The Fate of Mercury in Coal Utilization By-Products - DOE/NETL's Research Program

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The U.S. Department of Energy/National Energy Technology Laboratory (DOE/NETL) is conducting research and development (R&D) directed at increasing the beneficial use of coal utilization by-products (CUB). The goal is to increase the beneficial use of CUBs from 35% today to 50% by 2010. This article provides a summary of DOE/NETL's research on the environmental characterization and fate of mercury in CUB disposal and utilization applications.

INTRODUCTION

Coal utilization by-products (CUB) (also known as "coal combustion by-products" or "coal combustion products") are produced by the combustion or gasification of coal and include fly ash, bottom ash, boiler slag, gasifier ash and slag, and flue gas desulfurization (FGD) solids. The American Coal Ash Association (ACAA) estimates that in 2002 a total of approximately 129 million tons of CUB were produced in the United States.[1] Approximately 83 million tons (65%) of the CUBs were disposed of in either landfills or impoundments, while the remaining 46 million tons (35%) were recycled for use in a variety of beneficial applications. Some of the major beneficial applications for CUBs include use as a partial substitute for cement in concrete (fly ash), structural fill material (bottom and fly ash), blasting grit (boiler slag), and wallboard manufacture (FGD gypsum). Mine reclamation can represent a large-volume beneficial use application for several types of CUBs, especially fluidized bed combustion (FBC) ash, whose alkaline properties make the ash useful for remediating acidic mine backfills. Other smaller volume beneficial applications for fly ash include use as mineral filler for paints, roofing shingles, carpet backing, ceiling and floor tile, and many other building materials and industrial products.[2]

CUBs from coal-fired power plants are composed primarily of benign mineral components, but can also contain trace elements such as aluminum, arsenic, boron, cadmium, lead, mercury, and selenium. Testing conducted to date by DOE/NETL and others indicate there is minimal potential release of these trace elements from CUBs through leaching. CUBs from coal-fired power plants are regulated by the EPA under the Resource Conservation and Recovery Act (RCRA). Hazardous wastes are federally regulated under RCRA Subtitle C, while non-hazardous wastes are state regulated under RCRA Subtitle D. In its 1999 Report to Congress, EPA determined that CUBs did not generally exhibit the characteristics of a hazardous waste. Consequently, CUBs are currently categorized as non-hazardous wastes under RCRA and most state regulations. The continued regulatory categorization of CUBs as non-hazardous solid wastes is obviously an important factor in minimizing the cost of disposal and is critical to CUB marketability for beneficial use applications.

Future mercury emission reduction regulations for U.S. coal-fired power plants could result in higher concentrations of mercury in CUBs that lead to greater concern over their environmental characteristics in both disposal and utilization applications. Mercury control technologies currently available for coal-fired power plants include sorbent injection and co-benefit reductions using wet FGD systems. For plants using sorbent-injection technology, the spent sorbent can either be collected along with fly ash in an existing electrostatic precipitator or fabric filter, or collected separately in a downstream fabric filter. DOE/NETL is collecting data on the stability of mercury in fly ash and FGD solids as well as during the high-temperature wallboard manufacturing process using FGD gypsum.

DOE/NETL CUB RESEARCH PROGRAM

The U.S. Department of Energy/National Energy Technology Laboratory (DOE/NETL) is conducting a comprehensive research and development (R&D) program to continue to enhance the environmental performance of the current fleet of coal-based power systems. The goal of the DOE/NETL CUB research activity is to increase coal by-product use in the United States from current levels of about 35% to 50% by 2010. Achieving this goal will be challenging in four respects. First, increasing concern over the fate of mercury and other trace metals removed from the power plant flue gas and captured in by-products will bring about increased scrutiny as to how these materials are to be utilized and disposed. Second, the installation of FGD technology to comply with SO_2 regulations could significantly increase the amount of solid material generated by coal-fired power plants. Third, the injection of sorbents such as activated carbon to control mercury could negatively impact the sale of fly ash and FGD gypsum for cement and wallboard. Finally, nitrogen oxide (NOx) controls could also negatively impact the beneficial utilization of fly ash due to excessive levels of unburned carbon and/or ammonia.

