Fate of Mercury in Coal Byproducts from DOE's Mercury Control Technology Field Testing Program and Related Projects

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ABSTRACT

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 38% today to 50% by 2010. This technical paper provides a summary of DOE/NETL's research on the environmental characterization and fate of mercury in CUBs, focusing on results from DOE/NETL's mercury control technology field testing program. Test results to date indicate there is minimal potential release of mercury from CUBs in either disposal or beneficial use applications.

INTRODUCTION

According to U.S. Environmental Protection Agency (EPA) estimates, in 1999, U.S. power plants burned 786 million tons of coal containing approximately 75 tons of mercury. It is estimated that approximately 48 tons of mercury were emitted to the atmosphere, while the remaining 27 tons, along with 107 million tons of coal utilization by-products (CUB), were captured by air pollution control devices, such as electrostatic precipitators (ESPs) and flue gas desulfurization (FGD) systems (EPA, 2002). DOE/NETL uses the term coal utilization by-products (CUBs) to describe the solid materials produced by the combustion or gasification of coal − fly ash, bottom ash, boiler slag, gasifier ash and slag, and flue gas desulfurization (FGD) solids. CUBs become "products" when recycled for beneficial use; they become "wastes" when sent to a designated disposal site.

CUBs are subject to regulation by EPA under the Resource Conservation and Recovery Act (RCRA), but a series of regulatory determinations (most recently in 2000) have consistently exempted CUBs from Federal regulation under RCRA Subtitle C, which governs "hazardous wastes." EPA is currently drafting regulations for disposal of CUBs in landfills and surface impoundments under

Subtitle D of RCRA, which governs "non-hazardous" wastes. EPA decisions regarding regulation of mine placement of CUBs will not be made until after a National Academy of Sciences panel completes its review of the practice; this is not expected to occur until after the regulations governing landfills and surface impoundments are issued. In the meantime, EPA has kept the door open for future review of its 2000 regulatory determination pending additional studies that might provide evidence for a need to regulate CUBs as a hazardous waste.

Although it is generally assumed that most of the mercury captured in today's pollution control systems resides in the solid by-product materials, release of mercury from these materials has not resulted in their classification as "hazardous," and has not thus far been a serious impediment to CUB reuse. However, recently-issued EPA regulations to reduce mercury from U.S. coal-fired power plants will increase the capture of mercury, resulting in higher concentrations of mercury in CUBs that lead to greater concern over their environmental behavior in both disposal and utilization applications. For example, the use of activated carbon injection for mercury capture would increase the mercury concentration in fly ash collected by ESPs, and the increased deployment of selective catalytic reduction (SCR) systems for control of nitrogen oxides (NOx) may increase the amount of mercury captured with FGD by-products (Figure 1).

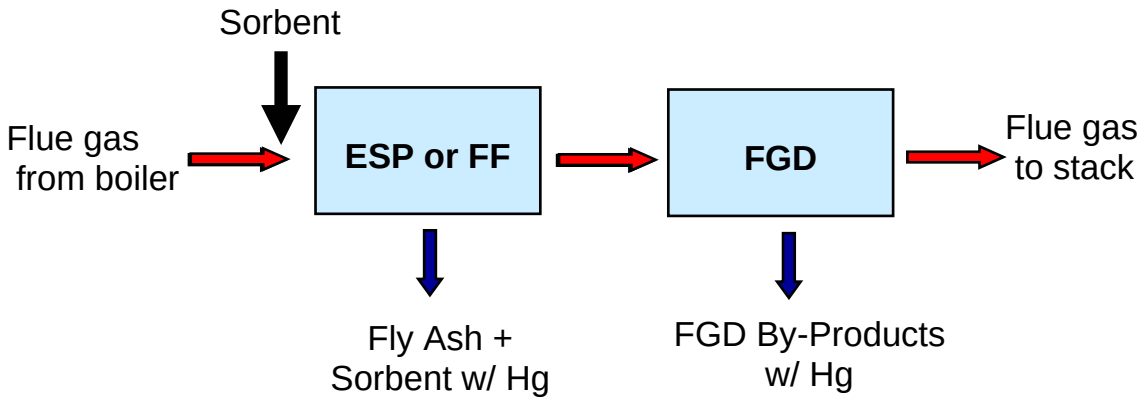

Figure 1. Mercury capture with CUBs.

