work on the integration of a variety of tests into a comprehensive leaching system (Eighmy and van der Sloot, 1994; van der Sloot, 1998).

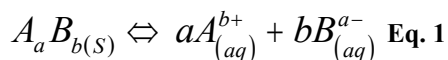
Leaching methods are categorized as static or dynamic methods. Within these categories, static methods are divided into batch and monolithic categories. Dynamic methods include column, serial batch, or sequential batch, although some methods are not uniquely defined within these categories. Due to the number of leaching methods, this discussion is not comprehensive. The intent is, rather, to identify commonly used leaching techniques.

Leaching Fundamentals²

Leaching Chemistry

As it applies to this study, leaching is the dissolution of a solid by an aqueous chemical solution. Leaching reactions are characterized as hydrolysis, caustic (alkaline), acidic, or oxidative reductive. In addition to water, acids and bases are commonly used as leaching agents. This process can be complicated by secondary reactions, such as precipitation, adsorption, or the formation of complexes. Although biochemical leaching may be important in natural processes and hydrometallurgy, it is not usually considered in regulatory or laboratory leaching tests.

The dissolution of mineral components and the behavior of dissolved components is controlled by the system variables, pH, eh, and the concentrations of the dissolved species (Demopoulos, 1999). A chemical reaction involving dissolution and precipitation can be written as:



where AB is the solid, A is the dissolved cation (metal), and B is dissolved anion (ligand). If the compound AB exists in solution, at equilibrium the reaction quotient, is equal to K, the equilibrium constant (Stumm and Morgan, 1996).

Reactions in solution are homogeneous reactions in one phase. Leaching involves heterogeneous reactions with at least two phases, liquid and solid. Since the reactant AB is a solid, its activity is considered fixed at unity and for this compound the equilibrium solubility product is:

²For a more thorough discussion of leaching chemistry refer to Demopoulos (1999), van der Sloot *et al.* (1998) and Stumm and Morgan (1996).

$$K_{sp} = [A^{b+}]^a [B^{a-}]^b \quad \text{Eq. 2}$$

The solubility product is considered constant for varying compositions of the aqueous phase at constant temperature and pressure for a pure solid phase. If K_{sp} and the concentration (mol/L) of one of the species is known, it is theoretically possible to calculate the concentration of the other species. When the metal or the ligand is distributed in more than one mineral, solubility calculations become more complex. Solubility products, if known, can be used to estimate the relative solubility of several coexisting minerals.

Because reactants must diffuse across the liquid solid interface, the surface area of the solid is a variable. A non-homogeneous material, in which an element is distributed in more than one chemical compound or crystalline phase, also complicates the formulation of solubility equations. Competing reactions, secondary reactions, and precipitation also may complicate the interpretation of leaching results.

The shrinking core model that has been applied to a variety of solids leaching processes describes a reaction front starting at the surface of the particle of radius r and moving inward with a velocity v . The rate of reaction is a function of the distance the reaction front moves in time t .

$$R(t) = 4\pi p_r [r - \lambda(t)]^2 v \quad \text{Eq. 3}$$

According to this model the reaction rate is greatest when the leaching solution is at the surface of the particle. Calculation of the reaction rate is more complex if the particle is not homogeneous, if more than one chemical reaction occurs, and if transport rates for reactants and products must be considered.

An adsorption/desorption model of intraparticle diffusion was developed by Chaiken (1992) to account for spatial heterogeneity of particle porosity and temporal changes in porosity due to leaching reactions.

$$f(\lambda) = \frac{h}{\lambda\sqrt{\pi}} e^{-h^2(\ln\lambda/\ln\lambda)^2} \quad \text{Eq. 4}$$

Leaching Methods

There are three types of leaching methods: (1) regulatory— those promulgated and approved by a regulatory agency to generate specific information for submission in a legal context; (2) standard methods are those adopted by a standards organization (ASTM, ISO) for a specific set of conditions and sometimes for specific materials; and (3) research methods developed for a particular objective. Most of this discussion deals with regulatory and standard methods, although examples of some commonly used research methods are included. Regulatory and standard methods are frequently used for research projects. However, results from different projects should be considered comparable only (1) if the method is appropriate to the problem studied; and (2) if the procedure is followed exactly.