This article addresses DOE/NETL's research on the fate of mercury in CUB disposal and utilization applications. The research includes testing of various CUB materials for potential environmental release mechanisms such as leaching, volatilization, and microbiological transformation. Table 1 lists the ongoing research projects whose focus is on the environmental fate of mercury in CUBs; the first two projects in Table 1 are especially relevant to recent concerns because they are examining the extent to which mercury is released from CUBs that are being generated when new mercury control technologies are employed at coal-fired power plants. Descriptions of these projects and the other projects in Table 1 are found in subsequent sections of this article. Test results to date indicate there is minimal potential release of mercury from CUBs in either disposal or beneficial use applications.

While much of the current research is focused on the fate of mercury, the impact of other trace metals such as arsenic, boron, selenium and non-trace-metal contaminants such as ammonia and activated carbon are also being evaluated. Table 2 presents a list of DOE/NETL's other CUB environmental characterization research projects. In addition, DOE/NETL directs a significant research effort toward the development of new and expansion of existing markets for CUBs. Additional information on all of DOE/NETL's CUB projects can be found at:
http://www.netl.doe.gov/coalpower/environment/ccb/index.html.

As shown in Tables 1 and 2, many of the DOE/NETL environmental characterization projects are being conducted through two consortia - CARRC and CBRC. Since 1998, DOE/NETL has sponsored the Coal Ash Resources Research Consortium (CARRC). CARRC is an international consortium of industry and government representatives, scientists, and engineers working together to advance coal ash utilization and is administered by the University of North Dakota Energy & Environmental Research Center (UNDEERC). Additional information on CARRC can be found at: http://www.undeerc.org/carrc/. Also formed in 1998, DOE/NETL's Combustion By-Products Recycling Consortium (CBRC) is administered through West Virginia University's

Water Research Institute. Academia, industry associations, federal and state regulatory agencies, and power generators provide assistance to CBRC through an advisory steering committee. Additional information on CBRC can be found at: http://wvwri.nrcce.wvu.edu/.

The following sections provide a brief description and summary of results from several of the DOE/NETL R&D projects that focus on the fate of mercury in CUBs.

CUB Analysis from Activated Carbon Injection Mercury Control Field Demonstrations

ADA-ES and Reaction Engineering International have conducted leaching tests of the ash by-products sampled during field testing of activated carbon injection (ACI) for mercury control conducted in 2001 and 2002 at four power plants - Alabama Power's E.C. Gaston, PG&E's Brayton Point, We Energies' Pleasant Prairie, and PG&E's Salem Harbor.[3, 4, 5, 6] It is expected that ACI may be a popular choice for mercury control at these and other plants that burn low-sulfur coals. In order to understand the results of the leaching tests, it is first necessary to describe the conditions under which the byproducts were generated at each plant

Mercury Control Test Site CUB Descriptions. The particulate collection configuration at the Gaston Plant was somewhat unique because it included both a hot-side ESP for primary particulate collection and a compact hybrid particulate collector (COHPAC) fabric filter bag house downstream of the ESP. During mercury control testing, the activated carbon was injected downstream of the ESP and upstream of the COHPAC to prevent carbon contamination of the ESP ash. The mercury concentration in the baseline (pre-ACI injection) ash from the COHPAC at Gaston was approximately 0.2 to 2 microgram per gram (μg/g); at an ACI feed rate of 1.5 pounds per million actual cubic feet (lb/MMacf) of flue gas, the combined activated carbon/ash by-product ranged from 10 to 50 μg/g mercury. Since most of the fly ash was captured in the hot-side ESP, the total mercury concentration in the COHPAC by-product was significantly higher than it would be in applications with ACI located upstream of the primary particulate control device.

The Brayton Point particulate collection system was also somewhat atypical because two cold-side ESPs were used in series. Most of the fly ash was collected in the upstream ESP; during mercury control testing, activated carbon was injected in between the upstream and downstream ESPs. The baseline ash from both the upstream and downstream ESPs contained 0.2 to 0.53 µg/g mercury; at an ACI feed rate of 10 to 20 lb/MMacf, the downstream ESP ash contained approximately 0.4 to 1.4 µg/g mercury. The reason for the relatively low mercury content of the downstream ESP ash at Brayton Point (compared to the Gaston COHPAC ash) is that most of the mercury in the flue gas was not captured by the activated carbon, but was captured by the fly ash in the upstream ESP. Apparently the unburned carbon in the fly ash was sufficient, on its own, to achieve a high degree of mercury capture across the upstream ESP, leaving only a small amount to be collected by ACI and the downstream ESP. However, because the mercury captured by the upstream ESP was diluted with the bulk of the ash product, total mercury concentration in the ash was very low.