DOE/NETL's CUB R&D PROGRAM

DOE/NETL is conducting a comprehensive research and development program whose goal is to increase total CUB use in the United States to 50% by 2010. Achieving this goal will be challenging in four respects. First, increasing public concern over the fate of mercury and other trace metals in CUBs will bring about increased scrutiny of both beneficial use and disposal practices. Second, sulfur

dioxide restrictions under EPA's Clean Air Interstate Rule (CAIR) could significantly increase the volumes of FGD by-products 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. Finally, NOx emission restrictions under CAIR may result in increased use of ultra-low NOx burners and SCR, thus negatively impacting the beneficial use of fly ash due to excessive levels of unburned carbon and/or ammonia.

The focus of this technical paper is DOE/NETL's research on the fate of mercury in CUBs. The research includes testing various CUB materials for potential environmental release mechanisms, such as leaching, volatilization, and microbiological transformation. Figure 2 depicts the various potential pathways for the environmental release of mercury from CUBs.

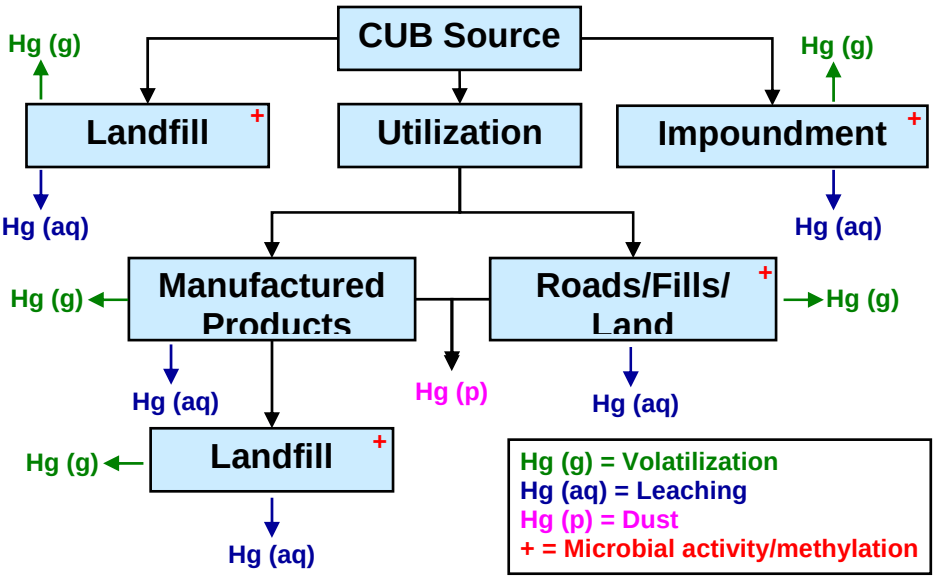

Figure 2. Potential pathways for environmental release of mercury from CUBs.

Table 1 lists ongoing research projects whose focus is on the environmental fate of mercury in CUBs. 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 environmental impact of other trace metals in CUBs, such as arsenic and selenium, and nontrace metals like ammonia and activated carbon are also being evaluated. In addition, DOE/NETL directs a significant research effort toward the development of technology to increase the beneficial use and market applications of CUBs. Additional information on all DOE/NETL CUB projects can be found online at: http://www.netl.doe.gov/coal/E&WR/cub.

