Optimization and Process Control of Air Quality Control Systems for Improved WFGD Oxidation Chemistry and Effluent Composition for Wastewater Treatment

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Abstract:
Wastewater treatment (WWT) of wet flue gas desulfurization (WFGD) effluent, mercury and selenium control are becoming critical issues for many utilities operating with coal-fired power generation. Research has shown that absorber slurry oxidation reduction potential (ORP) is a primary factor for determination of control of WFGD chemistry. Previously unexplained swings in the ORP of operating WFGD units have been observed in excess of 300 mV, both positive and negative. Such swings, and the associated changes in the oxidizer content of the absorber stream, can result in mercury re-emission and have negative impacts upon WWT. Research indicates that control of WFGD ORP may be possible. Should such control be implemented, the fraction of selenate passing to WWT and the risk of mercury re-emission are reduced. Further, cost of additives may be lowered for some plants should ORP be controlled. The control of reagent feed is an important parameter for optimization, as high oxidizer content can result in deleterious side reactions and lower pH. Parametric testing was performed at a Midwestern utility to examine the impacts of upstream unit operation performance and traditional WFGD control parameters upon WFGD ORP. Herein is discussed results of this parametric testing and potential tuning of absorber and upstream operations for improved WFGD oxidation chemistry and effluent composition.

Introduction:
Five weeks of field testing were conducted on two Limestone Forced Oxidation (LSFO) Wet Flue Gas Desulfurization (WFGD) units. These units will be referred to as Units A and B. This testing included full spectrum flue gas analysis by: Fourier Transform Infrared Spectroscopy (FTIR), speciated mercury measurements, $\text{SO}_3$ traverse, and velocity traverse. Absorber slurry samples were obtained throughout the test period and analyzed for oxidizer content, anions,
cations, dissolved oxygen, mercury and speciated selenium. Process information (PI) data was gathered and analyzed; this data included oxidation reduction potential (ORP) measurements.

The purpose of this testing was to elucidate the cause of high ORP and strong oxidizer formation within WFGD absorbers. Factors examined during testing included oxidation air flow rate and electrostatic precipitator (ESP) operation. Results of this testing are discussed herein.

**WFGD ORP**

ORP is important in WFGD absorber applications because it can be used to predict how slurry will react to materials which contact it and as a method to predict the oxidation state of slurry constituents. Consider ORP to be a threshold value. Using the ORP and pH of the slurry, and the electronegativity of a given chemical species, one may predict the thermodynamically preferred oxidation state of that chemical species for those conditions. These predictions correlate well to the dominant phase found within the slurry. [3,6]

Operating a scrubber without measurement and control of ORP is, in terms of wastewater chemistry, similar to operating it without monitoring and controlling pH. Using SO$_2$ input and stoichiometric ratio, one should be able to control a tower without relying solely on pH control. A shift in industry thought process shows that the SO$_2$ removal controls the pH; pH does not control the SO$_2$ removal. However, pH is always monitored, at least as a backup control – if not primary control – to ensure that the absorber does not experience severe excursions. ORP is a measurement of similar importance when wastewater treatment and/or alloy corrosion are concerns. As ORP indicates the oxidation state and phase partitioning of slurry constituents, it needs to be controlled for improved capture and removal of mercury, selenium and other metals, to ensure that significant levels of manganese do not precipitate out and promote corrosion, and to control downstream pH. Currently, all scrubbers operate without ORP control. Recently, the industry has started to monitor this parameter, which provides information equivalent to knowing the scrubber pH, but not being able to change it. ORP control of WFGD absorber slurry is also needed for process control related to wastewater treatment.

At ORP levels below about 300 mV, selenium will predominantly exist in the selenite form, a solid that is able to be removed by many wastewater treatment systems.[5] When the ORP is above about 300 mV, selenium will shift forms to selenate, a dissolved ion that is more difficult to treat.[3,5,6] Maintaining a lower ORP, below about 300 mV, would, therefore, improve selenium removal for most systems. ORP has also been implicated in mercury control because rapid change in ORP has been correlated to mercury re-emission events. Additionally, a negative ORP is expected to lead to a significant increase in mercury re-emission due to the elemental state being thermodynamically favored in WFGD slurry under these conditions.[10] High ORP (above about 500 mV) has also been shown to cause MnO$_2$ to precipitate from solution, increasing the risk of severe and accelerated alloy corrosion.[2] Further, high ORP can lead to liberation of hydronium ions within the solution and an evolution of halogen-containing
gas species.[2,3,6] These gas species could result in a false high value for measured acid gas emissions at the stack. Within the slurry, the liberated hydronium ions would lead to an increased need of reagent feed slurry to maintain the desired pH. After removal from the scrubber and solids removal, this same condition can result in low pH downstream, increasing the need for additives to neutralize the solution prior to wastewater treatment.[3,9] High oxidizer content itself may also result in negative impacts on systems with bioreactors.