The particulate collection systems at Salem Harbor and Pleasant Prairie were more typical of existing plants (one cold-side ESP unit at each plant), except that the ESP specific collection areas (collection plate area divided by flue gas flow rate) were comparatively large. Baseline ash from the Pleasant Prairie ESP contained less than 0.5 µg/g mercury; at an ACI feed rate of 10 lb/MMacf, the ash by-product contained approximately 0.5 to 5 µg/g mercury. At Salem Harbor, ash Hg concentrations ranged from approximately 0.1 to 0.7 µg/g during both baseline and ACI testing conditions. As at Brayton Point, much of the Hg in the flue gas at Salem Harbor was collected by the carbon in the baseline fly ash, with comparatively little additional Hg removal via ACI, thereby minimizing the addition of Hg to the ash as the result of ACI.

Leaching Test Descriptions and Results. Leaching analyses were conducted using the standard toxicity characteristic leaching procedure (TCLP) and another procedure developed by UNDEERC known as the synthetic ground water leaching procedure (SGLP) on the combined activated carbon-fly ash by-products that were collected during the ACI testing. The TCLP method was designed to simulate leaching in an unlined sanitary landfill and typically an acetic acid solution is used as the leaching solution. UNDEERC developed the SGLP method to more realistically simulate leaching of CUBs in typical disposal environments. In SGLP, deionized water is used as the leaching solution with a 20:1 liquid to solid ratio.

A summary of the leaching test results for the ash by-products at the four ACI test plants is shown in Table 3. For the Gaston and Pleasant Prairie ash samples, the amount of mercury in the leachate was at or below the 0.01 microgram per liter (µg/L) measurement detection limit. At Salem Harbor, only one sample exceeded the detection limit (0.034 µg/L); this sample came from the baseline (no ACI) ash. At Brayton Point, leachate of samples from both the non-treated (upstream) ESP and the ACI-treated (downstream) ESP contained detectable amounts of mercury (0.01 to 0.07 µg/L). However, no discernable differences in leachate concentrations were found between the upstream and downstream ESP, or at different levels of ACI injection. Again, this appears to be related to the fact that most of the Hg removal at Brayton Point occurred as the result of high carbon levels in the baseline ash. It should be noted that the leachate mercury concentrations at all plants were more than an order of magnitude lower than the 0.77 µg/L freshwater criterion continuous concentration (CCC) and 1.4 µg/L freshwater criterion maximum concentration (CMC) for mercury under the federal EPA water quality criteria for protection of aquatic life.

Ash by-product samples from Gaston and Pleasant Prairie were also tested using other leaching procedures for comparison to the standard TCLP and SGLP. Samples from Gaston were analyzed using a sulfuric acid leaching solution at a pH of 2 using procedures similar to TCLP and SGLP in order to simulate utilization in an acid mine drainage environment. Ash by-product samples from Pleasant Prairie were analyzed using the ASTM water leaching procedure (ASTM D-3987). Pleasant Prairie samples were also leached over longer times (30 and 60 day) using SGLP due to concerns with potentially slower reactions that can take place with high calcium ashes. All of the additional test results were below or equal to the 0.01 µg/L detection limit.

CUB Analysis from Wet FGD Reagent Mercury Control Field Demonstrations

In 2001, Babcock & Wilcox and McDermott Technology, Inc. (B&W/MTI) carried out full-scale field testing of a proprietary liquid reagent to enhance mercury capture in coal-fired power plants equipped with wet FGD systems.[7] The field testing was conducted at two power plants, Michigan South Central Power Agency's 60 MW Endicott Station and Cinergy's 1300 MW Zimmer Station. Both plants burn Ohio high-sulfur bituminous coal and use cold-side ESPs for particulate control. The Endicott Station utilizes a limestone wet FGD system with in-situ forced oxidation, while the Zimmer Station utilizes a magnesium-enhanced lime wet FGD system with ex-situ forced oxidation.