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	University of North Dakota Energy & Environmental Research Center
Fate of Mercury in Synthetic Gypsum Used for Wallboard Production	USG Corp.
Stability of Mercury on Fly Ash with Activated vs. Unburned Carbon	NETL in-house
Mercury Adsorption Capacity of CUBs	NETL in-house
Mercury Release from FGD By-products	NETL in-house

The following sections provide a brief description and summary of results on the fate of mercury in CUBs from several DOE/NETL research projects. Further details on the test procedures, conditions, and results for other trace metals can be found in the referenced technical reports and conference papers.

CUB Analysis from Mercury Control Field Demonstrations of Activated Carbon Injection

In 2001 and 2002, under DOE/NETL sponsorship, ADA-ES Inc. and Reaction Engineering International conducted field demonstrations of activated carbon injection (ACI) for mercury control at four coal-fired power plants: Alabama Power's E.C. Gaston, PG&E's Brayton Point, We Energies' Pleasant Prairie, and PG&E's Salem Harbor (Senior, et al. 2002; Senior, et al. 2003a; Senior, et al. 2003b; Feeley, et al. 2003). Results of leaching tests of the CUBs produced during these field demonstrations are described below.

E.C. Gaston The particulate collection configuration at the Gaston power plant (Figure 3) was unique because it included both a hot-side ESP for primary particulate collection and a compact hybrid particulate collector (COHPAC) fabric filter baghouse downstream of the ESP. During mercury

control testing, activated carbon was injected downstream of the ESP and upstream of the COHPAC to prevent carbon contamination of the ESP ash. Mercury concentrations in the baseline (pre-ACI injection) ash from the COHPAC measured 0.2–2 microgram per gram (µg/g); whereas, at an ACI feed rate of 1.5 lb per million actual cubic feet (lb/MMacf) of flue gas, mercury concentrations in the combined activated carbon/fly ash byproduct ranged from 10 to 50 µg/g. Since most of the fly ash was captured in the hot-side ESP, total mercury concentration in the COHPAC byproduct was significantly higher than it would be in applications with ACI located upstream of the primary particulate control device.

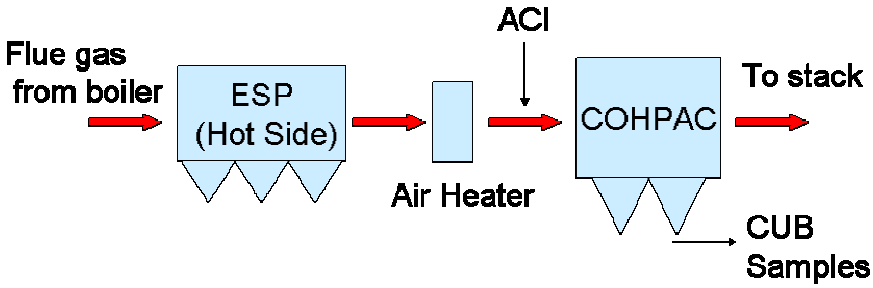

Figure 3. ACI and particulate control configuration at E. C. Gaston Plant.

Brayton Point 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 between the upstream and downstream ESPs. The baseline ash from both the upstream and downstream ESPs contained 0.2–0.53 µg/g of mercury; whereas, at an ACI feed rate of 10–20 lb/MMacf, the downstream ESP ash contained 0.4–1.4 µg/g of 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 instead 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 concentrations in the ash were very low.

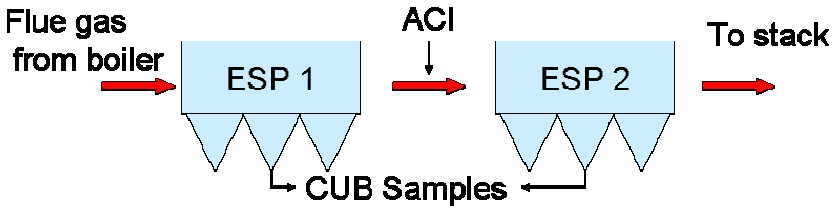

Figure 4. ACI and particulate control configuration at Brayton Point.