Batch leaching methods are those in which a sample is placed in a given volume of leachant solution for a set period of time. Most of these methods require some type of agitation to insure constant contact between the sample and the leachant. At the end of the leaching period, the liquid is removed and analyzed. The most commonly used batch leaching methods are:

- C the Toxicity Characteristic Leaching Procedure (TCLP),
- C the Extraction Procedure Toxicity Test (EPTOX),

- C the Synthetic Precipitation Leaching Procedure (SPLP),
- C the Standard Test Method for Shake Extraction of Solid Waste with Water (ASTM-D3987), and
- C the California Waste Extraction Test (WET).

The Availability Test for Granular Materials (NEN 7341) is a Dutch Standard leaching test (Van der Sloot *et al.*, 1994), the Leachate Extraction Procedure (LEP) is a procedure approved by the Canadian General Standards Board, and the Synthetic Groundwater Leaching Procedure (Hasset, 2000) is a draft ASTM procedure for long-term leaching.

In serial batch methods, a sample of waste is leached successively with fresh aliquots of the same leaching fluid. This method is intended to eliminate the effect of concentration on solubility and to simulate long-term exposure to the leachant solution. These methods include:

- C EPA's Multiple Extraction Procedure (MEP),
- C the Standard Test Method for Sequential Batch Extraction of Waste with Acidic Extraction Fluid (ASTM D 5284), and
- C the Standard Test Method for Sequential Batch Extraction of Waste with Water (ASTM D 4793).

Column leaching tests are considered as simulating the flow of percolating groundwater through a porous bed of granular material. The flow of the leaching solution may be in either down-flow or up-flow direction and continuous or intermittent. The flow rate is generally accelerated when compared to natural flow conditions. However, it should be slow enough to allow leaching reactions to occur. A basic assumption in column leaching is that the distribution of the leaching solution is uniform and that all particles are exposed equally to the leachant solution. Precipitation or sorption within the column may affect the results.

The Standard Test Method for Leaching Solid Material in a Column Apparatus (ASTM D-4874) is intended to maximize the leaching of metallic species from a solid. The aqueous fluid passes through particles of known mass in a saturated up-flow mode. The Dutch Standard Column Test (NEN 7343) is also an up-flow application, and the Nordtest Column Method (NORDTEST) is similar to the Dutch Column test, except that column dimensions are optional. The up-flow column procedures are designed to insure that the leachant solution is equally distributed throughout the column. However, gravity flow columns also can be used to study leaching of porous media. Column experiments more closely approximate the flow conditions, particle size distribution and pore structure, leachant flow, and solute transport found in the field (Zachara and Streile, 1990). Column experiments can be conducted in both saturated and unsaturated conditions. Unsaturated conditions are usually intended to mimic vadose zone placement. Intermittent addition of a given volume of leachant solution at the top of the column can provide uniform distribution of the fluid and approximate a constant fluid front moving through the unsaturated column. Saturated columns are obtained by a constant fluid flux and allowing the fluid to pond at the top of the column. Variables, such as leachate collection, sampling frequency, leachant flow rate, and duration of the experiment are determined by the experimental objectives.

Sequential leaching tests use a single sample that is leached by a series of different leaching fluids. The constituents extracted with a particular leachant are associated with a particular mineral phase or chemical species. Speciation is considered one of the controlling factors in the potential release of cations to the environment. The USGS Sequential Leaching Method was developed as a rapid indirect method of determining the modes of occurrence of trace elements in coal (Palmer *et al.*, 1999). A Short Sequential Procedure uses two steps to assess the lability of heavy metals in soil particles (Maiz *et al.*, 2000). Like the later USGS sequential extraction procedure, Tessier (1979) uses a series of four extractant fluids to dissolve metals associated with particular ligand phases in a complex sample. A modified Tessier procedure uses aqua regia in place of hydrofluoric/nitric acid (Raksataya *et al.*, 1996). A three-step sequential extraction procedure developed by the commission of the European Communities Bureau of Reference (Quevavller *et al.*, 1994) also has been modified (Raksataya *et al.*, 1996) to include aqua regia digestion of the residual material.

Monolithic leaching methods are used to evaluate the release of elements from a material that normally exists as a massive solid, cement for example. They are frequently used to characterize the release of pollutants from stabilized waste materials. The release of an element is a function of the exposed surface area as opposed to the mass. Flow around systems relate solubility to the surface area of a particular volume. Flow through systems also consider the internal pore surface. And some systems take into account the rate of diffusion of the leachant solution into the

pores.