Table 4 presents a summary of the average mercury concentration for the coal and process by-product stream samples for both Endicott and Zimmer. For both plants, the majority of mercury was found in the wet FGD slurry fines, rather than in the gypsum. Although not shown in the table, the majority of liquid stream samples were non-detects for mercury (less than 0.5 μg/L), with a few samples measuring from 1.0 to 3.0 μg/L.

B&W/MTI also evaluated the by-product stream samples for their potential to volatilize mercury at elevated temperatures using a thermal dissociation test (TDT) developed by MTI. The TDT method involves the gradual heating of a CUB test sample in an oven while measuring the off-gas mercury concentration. Results of TDC testing for Endicott and Zimmer FGD gypsum indicated there is minimal mercury volatilization below 140°C (284°F) and a peak at approximately 250°C (482°F). The 140°C hold temperature was chosen as representative of temperatures FGD by-products are likely to encounter when used as feedstocks in wallboard manufacturing processes. However, some wallboard manufacturing processes may involve exposure of FGD by-products to slightly higher temperatures than 140°C; therefore, NETL is sponsoring additional research (described later in this paper) to determine the fate of mercury in wallboard manufacturing facilities.

One of the significant findings from the B&W/MTI test program was that the mercury in the wet FGD waste slurry from both plants was associated primarily with the fines and not bound to the larger gypsum particles. Therefore, it may be possible to use particle separation techniques and provide separate landfill disposal of the fines if necessary for beneficial use applications of gypsum where mercury release is a concern.

CUB Analysis from Ash and FGD By-Product Disposal and Beneficial Use Applications

CONSOL Energy CUB Mercury Release Study. CONSOL Energy is conducting an extensive evaluation of mercury in CUBs from 14 coal-fired power plants.[8, 9] The project began in August 2000 and is scheduled for completion in October 2004. The plants represent a range of coal ranks and air pollution control device (APCD) configurations. The evaluation includes leaching and volatilization tests of bottom ash, fly ash, wet and dry FGD scrubber solids, and products from activated carbon injection tests. Testing is also being conducted on products made from CUBs such as cement, gypsum wallboard, and manufactured aggregates. In addition, ground water monitoring wells at two CUB disposal sites are being evaluated for mercury quarterly over one year.

Mercury leaching rates from 8 different CUBs, representing fly ashes, bottom ashes, FGD sludges, and spray dryer ashes, were measured using TCLP tests with leaching solutions at three pHs (2.8, 4.9, and distilled water). Mercury concentrations in all leachates were less than the 1 µg/L detection limit. (Note: These leaching tests were conducted for screening purposes; the detection limit was relatively high but was below the drinking water standard of 2 µg/L.) Six leachate samples from fly ashes at two sites (3 samples per plant) were tested at a lower mercury detection limit of 0.0002 µg/L. The mercury concentrations from these six samples ranged from 0.0075 µg/L to 0.084 µg/L.

Mercury volatilization tests were conducted using a procedure developed by CONSOL. The CUB sample was split into two ovens and held constant at 100°F (38°C) and 140°F (60°C) for six months. Some preliminary results from the fly ash volatilization testing are shown in Table 5. The volatilization test results indicate a slight increase in mercury concentration in the CUB solids over time, suggesting the possibility the ash samples could have adsorbed additional mercury from the ambient air.

Ground water monitoring wells at an active wet FGD disposal area and an active fly ash slurry impoundment are being evaluated quarterly over one year for possible mercury release. Samples from the monitoring wells are analyzed with a detection limit of 1.0 µg/L. Preliminary results for the first and second quarter samples from the FGD disposal site indicate less than 1.0 µg/L mercury concentration for all six monitoring wells and two seepage sites. Likewise, the first quarter results for the ash impoundment site indicate less than 1.0 µg/L mercury concentrations for all eleven monitoring wells and one leachate site.