Pleasant Prairie and Salem Harbor The particulate collection systems at Salem Harbor and Pleasant Prairie were more typical of the current fleet of coal-fired power plants in the United States, one cold-side ESP unit at each plant, except that the ESP's specific collection areas (i.e., the collection plate area divided by flue gas flow rate) at both plants were comparatively large. Baseline ash from the Pleasant Prairie ESP contained less than 0.5 µg/g of mercury; whereas, at an ACI feed rate of 10 lb/MMacf, the ash byproduct contained 0.5–5 µg/g of mercury. At Salem Harbor, mercury concentrations ranged from 0.1 to 0.7 µg/g during both baseline and ACI testing conditions (10 lb/MMacf). Like Brayton Point, much of the mercury in the flue gas at Salem Harbor was collected by the carbon in the baseline fly ash, thereby minimizing the addition of mercury to the ash as the result of ACI.

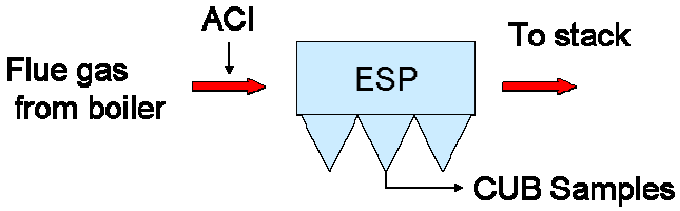

Figure 5. ACI and particulate control configuration at Pleasant Prairie and Salem Harbor.

Leaching Test Descriptions and Results Leaching analyses were conducted on the combined activated carbon/fly ash by-products collected during ACI tests. Both the standard toxicity characteristic leaching procedure (TCLP) and a synthetic groundwater leaching procedure (SGLP) developed by the University of North Dakota Energy & Environmental Research Center (UNDEERC) were used. The TCLP method was designed to simulate leaching in an unlined sanitary landfill using an acetic acid as the leaching solution. UNDEERC developed the SGLP method to more realistically

simulate CUB leaching in typical disposal environments. For the SGLP analysis, deionized water was used as the leaching solution with a 20:1 liquid:solid ratio.

Table 2 summarizes the leaching test results at the four ACI test plants. For the Gaston and Pleasant Prairie ash samples, the amount of mercury in the leachate was at or below the measurement detection limit of 0.01 microgram per liter (µg/L). For Salem Harbor, only one sample exceeded the detection limit (0.034 µg/L); this sample came from the baseline ash (i.e., no ACI). For Brayton Point, leachate of samples from both the nontreated (upstream) ESP and the ACI-treated (downstream) ESP contained detectable amounts of mercury (0.01–0.07 µg/L). However, no discernable differences in leachate concentrations were found between the upstream and downstream ESPs, or at different levels of ACI injection. This appears to be related to the fact that most of the mercury 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 four plants were more than an order of magnitude lower than the 0.77-µg/L freshwater criterion continuous concentration and 1.4-µg/L freshwater criterion maximum concentration for mercury under the federal water quality criteria for protection of aquatic life.

Table 2. ADA-ES leaching test results for ACI ash by-products.

Plant	Sample Location	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[a]
Gaston	COHPAC B-Side	1.5	10 – 50	N/A[b]	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

[a]BDL = below detection limit of 0.01 µg/L. [b]N/A = not available.