In static monolithic leaching, a particle of regular geometry and known surface area is immersed in a volume of leachant solution. The same leachant solution is sampled at defined intervals and replaced with fresh solution (Hoberg *et al.*, 2000). The flow through leaching test (Poon *et al.*, 2001) is used to characterize leaching from a waste that is more permeable than the surrounding material. The solid sample is placed in a flexible wall permeameter. The leaching solution is DI water at a mean flow rate of .0166 mL/min at a pressure of 400 kPa.

Bulk leaching generally refers to leaching large samples, either in a large column or in heaps. They are either industrial systems or used in a research setting to leach a nonhomogeneous sample with a large particle size and are not particularly applicable to fly ash. (ASTM Monolithic, ISO seawater)

The International Ash Working Group (IAWG) has designed a leaching protocol to quickly determine the total leachable elements in a material and to estimate metal release in a normal environmental setting (van der Sloot *et al.*, 1994; van der Sloot, 1998). An availability test is based on the extraction of fine-grained material at a L/S of 100 at a controlled pH of 4, which is assumed to be a lower pH limit found in natural environments. A second test at a pH of 8 is used to determine leachability of oxyanionic species. From the total acid consumption, the acid neutralization capacity of the material is estimated. Total elemental release as a function of time is estimated by leaching at different L/S values in a serial batch test. The release of contaminants is usually expressed in mg/kg leached against the L/S ratio.

Comparison of Leaching Methods

Several studies have attempted to compare different leaching methods, frequently in an attempt to correlate data from disparate techniques. Most comparisons were based on comparative release of particular elements by 2 or more specific procedures. Differences in such factors as test objective, leachant volume, sample size, and test duration were not considered.

In 1981, researchers at the Department of Energy/Los Alamos Scientific Laboratory (DOE/LASL) compared EPTOX with a procedure used at the laboratory (Heaton, *et al.*, 1981). The samples were coal preparation wastes. The LASL static leach procedure was similar to EPTOX and the release of RCRA elements was found to be comparable with both procedures.

The Electric Power Research Institute (EPRI) sponsored a round robin evaluation of TCLP and EPTOX (Mason and Carlile, 1986) that was intended to evaluate the reproducibility of the TCLP and compare the results to those obtained with EPTOX. Seven CCB samples were sent to each of three laboratories that performed duplicate determinations with both TCLP and EPTOX. For the individual procedures, most of the variability was related to consistent differences in the results from one of the three laboratories. When comparing the methods, the TCLP and EPTOX concentrations of 14 elements were comparable for approximately 60 percent of the determinations. Eighty-three percent of the concentrations determined with TCLP were equal to or greater than those determined with EPTOX.

In a report to EPRI (Zachara and Streile, 1990), static (batch) and dynamic (column) methods were compared. Based on a review of the literature, batch systems tend to be inexpensive, simple, and they generate chemical data for mechanistic applications. Column methods are more expensive and more operationally complex, but they generate results that reflect real systems subject to fluid flow and solute transport.

The Netherlands Energy Research Foundation (ECN) compared regulatory test procedures used in the United States, Canada, Germany, France, Switzerland, and the Netherlands (van der Sloot *et al.*, 1991). Although the effect of pH on release is established, the effects of changes in redox potential and the concentration of complexing agents, as well as the effect of temperature differences, are not known.

The European Commission on Normalization, through its technical committees, is addressing the integration of leaching methods for various materials. The committee on waste materials (CEN/TC292) addresses issues related to

disposal of wastes and also to by-products or secondary raw materials intended for reuse (van der Sloot *et al.*, 1998).

Leaching Methods Summary

Leaching can be described as the fluid extraction of a compound or element from a solid. It is an interactive process in which both leachant and solid variables control the results. The pH of the leachate, which is determined by the pH of the leachant and the alkalinity/acidity of the solid is generally recognized as a controlling factor. The effects of oxidation reduction potential, dissolution/precipitation equilibrium, complexation, temperature, and the concentration of dissolved CO₂ and O₂ is not addressed in most leaching methods.

Leaching methods include those to determine regulatory compliance, those approved by standards organizations, and methods developed for a particular objective. With exact duplication of regulatory or standard methods, there is a 60 to 80 percent probability that tests conducted by different laboratories with the same protocol will have comparable results. However, compliance tests and standard methods are not necessarily appropriate for leaching tests to simulate natural processes, obtain data on reaction mechanisms, or unravel complex solubility relationships. For these, it is necessary to select or develop a procedure that addresses the experimental objective, meets the procedural constraints, and produces data that is directly or functionally related to the problem being studied. Data obtained by different laboratories using standard or regulatory tests are probably comparable. Studies performed with different leaching methods do not necessarily produce comparable data, although researchers using different methods may arrive at similar conclusions.