UNDEERC CUB Mercury Release Studies. UNDEERC is conducting a multi-faceted set of experiments to determine the level of mercury that may volatilize from CUBs and the potential for microbiological activity to release mercury from CUBs.[10, 11] Mercury vapor release tests were conducted on six fly ash samples at ambient and near-ambient (37°C/99°F) temperatures and microbiological tests were conducted on two of the samples. The fly ash samples were from two PRB coals, two eastern bituminous coals, and two South African coals. The fly ashes were selected because of their relatively high mercury concentrations (range of 0.112 to 0.736 μg/g) and corresponding potential for releasing measurable amounts of mercury vapor. However, as in the CONSOL volatilization experiments, five of the six samples acted as mercury sinks (i.e., the mercury content of the ashes increased over time); for the sixth sample, its behavior as a mercury source or sink could not be determined.

Results from the microbiological testing are not yet available because the testing protocols have recently been redesigned to take advantage of improved analytical procedures for determining organomercury and methyl mercury species that may be produced via microbiological processes. Preliminary results suggest that microbiologically-mediated vapor releases of mercury from CUBs may be somewhat greater than in non-microbiologically-mediated experiments, but are still very low (less than 60×10^{-12} g/g). Microbiologically-mediated mercury releases appeared to be enhanced when aerobic conditions and a ready food source for bacteria were present.

Fate of Mercury in Synthetic Gypsum Used for Wallboard Production

TVA Wallboard Study. Tennessee Valley Authority (TVA) is conducting a CBRC funded laboratory study to examine thermal decomposition profiles and leaching characteristics of mercury in wet FGD by-product materials and gypsum wallboard. The one-year study is scheduled for completion in 2004. The study includes mercury measurements using a laboratory-scale wallboard manufacturing process. Due to the relatively low mercury concentrations, analysis of these materials will be accomplished using CVAF spectroscopy. Results from this study are not yet available.

USG Wallboard Study. In July 2004, USG Corporation signed a Cooperative Agreement with DOE/NETL to perform a two-year study to measure potential losses of mercury from synthetic FGD gypsum during the wallboard manufacturing process. Testing will be conducted at three wallboard manufacturing plants using synthetic FGD gypsum produced from four power plants. The four power plants represent a broad cross-section of synthetic gypsum sources including bituminous- and Texas lignite-fired boilers, with and without selective catalytic reduction (SCR) NOx controls, and limestone- and lime-FGD processes. The field testing includes mercury measurements of all input and output process streams in order to obtain complete mercury balances for the wallboard manufacturing plants. Samples of the synthetic FGD gypsum will also be evaluated in laboratory simulation tests as a means of comparison to the field measurements. In addition, TCLP leaching tests will be conducted on the wallboard products to determine potential mercury release in municipal landfills. Testing at the first wallboard plant began in July 2004; the project is scheduled for completion by October 2005.

CUB Analysis for Mercury Control Technology Field Testing in 2004-05

DOE/NETL issued a competitive solicitation in July 2004 for selection of one or more contractors to conduct independent laboratory analysis of CUBs generated during DOE/NETL's mercury control technology field testing being conducted at 14 coal-fired power plants in 2004-05. The purpose of the solicitation is to ensure accurate and consistent laboratory procedures are used to determine the environmental fate of mercury in the CUBs.

DOE/NETL IN-HOUSE CUB RESEARCH

An important part of the overall CUB research program is the environmental characterization evaluations performed by DOE/NETL's in-house research team. The in-house research effort is directed at providing an unbiased source of data on the environmental characteristics of coal by-products and developing new CUB end-use applications. Recent research has focused on the development of a short-term leaching test that can be used by industry and state regulatory agencies to inexpensively design appropriate coal by-product management strategies. DOE/NETL's in-house CUB research projects related to mercury are summarized below.

Column Leaching Tests

DOE/NETL has been conducting column leaching tests on numerous CUB samples using seven different leachant solutions - deionized water, synthetic ground water, synthetic precipitation, acetic acid, sodium carbonate, sulfuric acid, and ferric chloride.[12, 13, 14] In one study, leaching tests were conducted on 38 fly ash samples collected from pulverized coal power plants across the United States. Leachate samples were analyzed for iron, aluminum, manganese, magnesium, calcium, sodium, potassium, sulfur, arsenic, barium, beryllium, cadmium, cobalt, chromium, copper, nickel, lead, antimony, selenium, and zinc.