Oxidation reduction potential, or redox potential, is a measure of a solution’s potential to oxidize or to reduce anything that it may come into contact with. This is a single voltage measurement against a reference electrode. In literature, the redox potential is often expressed against a standard hydrogen electrode (SHE), while in industry, ORP is often measured using an Ag/AgCl electrode. To convert a SHE voltage to an ORP voltage, about 200mV should be subtracted from the SHE potential. The more positive the voltage, the more likely that a solution would oxidize (attract electrons from) other sources. The more negative the voltage, the more strongly a solution would reduce (gain electrons from) other sources.

Unlike some measurement techniques, ORP is not selective of any one specific chemical species. It is a measurement based upon the properties of the solution as a whole. As such, many oxidizers could increase scrubber ORP. Persulfate and hypochlorous acid are thought to be the main oxidizers within the WFGD slurry.[2] If a strong oxidizer was brought into contact with a solution, it may react to form a weaker oxidizer, with itself being reduced by a corresponding amount in the process. For example, if ozone were brought into contact with scrubber slurry, it may react with slurry constituents to form persulfate. The persulfate may, in turn, react with the slurry to form hypochlorous acid.

The thermodynamically favored oxidation state for a given species in a pure solution is a function of pH and electrochemical potential. Pourbaix diagrams are used to convey this information.[10] Here, electrochemical potential is expressed against a SHE, so subtract about 200 mV from SHE of y-axis to convert to Ag/AgCl electrode used in ORP measurements. Though idealized information, metals within the WFGD absorber slurry often follow the trends predicted by these diagrams, but the splits are, naturally, less than the 100% of pure ideal conditions.

**ORP and Selenium**

One element of particular concern, for which ORP is an important predictor of form, is selenium. In WFGD absorber slurries, selenium occurs mainly in two forms: selenite ions and selenate ions. Selenite ions tend to form precipitates and are partitioned towards the solid phase; these ions are removable by many wastewater treatment systems. Selenate ions, however, exists as a dissolved ions and can be very difficult to treat.

The selenium atom in selenite is in the +4 oxidation state, while the selenium atom is in the +6 oxidation state in a selenate ion. Within scrubber slurries, selenium has been shown to exist
predominantly as selenate ions at ORP values greater than about 300 mV, and to remain as selenite ions at lower values of ORP. Therefore, maintaining ORP less than about 300 mV is a method to improve selenium removal for many wastewater treatment systems, especially phys-chem systems.

**ORP and Mercury**

Mercury re-emission is another reason that measuring and controlling WFGD ORP is important. When ORP swings, stored mercury may re-emit from the slurry within the absorber reaction tank. Such re-emission would occur as brief spikes for transient changes in ORP, but extended periods of ORP upset can result in significant mercury emissions.

ORP within LSFO WFGD absorber slurries generally ranges from approximately 100 to 800 mV. Interestingly, the ORP of the absorber slurry will often either be low (below about 300 mV) or high (above about 500 mV), remaining within one profile before shifting to the other profile rapidly, approximated as a step-change or S-shaped curve. Such transitions can occur quickly. Based on previous research on LSFO WFGD absorber reaction tank (ART) absorber slurries within the industry, a low level of total oxidizers (<100 ppm) is expected in LSFO WFGD absorber slurries.[2] This level of oxidizer concentration is found in the low ORP profile and is necessary for the oxidation of sulfite to sulfate within the ART.[8] For slurries with high ORP, total oxidizer concentrations above about 1500 ppm have been observed from analyses of samples from a number of sites collected to date. The source of this change in chemistry is not well understood.

**Materials and Methods:**

**Flue Gas Testing**

To understand the flue gas flow on the test unit, a velocity traverse and a SO₃ traverse were performed to provide a profile of the gas flux. The velocity traverse was performed using EPA Method 2 using a 21-point traverse consisting of 7 equally spaced ports across the width of the duct at 3 depths. For SO₃ measurements, a modified version of EPA method 8A was used – named the *controlled condensation method*. Triplicate SO₃ measurements were performed at each of the 7 ports traversed at a single depth across the width of the ductwork.

Controlled condensation involves withdrawing a sample from the flue gas stream at a constant flow rate from the source using a glass-lined probe heated to 316°C ± 14°C, (600 °F ± 25 °F) and through a quartz fiber filter maintained at a temperature of 288°C ± 14°C (550 °F ± 25 °F). The gas stream sample is passed through an impaction type condenser for collection of residual sulfuric acid vapor and/or mist. The condenser temperature is regulated by a water jacket in the range of 60°C to 71°C (140 °F to 160 °F), this is approximately 11°C above the water dewpoint, and well below the sulfuric acid dewpoint. Sample gas then continues through a series of two impingers containing a solution of hydrogen peroxide in water, one empty impinger, and one
impinger containing silica gel for residual moisture removal. The sample gas then flows into a dry gas meter where the collected gas sample volume is determined. A calibrated, dry gas meter, or an orifice-based flow meter, is used to measure the sample gas volume. The probe rinse, filter and the condenser collection media are each extracted separately with deionized water, and the extractions are analyzed for sulfate using ion chromatography (IC). Alternatively, condenser rinse (SO$_3$ fraction) may be collected using a 20% deionized water – 80% isopropyl alcohol mixture and subsequently titrated with barium chloride-thorin solution.