Ash byproduct samples from Gaston and Pleasant Prairie were also tested using other leaching procedures for comparison. Samples from Gaston were analyzed using a sulfuric acid leaching solution with a pH of 2, using procedures similar to TCLP and SGLP to simulate use in an acid mine drainage environment. Ash byproduct samples from Pleasant Prairie were analyzed using the ASTM water leaching procedure (ASTM D-3987). The Pleasant Prairie samples were also leached over longer periods of 30 and 60 days using SGLP, due to concerns that potentially slower reactions 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 (B&W) and McDermott Technology Inc. (MTI) carried out joint full-scale field testing of a proprietary liquid reagent to enhance mercury capture in coal-fired power plants equipped with wet FGD systems (B&W, 2002). The field tests were conducted at two power plants: Michigan South Central Power Agency's 60-MW Endicott Station and Cinergy Corp.'s 1300-MW Zimmer Station. Both plants burn Ohio high-sulfur bituminous coal and use cold-side ESPs for particulate control. Endicott uses a limestone wet FGD system with in-situ forced oxidation; while Zimmer uses a magnesium-enhanced lime wet FGD system with ex-situ forced oxidation. Table 3 presents a summary of the average mercury concentrations for the coal and process byproduct stream samples for both Endicott and Zimmer. Although not shown in Table 3, the majority of liquid stream samples were "nondetects" for mercury (i.e., measuring less than 0.5 µg/L), with a few samples measuring 1–3 µg/L.

Table 3. Mercury concentration in B&W and MTI 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
FGD slurry	0.76	0.49
FGD fines	38 (by TDT)	13.3

B&W and MTI also evaluated the byproduct 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. To represent the temperature-time conditions that FGD by-products are likely to encounter when used as feedstock during the manufacture of wallboard, a temperature of 140 °C was held for about 10 minutes in the early portions of the tests. Results of TDTs for Endicott and Zimmer FGD gypsum indicated that only about 3% of the total mercury evolved during the course of the tests occurred at or below 140 °C. By contrast, a peak in mercury volatilization occurred at about 250 °C (482 °F). Since some wallboard manufacturing processes may expose FGD by-products to temperatures between 140 °C and 250 °C, DOE/NETL is sponsoring additional research (described later in this article) to further determine the fate of mercury in wallboard manufacturing facilities.

One of the significant findings from the B&W and MTI test program was that the mercury in the wet FGD material from both plants was associated primarily with small particle size impurities in the slurry (fines) and was 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 use in applications where mercury release is a concern.

CUB Analysis from Ash and FGD Byproduct Disposal and Beneficial-Use Applications

CONSOL Energy Study CONSOL Energy conducted an extensive evaluation of mercury in CUBs from 14 coal-fired power plants from August 2000 to October 2004 (Withum, et al. 2002; Schwalb and Withum, 2003). The plants represented a range of coal ranks and air pollution control device configurations and the evaluation included leaching and volatilization tests of bottom ash, fly ash, wet and dry FGD scrubber solids, and products from ACI tests. Testing was also conducted on products made from CUBs, such as cement, gypsum wallboard, and manufactured aggregates. In addition, groundwater-monitoring wells at two CUB disposal sites were evaluated for mercury on a quarterly basis over one year.

Mercury leaching rates from eight CUBs were measured using modified TCLP tests with leaching solutions at three pH values: 2.8, 4.9, and 7.0 (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 Federal drinking water standard of 2 µg/L.) Six leachate samples from fly ashes at two sites (three 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 to 0.084 µg/L.

Mercury volatilization tests were conducted using a procedure developed by CONSOL. The CUB samples were split into two ovens and held at constant temperatures of 38 °C (100 °F) and 60 °C (140

°F) for six months. The results indicate a slight (but perhaps not significant) increase in mercury concentration in the CUB solids over time, suggesting the possibility that the ash samples could have adsorbed additional mercury from the ambient air.

Groundwater monitoring wells at an active wet FGD disposal area and an active fly ash slurry impoundment were evaluated quarterly for one year for possible mercury releases. Preliminary results for the first and second quarter samples from the FGD disposal site indicate less than 1 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 μg/L mercury concentrations for all 11 monitoring wells and a leachate collection site.