Table 6 presents a summary of column leaching test results for mercury. The data are presented in terms of cumulative leached mercury measured in nanogram per gram (ng/g) of sample. (Note: A nanogram is equivalent to 10^{-9} gram.) Leaching tests were shutdown once leachant concentration had fallen below the measurement detection limit. As a result, the leaching tests vary in duration from 30 to 180 days. Although the data appear to vary, with one exception, all of the leaching results indicate less than 0.001% of the mercury leached from the ash samples. The exception is Sample #FA58 which leached approximately 0.006% of the mercury using the sodium carbonate leachant.

Rapid Leaching Protocol

The laboratory column leaching test described above is not always practical for evaluation of CUBs for beneficial applications since it is time consuming and requires significant analytical support. However, the column leaching method test results are being used by DOE/NETL to develop a simpler, short-term, rapid leaching protocol that can be used as a screening method for analysis of environmental characteristics associated with CUB applications. The rapid leaching protocol is based on determination of the CUB's availability for leaching. The availability test includes a serial-batch test using different liquid-to-solid (L/S) ratios at controlled pH's of 8, 4, 2, and the natural pH of the material, if higher than 8. Changes in leaching and the total amount of leaching as a function of time can be assessed by testing at different L/S ratios. The continuous addition of water to the CUB material simulates the cumulative addition of natural precipitation over a period of time. If successful, the rapid leaching protocol could provide leaching results in only two to three days.

Mercury Adsorption Capacity of CUBs

DOE/NETL in-house is also conducting tests to measure the mercury adsorption capacity of various fly ashes.[12] The adsorption tests are conducted by mixing fly ash in a water solution that is spiked with a known amount of mercury. Adsorption isotherms are calculated for each fly ash sample that plot the amount of mercury adsorbed versus the amount of mercury in solution. Based on adsorption tests of two bituminous fly ash samples it appears that carbon content is a significant ash property affecting adsorption, with high-carbon ash having a higher mercury adsorption capacity than low-carbon ash. For example, at a solution pH of 2 and 1,000 μg/L of mercury in solution, the high-carbon ash (5.2% LOI) adsorbed approximately 20,000 μg/kg mercury compared to approximately 2,500 μg/kg mercury for the low-carbon ash (1.3% LOI).

SUMMARY

DOE/NETL's CUB research has helped to further our understanding of the environmental characteristics related to both the disposal and beneficial utilization of coal by-products. Some general observations can be drawn from results of the research that has been carried out to date:

- There appears to be only minimal mercury release to the environment in typical disposal or utilization applications for CUBs generated using activated carbon injection control technologies.

- There appears to be only minimal mercury release to the environment in typical disposal and utilization applications for CUBs generated using wet FGD control technologies. The potential release of mercury from wet FGD gypsum during the manufacture of wallboard is still under evaluation.

- The amount of mercury leached from CUB samples tested by DOE/NETL has been significantly lower than the federal EPA drinking water standards and water quality criteria for protection of aquatic life; in many cases, leachate concentrations were below standard test method detection limits.

DOE/NETL will continue to partner with industry and other key stakeholders in carrying out research to better understand the fate of mercury and other trace elements in the by-products from coal combustion.

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DISCLAIMER

References in this article to any specific commercial product or service are to facilitate understanding and do not imply endorsement by the U.S. Department of Energy.

Table 1 - DOE/NETL CUB Research Projects Focused on the Fate of Mercury

Project Title	Lead Company
CUB Analysis from Activated Carbon Injection Mercury Control Field Demonstrations	ADA-ES and Reaction Engineering
CUB Analysis from Wet FGD Reagent Mercury Control Field Demonstrations	Babcock & Wilcox
Characterization of Coal Combustion By-Products for the Re-Evolution of Mercury into Ecosystems	CONSOL Energy
Mercury and Air Toxics Element Impacts of Coal Combustion By-product Disposal and Utilization	UNDEERC
The Effect of Mercury Controls on Wallboard Manufacture	CBRC - TVA
Fate of Mercury in Synthetic Gypsum Used for Wallboard Production	USG
Column Leaching Tests	NETL In-house
Rapid Leaching Protocol	NETL In-house
Mercury Adsorption Capacity of CUB	NETL In-house