Results of Laboratory CCB Leaching Studies

A number of researchers have addressed the release of captions, particularly heavy metals from coal combustion by-products (Reviews: Mattigod, Eary, EPRI). Many of these attempt to estimate the potential effects on groundwater if the CCBs are placed as bulk fills or used in mine remediation. Studies conducted during the last 25 years are summarized below. The disparity in leaching conditions, the duration of leaching and the different samples, make direct comparisons of results very difficult. However, the results of the individual studies can be correlated sufficiently to discern general trends. Leaching conditions for each study are summarized in Table 2, and results are summarized in Table 3.

RCRA Leaching Tests of CCB

The most common methods used to determine the environmentally “hazardous” characteristics of solid waste materials for RCRA purposes are TCLP and SPLP. Data on RCRA tests of CCB were obtained from surface mine permit files of the Pennsylvania Department of Environmental Protection (PADEP). Test results of 196 TCLP tests (Table 4) and 20 SPLP tests (Table 5) were reviewed (Kim and Cardone, 1997). There was one exceedence for mercury in the TCLP tests, and no exceedences in any of the SPLP tests. Approximately 33% of the values in the TCLP tests and approximately 75% in the SPLP tests were below detection limits.

Standard leaching protocols were used to determine the leachate concentrations from ash produced from various fuels including coal, waste coal, and petroleum coke (CIBO, 1997). For a total of 240 samples of fly ash, bed ash, and combined ash, one sample exceeded the RCRA limit for mercury (.29 mg/L) and one sample exceeded the RCRA limit for selenium (2.5 mg/L). In this sample population, the percentage of exceedences was less than one percent (0.8).

The results of both EPTOX and TCLP leaching tests on 17 samples of fly ash, bottom ash and FGD sledge are reported by EPRI (1987). In 34 tests, one sample exceeded the RCRA toxicity limit for arsenic and for chromium.

According to the results of the tests reviewed, less than one percent of CCB exhibit the characteristic of toxicity as determined by regulatory leaching tests.

Summary

There is a plethora of leaching protocols, regulatory, standard, and those commonly used for a specific purpose. The

research studies summarized used a variety of methods. In spite of the disparity of experimental conditions, some general conclusions are apparent.

- Almost all of the cations in CCBs, including the trace elements, are sparingly soluble at circumneutral pH.
- Most cations are more soluble in acid solutions.
- Those cations that form oxyanions are more soluble in basic solutions.
- The exceedence rate for RCRA metals as determined by regulatory leaching tests is less than one percent.

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Ann Kim is a Physical Scientist in the Environmental Science and Technology Division at the Department of Energy's National Energy Technology Laboratory. She currently serves as Team Leader for the By-Product Utilization Team in the Environmental Science and Technology Division. She is responsible for leading an in-house research team effort that includes determining environmental consequences of utilizing coal combustion by-products from conventional and innovative electricity producing systems. She is the primary author of more than 75 technical publications. She holds a BA in Chemistry/Physics from Carlow College, an MS in Earth and Planetary Science from the University of Pittsburgh, and an MS in Engineering Management from the National Technological University. She is currently completing her Ph.D in geochemistry at the University of Pittsburgh.

Table 1. Comparison of method parameters for static leaching methods.

Method	Leachant	Sample size, g	pH	L/S	Results as	Time, hr
ASTM	Water	70		20	mg/kg	18
EPTOX	Water	100	5.0	20	mg/L	24
LEP	Water	50	5.0	20		24
SPLP	Water acidified with nitric and sulfuric acids	100	4.2	20	mg/L	18
TCLP	Acetic Acid or Acetate Buffer	100	2.88	20	mg/L	18
CA WET						
NEN7341						
LEP						
SGLP						