UNDEERC Studies The University of North Dakota Energy & Environmental Research Center (UNDEERC) is conducting a multifaceted set of experiments to determine the level of mercury that may leach or volatilize from CUBs, and the potential for microbiological activity in the release of mercury from CUBs (Hassett, et al. 2002; Hassett and Heebink, 2003). Mercury vapor release tests were conducted on six fly ash samples at ambient and near-ambient temperatures (37 °C/99 °F). The fly ash samples were taken from two Powder River Basin (PRB) coals, two eastern bituminous coals, and two South African coals. Microbiological tests were conducted on two samples that were selected because of their relatively high mercury concentrations, ranging from 0.112 to 0.736 μg/g, and their corresponding potential for releasing measurable amounts of mercury vapor. However, as with 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 tests 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 nonmicrobiologically mediated experiments, but are still very low (i.e., less than 60 x 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

USG Corp. is conducting a two-year study to measure potential releases of mercury from synthetic FGD gypsum during the wallboard manufacturing process. Testing is being 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) controls, and limestone- and lime-FGD processes. The field tests include mercury measurements of all input and output process streams to obtain complete mercury balances for the wallboard manufacturing plants. Samples of the synthetic FGD gypsum are being evaluated in laboratory simulation tests as a means of comparison to the field measurements. In addition, TCLP leaching tests are being conducted on the wallboard products to determine potential mercury releases in landfills.

Results are currently available from the first test that evaluated wallboard production using synthetic gypsum from a limestone forced-oxidation FGD system on a plant that burns high-sulfur bituminous coal, with an SCR in-service, and does not employ gypsum fines blowdown during de-watering (Marshall, 2005). Based on Ontario Hydro method stack testing, an average of 5% of the mercury in the gypsum was emitted during wallboard production. However, based on solids analyses of the gypsum and wallboard there was only a 2% loss of mercury during wallboard production.

CUB Analysis for Mercury Control Technology Field Testing in 2004 - 2006

DOE/NETL recently awarded a contract to Frontier Geosciences, Inc. to conduct independent laboratory analysis of CUBs generated during DOE/NETL's mercury control technology field tests that are being conducted at 22 coal-fired power plant units in 2004-2006. The purpose of the independent laboratory analysis is to ensure accurate and consistent laboratory procedures are used to determine the environmental fate of mercury in CUBs. Test results are not yet available.

DOE/NETL In-House Research on Mercury in CUBs

An important part of the CUB research program is being performed by DOE/NETL's Office of Science, Technology, and Analysis (OSTA). These "in-house" studies are directed at providing an unbiased source of data on the environmental characteristics of coal by-products and developing new applications for CUBs. DOE/NETL's current in-house CUB research projects related to mercury are summarized below.

Stability of Mercury on Fly Ash with Activated vs. Unburned Carbon Recent studies have compared the stability of mercury on fly ash containing activated carbon (AC) to fly ash containing only unburned carbon (UBC) from coal combustion. Column leaching studies of nine high mercury fly ash samples (three with UBC from high mercury coal, three from pilot scale studies of AC injection, and

three from full-scale AC injection demonstrations), indicated that mercury on all types of fly ashes were only slightly soluble. For example, long-term leaching tests showed that the cumulative amount of mercury leached was less than 1 % of the amount present in the fly ash samples (Kazonich, et al. 2003). In all cases, the mercury concentrations in the column leachates were less than the Federal drinking water standard. Unlike other metals, pH did not appear to be the dominant control on mercury stability. Comparing samples with similar carbon concentrations, fly ashes containing AC had lower mercury release rates than fly ashes containing only UBC.

Mercury Adsorption Capacity of CUBs DOE/NETL is also conducting tests to measure the mercury adsorption capacity of fly ash (Kim, 2003). 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 affects adsorption, with high-carbon ash having a higher mercury adsorption capacity than low-carbon ash. For example, with a pH of 2 and 1,000 μg/L of mercury in solution, the high-carbon ash (5.2% loss-on-ignition, LOI) adsorbed approximately 20,000 μg/kg of mercury, compared to only 2,500 μg/kg of mercury adsorbed by the low-carbon ash (1.3% LOI).