Table 2 – Other DOE/NETL CUB Environmental Characterization Research Projects

Project Title	Lead Company
Water Quality Monitoring at an Abandoned Mine Site	CBRC - USGS
Varra Coal Ash Burial Project	CBRC - CGRS
Environmental Performance Evaluation of Filling and Reclaiming a Surface Coal Mine with Coal Combustion By-products	CBRC - Ish, Inc.
Effects of Large-Scale CCB Applications on Ground Water: Case Studies	CBRC - West Virginia University
Boron Transport from Coal Combustion Product Utilization and Disposal Sites	CBRC - Southern Illinois University
Effects of Ammonia Absorption on Fly Ash Due to Installation of SCR Technology	CBRC - GAI Consultants
Speciation and Attenuation of Arsenic and Selenium at Coal Combustion By-Product Management Facilities	EPRI
The Impact of Adsorption on the Mobility of Arsenic and Selenium Leached from Coal Combustion Products	CBRC - Southern Illinois University
Soil Stabilization and Drying by Use of Fly Ash	CBRC - University of Wisconsin
Environmental Evaluation for Utilization of Ash in Soil Stabilization	CARRC - UNDEERC
Environmental Effects of Large-Volume FGD Fill	CBRC - GAI Consultants
Flue Gas Desulfurization By-products Provide Sulfur and Trace Mineral Nutrition for Alfalfa and Soybean	CBRC - Ohio State University
Quantifying CCBs for Agricultural Land Application	CBRC - UNDEERC
CUB as Capping Material	NETL In-house

Table 3 - ADA-ES Leaching Test Results for ACI Ash By-Products

		ACI Rate, lb/MMacf	Mercury in Solid, µg/g	Mercury in Leachate, µg/L	
				TCLP	SGLP
Gaston	COHPAC B-Side	1.5	10 – 50	0.01	BDL*
Gaston	COHPAC B-Side	1.5	10 – 50	N/A+	BDL
Gaston	COHPAC B-Side	1.5	10 - 50	BDL	BDL
Pleasant Prairie	ESP Hopper Composite	10	0.5 - 5	BDL	BDL
Pleasant Prairie	ESP Hopper Composite	10	0.5 - 5	BDL	BDL
Pleasant Prairie	ESP Hopper Composite	10	0.5 – 5	BDL	N/A
Brayton Point	Downstream ESP	0	0.2 – 0.53	BDL	0.01
Brayton Point	Upstream ESP	0	0.2 – 0.32	0.02	0.05
Brayton Point	Downstream ESP	10	0.4 – 1.4	0.07	0.03
Brayton Point	Upstream ESP	10	N/A	0.03	0.01
Brayton Point	Downstream ESP	20	0.4 – 1.4	BDL	0.01
Brayton Point	Upstream ESP	20	N/A	0.02	0.02
Salem Harbor	ESP Row A	0	0.1 – 0.7	0.034	BDL
Salem Harbor	ESP Row A	10	0.1 – 0.7	BDL	BDL
Salem Harbor	ESP Row A	10	0.1 – 0.7	BDL	BDL

*BDL = Below Detection Limit of 0.01 µg/L +N/A = Not Available

Table 4 - B&W/MTI Mercury Concentration in Process Samples

	Mercury, µg/g (dry)	
Process Sample	Endicott	Zimmer
Coal	0.21	0.15
ESP Ash	0.32	0.016
Gypsum	0.70	0.055
Wet FGD Slurry	0.76	0.49
Wet FGD Fines	38 (by TDT)	13.3

Table 5 - CONSOL Fly Ash Mercury Volatilization Test Results

Plant I.D.	CUB Type	Control Equipment	Coal Source	Mercury in Solid CUB, µg/g				
				As Received	3 Month		6 month	
					100°F	140°F	100°F	140°F
3	Bottom ash	Mg Lime FGD	Ohio high sulfur bituminous	0.09	0.09	0.10	0.12	0.17
6	Fly ash	ESP	IL/W.KY blend bituminous	0.29	0.34	0.32	0.38	0.34
6	Fly ash	ESP	IL/W.KY blend bituminous	0.19	0.22	0.25	0.28	0.24
6	Fly ash	ESP	IL/W.KY blend bituminous	0.69	0.72	0.69	0.69	0.69
4	Fly ash	ESP	Illinois No.6 bituminous	0.08	0.11	0.12	0.13	0.12
4	Fly ash	ESP	Illinois No.6 bituminous	0.08	0.09	0.10	0.11	0.13