Table 2. Summary of Experimental Parameters for Laboratory Leaching Experiments

Reference	Leach Type	CCB	Sample Size	Leachant Solution	Volume/Flow Rate	pH	Time
Dreher <i>et al.</i>	Column	FBC+CSS		H ₂ O	1 pore volume/wk	>8	15 wk
	Batch	FBC+CSS		H ₂ O	L/S = 4:1	>8	3 <> 180 d
Dreesen <i>et al.</i>	Batch	ESP FA		0.1 M citric acid 1.0 M Hcl 0.001 to 1.0 M HNO ₃ H ₂ O 0.1 M NH ₄ OH	L/S = 4:1		3 h
Dudas	Column	PC Fly Ash (Western Bituminous)	250 g	H ₂ O	124 L 245 L 421 L	> 12 to 8	2 yr max
Fishman <i>et al.</i>	Batch	“upstream” ESP FA “downstream” ESP FA		DI H ₂ O	L/S = 20:1	>8 <4	18 hr
Fleming <i>et al.</i>	Column	Coal FA MSW FA		Acetic Acid		3.0 4.1 6.8	
Griffin <i>et al.</i>	Batch	PC FA Char Slag		H ₂ O + NaOH H ₂ O + NaOH H ₂ O H ₂ O + HNO ₃	10% weight to volume	8.8 8.0 4.0 2.7	3-6 months
Hequet <i>et al.</i>	Batch	3 FA	5 g	H ₂ O Acetic Acid/Acetate buffer	L/S = 10:1	>6.5 2 4.6	24 hr
Hjelmar	Lysimeter	2 FA	10-18 t	Rain/snow			7 yr
	Column	2 FA	8-16 kg	SP	17-145 mm/d	>11	

Reference	Leach Type	CCB	Sample Size	Leachant Solution	Volume/Flow Rate	pH	Time
	Serial Batch	1 FA		H ₂ O	L/S = 2.5, 5.8		5 d
Karapanagiota & Atalay	Batch	Coal FA	10 g	H ₂ SO ₄	20 - 1900 mL	1	
		FBC FA				4	
Kim & Kazonich	Column	38 PC FA 2 non-utility FA 1 steel slag 5 FBC FA 1 BA 1 Weathered FA	1 kg	H ₂ SO ₄	~130 mL/d to 230 mL/d	1.2	From 15 d to > 6 mo
				H ₂ O		6	
				Acetic Acid		2.88	
				SGW		6.7	
				SP		4.2	
				FeCl ₃		1.95	
				NaCO ₃		12.1	
Nathan <i>et al.</i>	Batch	4 FA	1 kg	H ₂ O	2, 10, 20	>10	18, 24 hr
				Acetic Acid	20	>4	18 hr
Nugteren <i>et al.</i>	NEN7343	1 FA		H ₂ O	L/S = 10:1	4	3 wk
Paul <i>et al.</i>	Batch	Class F Uox FGD Ox FGD		HAc H ₂ O	L/S = 20		18 hr
	Column			Groundwater			<100 mL/d
Pritts <i>et al.</i>	TCLP	FGD + waste FBC + waste					
Querol <i>et al.</i>	Column	6 FA	2 g	H ₂ O	50 mL/hr		
	Batch	6 FA		DI H ₂ O	50 mL/g		24 hr
Rice <i>et al.</i>	Batch	FA, BA, Coal	10 g	H ₂ O	200 MI		18 hr

Reference	Leach Type	CCB	Sample Size	Leachant Solution	Volume/Flow Rate	pH	Time
	Batch	3 FA		H ₂ O	L/S = 20/1		< 1 hr
	Column	4 FA		H ₂ O	0.75:1 - 15:1		64 d
Roy & Griffin	Batch	5 FA	1700 g	DI H ₂ O	17 L	varied	140 d
Seidel <i>et al.</i>	Batch	FA	varies	H ₂ SO ₄	300 mL		24 hr
Seidel & Zimmels	Batch	FA		H ₂ SO ₄	300 mL		12 d
Shabtai & Mukmenev	Batch	FA	70 kg	H ₂ O & H ₂ SO ₄	230 L	0.9	2 hr
Steenari <i>et al.</i>	Batch	CFB		H ₂ O H ₂ SO ₄	L/S = 16		10 x 24
Stewart <i>et al.</i>	Column	FA + coal refuse		SP	2.5 cm/4 d	4.6	4 yr
	Column	FA + coal refuse	varies	SP	2.54 cm/wk		3 yr
Talbot <i>et al.</i>	Batch	Ponded FA ESP FA	1 g	H ₂ O	L/S = 1000		~ 6 months
	Batch			H ₂ O		1 <> 12	1 wk
Teixeira <i>et al.</i>	EPTOX	PC FA		H ₂ O, HAc	16/1	5	24 hr
	INSA	PC FA	100 g	H ₂ O	3 x 1 L	>9	3 x 24 hr
	Column	PC FA	100 g	H ₂ O	20 L	>9	546 hr
Theis & Wirth	Sequential	11 FA		NH ₄ Oxalate			
				Hydroxylamine Hydrochloride			
				H ₂ O	200 g/L	varied	24 hr

Table 3. Summary of Laboratory Leaching Studies of CCB.