Mercury Release from FGD By-product. Recent OSTA work has concentrated on mercury release from FGD by-products (Kairies, 2005). Mercury balances across FGD units have shown that oxidized mercury can be captured and strongly retained in some FGD units, especially those employing SCR (which enhances mercury oxidation upstream of the FGD system) and forced oxidation within the limestone-based FGD system to produce a gypsum product. Experiments conducted to determine the mobility of FGD-captured mercury show that, at least in some cases, it is very limited. Neither contact with hot aqueous solution up to 100^{o}C nor contact with acidic water down to pH values less than 3 mobilize the mercury. Further, the agent responsible for the immobilization appears to be not gypsum, but an iron- or iron/aluminum-rich impurity that is probably introduced with the limestone. Further characterization studies are underway to investigate this effect.

SUMMARY

DOE/NETL's research has helped to further scientific understanding of the environmental behavior of CUBs in both disposal and beneficial utilization applications. The following 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 ACI 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 is significantly lower than the federal drinking water standards and water quality criteria for the protection of aquatic life; in many cases, leachate concentrations were below the detection limits of the analytical methods.

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.

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.

REFERENCES

Babcock & Wilcox Co., Barberton, OH, and McDermott Technology Inc., Houston, TX, Full-Scale Testing of Enhanced Mercury Control Technologies for Wet FGD Systems; Final Report to the U.S. Department of Energy under Contract No. DE-FC26-00NT41006, August 2002.

EPA, Control of Mercury Emissions from Coal-Fired Electric Utility Boilers: Interim Report. EPA Report No. EPA-600/R-01-109, April 2002.

Feeley, T.J.; Murphy, J.T.; Hoffmann, J.W.; Granite, E.J.; Renninger, S.A. DOE/NETL's Mercury Control Technology Research Program for Coal-Fired Power Plants; Environmental Management, 2003, October, 16-23.

Hassett, D.J. et al. Potential for Mercury Release from Coal Combustion By-Products. Presented at the Air Quality III Conference, Arlington, VA, September 2002.

Hassett, D; Heebink, L. Long-Term Mercury Vapor Release from CCBs. Presented at the Air Quality IV Conference, Arlington, VA, September 2003.

Kairies, C.L. et al. Distribution of Mercury in FGD Materials. Presented at the Air Quality V Conference, Arlington, VA, September 2005.

Kazonich, G.; Kim, A.; Dahlberg, M. Comparison of Leaching Results for Three High Mercury Fly Ash Samples. Presented at the Air Quality IV Conference, Arlington, VA, September 2003.

Kim, A. NETL CUB Characterization. Presented at the DOE/NETL Mercury Control Technology Research and Development Program Review Meeting, Pittsburgh, PA, August 2003.

Marshall, J. et al. Fate of Mercury in Synthetic Gypsum Used for Wallboard Production, Task 1. Presented at the Air Quality V Conference, Arlington, VA, September 2005.

Senior, C. et al. Characterization of Fly Ash from Full-Scale Demonstration of Sorbent Injection for Mercury Control on Coal-Fired Power Plants. Presented at the Air Quality III Conference, Arlington, VA, September 2002.

Senior, C. et al. Characterization of Fly Ash from Full-Scale Demonstration of Sorbent Injection for Mercury Control on Coal-Fired Power Plants. Presented at the Mega Symposium, Washington, DC, May 2003a.

Senior, C. et al. Characterization of Fly Ash from Full-Scale Demonstration of Sorbent Injection for Mercury Control on Coal-Fired Power Plants. Presented at the Air Quality IV Conference, Arlington, VA, September 2003b.

Withum, J.; Schwalb, A.; Statnick, R. Characterization of Coal Combustion By-Products for the Re-Evolution of Mercury into Ecosystems. Presented at the Air Quality III Conference, Arlington, VA, September 2002.

Schwalb, A.M.; Withum, J.A. The Evolution of Mercury From Coal Combustion Materials and By-Products. Presented at the DOE/NETL Mercury Control Technology Research and Development Program Review Meeting, Pittsburgh, PA, August 2003.