Table 6 - NETL Column Leaching Test Results for Mercury

Ash Sample #	Source	Mercury ng/g	LOI %	Cumulative Leached Mercury, ng/g				
				Leachant Solution				
				H_2O	HAc	Na_2CO_3	SP	H_2SO_4
FA50	NETL pilot combustor	1,156	1.31	0.259	0.410	0.130	0.094	0.148
FA53	NETL pilot combustor	1,091	2.45	0.010	0.112	0.008	0.015	0.025
FA56	NETL pilot combustor	1,209	1.89	0.005	0.146	0.058	0.023	0.042
FA52	Carbon injection ash - Gaston	88,100	28.66	0.003	0.047	0.026	0.003	0.004
FA55	Carbon injection ash - Brayton Point	1,527	16.08	0.846	0.043	1.263	0.465	0.083
FA51	Power plant	1,587	6.46	0.012	0.754	0.007	0.009	0.020
FA58	NETL pilot combustor	87	1.79	0.015	0.045	0.517	0.0005	0.012

References

[1] 2002 *Coal Combustion Product Survey.* American Coal Ash Association. http://www.ACAA-USA.org

[2] *Buyer's Guide to Coal Ash Containing Products.* University of North Dakota, Energy & Environmental Research Center. http://www.undeerc.org/carrc/BuyersGuide/default.asp

[3] Senior, Constance et al. *Characterization of Fly Ash From Full-Scale Demonstration of Sorbent Injection for Mercury Control on Coal-Fired Power Plants.* Presented at Air Quality III Conference, Arlington, VA, September 2002.

[4] Senior, Constance et al. *Characterization of Fly Ash From Full-Scale Demonstration of Sorbent Injection for Mercury Control on Coal-Fired Power Plants.* Presented at Mega Symposium, Washington, DC, May 2003.

[5] Senior, Constance et al. *Characterization of Fly Ash From Full-Scale Demonstration of Sorbent Injection for Mercury Control on Coal-Fired Power Plants.* Presented at Air Quality IV Conference, Arlington, VA, September 2003.

[6] Feeley, Thomas et al. *DOE/NETL's Mercury Control Technology Research Program for Coal-Fired Power Plants*; *EM* **2003**, *October,* 16-23.

[7] *Full-Scale Testing of Enhanced Mercury Control Technologies for Wet FGD Systems;* Final Report to the U.S. Dept. of Energy under Contract No. DE-FC26-00NT41006; Babcock & Wilcox Company and McDermott Technology, Inc, August 2002.

[8] Withum, Jeffrey; Schwalb, Allyson; Statnick, Robert *Characterization of Coal Combustion By-Products for the Re-Evolution of Mercury into Ecosystems*. Presented at Air Quality III Conference, Arlington, VA, September 2002.

[9] Schwalb, A.M. and Withum, J.A. *The Evolution of Mercury From Coal Combustion Materials and By-Products.* Presented at DOE/NETL Mercury Control Technology R&D Program Review Meeting, Pittsburgh, PA August 2003.

[10] Hassett, David J. et al. *Potential for Mercury Release from Coal Combustion By-Products.* Presented at Air Quality III Conference, Arlington, VA, September 2002.

[11]Hassett, David and Heebink, Loreal *Long-Term Mercury Vapor Release from CCBs*. Presented at Air Quality IV Conference, Arlington, VA, September 2003.

[12] Kim, Ann *NETL CUB Characterization.* Presented at DOE/NETL Mercury Control Technology R&D Program Review Meeting, Pittsburgh, PA August 2003.

[13] Kazonich, George; Kim, Ann; and Dahlberg, Michael *Comparison of Leaching Results for Three High Mercury Fly Ash Samples.* Presented at Air Quality IV Conference, Arlington, VA, September 2003.

[14] Kim, Ann and Kazonich, George *Coal Combustion By-Products: Major Cation Solubility*. Presented at the International Ash Utilization Symposium hosted by the University of Kentucky Center for Applied Energy Research in 2001.