Reference	Publication Date	Summary of Results
Dreher <i>et al.</i>	1990	B, Ni, Mo, Se and Sr reported in alkaline leachate generated by FBC ash
Dreesen <i>et al.</i>	1977	Maximum extraction = 30% in strongly acid solution
Dudas	1981	Initial release of cations from simple salts, followed by dissolution of glassy ash matrix.
Eary <i>et al.</i>	1990	Trace elements acid soluble; pH controlled leaching of FA
Fishman <i>et al.</i>	1997	Ash spheres coated with soluble poorly crystalline aluminum potassium sulfate
Fleming <i>et al.</i>	1996	Acid leachable Cd, Cr, Al, Pb, Hg and Ag assumed to be present as oxides
Griffin <i>et al.</i>	1980	Concentration of Al, B, Be, Ca, Cd, Cu, Co, Mg, Mn, Ni, Si, Sr, and An increased at low pH; K, Mo and Na more soluble at high pH
Hequet <i>et al.</i>	1999	Cu and Zn absorbed from solution on FA, <1% Cu and <15% Zn released by subsequent leaching with H ₂ O, higher % released in acid, acetate buffer
Hjelmar	1990	Na and K leached initially; Ca dominates long-term leachate. Concentration decreases with increased L/S
Karapanagioti and Atalay,	1996	AMD metals absorbed by alkaline CCB>pH=4. Metals released at pH=1. Buffer capacity related to Ca in ash
Kim & Kazonich	2001	Solubility not a function of concentration in solid; solubility influenced by pH, <50% of metal extracted
Mattigod <i>et al.</i>	1990	Ca, Na, K released initially; negligible Fe, Mg, Si and Al released. Water releases <10% of Ca and Na;
Nathan <i>et al.</i>	1997	Release of heavy metals related more to source of coal than to pH of leachate
Nugteren <i>et al.</i>	1999	Washing FA with buffers reduced Cr, Mo, Sb, Se, and V leached from residues
Paul <i>et al.</i>	1994	Some elements absorbed from groundwater by CCB. ASTM was considered superior to TCLP
Querol <i>et al.</i>	2001	Water soluble major and trace elements more soluble in open

Reference	Publication Date	Summary of Results
Rice <i>et al.</i>	1999	pH of leachate is controlling factor, soluble aluminum potassium sulfate (APS) coating absorbed on glassy particles; Cd, Co, Cu, Mn, Ni, Pb, and Zn are acid leachable, As, Mo, and V soluble in alkaline leachates
Roy & Griffin	1984	Anhydrite controlled release of Ca; Al in equilibrium with mullite and insoluble hydroxide
Seidel <i>et al.</i>	1999	Calcium sulfate precipitation on particles inhibit the solubility of Al
Seidel and Zimmels	1998	30% of the Al and Fe in the ash leached, formation of porous layer of calcium sulfate inhibits solubility. 90% of the Ca, As, Cd, Cr, Cu, Hg, Pb and Zn were extracted at a pH <1
Steenari <i>et al.</i>	1997	80% of the Ca soluble in acid, less than 20% of K was leached from the fly ash samples
Stewart Stewart Stewart <i>et al.</i>	1995 1996 1997	Coal ash buffered acid formations from coal refuse. Alkalinity from CCB limits oxidation of pyrite in the coal refuse; metal release at low pH
Talbot <i>et al.</i>	1978	Fe, Al, Si - acid soluble; Ca, Mg, Na solubility not pH dependent below 10
Teixeira	1992	Ca & Mg acid and alkaline soluble; Na & K more soluble in alkaline solution. Mn, Ni, Co, and Cu soluble in acid; Mo, Cr, and V alkaline soluble. Trace element solubility < 20%
Theis & Worth	1977	Mullite, hematite and magnetite on the surface of amorphous particles controlled the release of trace elements. Except As, elements acid soluble.
Yaman & Kucukbayrak	1997	alkaline fly ash extract neutralized the sulfuric acid produced in the oxydesulfurization of Turkish lignite