As expected, the gas flow showed a parabolic shape upon introduction into the WFGD inlet and the SO$_3$ gas flow demonstrated stratification instead of uniform distribution.

Fourier Transform Infrared Spectroscopy (FTIR) monitoring was performed at the WFGD inlet. This technique involves shining a beam of infrared light through the sample to excite the gas molecules. As the molecules fall back to their ground state, characteristic patterns are produced based on the chemical structure and vibrational transitions of each gas constituent. The spectrographs of each scan are processed and chemical species are quantified based on the area of the processed spectrograms. This technique provides real-time, continuous data about flue gas composition. For this testing, the FTIR probe was positioned in the second test port from the end of the duct. Species analyzed and reported during this testing included: CO, CO$_2$, CH$_2$O, H$_2$O, H$_2$SO$_4$, HCl, HF, HBr, N$_2$O, NH$_3$, NO, NO$_2$, O$_3$, and SO$_2$. These are all quantitative measurements other than O$_3$, which is a qualitative measurement.

Mercury profiling was done in the gas phase by a combination of Thermo Freedom continuous emissions monitoring system (CEMS) analysis and sorbent traps. Thermo CEMS utilizes extractive sampling through a sintered metal fast loop to remove ash from the flue gas. The extracted sample is then diluted by an in-line dilution module and split into two separate legs. One leg of the diluted sample passes through a thermal reduction chamber to cause any oxidized mercury to be converted to elemental mercury. This leg is considered the total mercury sample. The other leg does not pass through the thermal converter and is analyzed as elemental mercury. Both legs are fed into the switching module which alternatively floods the analytical cell with either total or elemental mercury sample streams. The gas is analyzed for mercury content using atomic fluorescence.

Speciated carbon traps utilize selective adsorption of oxidized and elemental mercury fractions onto two individual beds. Flue gas is introduced into the speciated trap through a glass fiber filter at the tip of the glass trap located in the flue gas stream and maintained at flue gas temperatures. Particulate-free flue gas then travels through a packed bed of sodium carbonate for acid gas removal. Four beds collect the remaining gas-phase mercury, two beds of potassium chloride (KCl) followed by two beds of iodated carbon. The sample gas then flows into a dry gas meter, where the collected gas sample volume is determined. A calibrated, dry gas meter, or an orifice-based flow meter is used to measure the sample gas volume. All sections of the trap are analyzed separately for the mass of mercury adsorbed. Oxidized mercury fraction is
calculated from the sum of the adsorbed mercury masses on the acid gas scrubber and KCl sections. Elemental mercury is calculated from the sum of the masses of mercury adsorbed onto the carbon beds. Particulate mercury is reported separately and is calculated from the mass of mercury adsorbed onto the particulate filter and collected ash. Final mercury concentrations (µg Hg/m³ or equivalent reporting concentration) are calculated by normalizing the mercury masses in each section to the metered volume of dry gas drawn through the sampling system.

**Process Monitoring**

Process information (PI) data was gathered from the plant and monitored throughout the field test period.

ORP of the absorber slurry was continuously monitored. The ORP probes were installed in the pH sampling sink; they were in this location for the entire duration of the test period. For LSFO WFGD absorber slurries, a variance of ±50 mV values of ORP is common, and is therefore, often considered to be within the expected scatter of the data.

**WFGD Absorber Slurry Sampling and Analysis**

A 0.45 µm filter was used to separate slurry filtrate from solids using a syringe filter on-site, at process temperatures. Samples of absorber slurry were also taken. Upon collection, samples were analyzed for pH, dissolved oxygen (DO) content, ORP and conductivity. Samples were then sent to an off-site laboratory for a battery of analyses. Anion analysis was conducted on slurry filtrate samples using ion chromatography (IC). Species analyzed included: fluoride, chloride, nitrite, bromide, nitrate, phosphate, sulfate, and ammonium. Slurry samples were analyzed for metals composition by inductively coupled plasma mass spectroscopy (ICP-MS), a precise method for compositional analysis. Slurry filtrate was analyzed to determine the concentration of dissolved metals. Samples of the complete slurry were microwave digested using HNO₃, HCl, and HF to determine the total concentration of each metal within the slurry (filtrate and solids).

Total and dissolved mercury concentrations within the WFGD absorber slurry samples were quantified by a modification of EPA Method 1631e. Dissolved mercury samples were acidified with BrCl and heated in an oven at 100 °C for one hour. If samples remained a pale yellow color, they were diluted and analyzed by purge-and-trap cold vapor atomic fluorescence spectroscopy (CVAFS). Clear samples were treated with additional BrCl and heated until they retained the pale yellow color. Total mercury samples were prepared by a strong acid microwave digestion including HNO₃, HCl and HF, and subsequently diluted into dilute BrCl for analysis by purge-and-trap CVAFS.

Selenium speciation was performed using an ultra high-performance liquid chromatography (UHPLC) coupled to a triple quadrupole inductively coupled plasma mass spectrometer (ICP-MS) method internal to SRI. For each sample, separation of the various oxidation states of
selenium occurs on the specially designed LC column and method. As each oxidation state selenium species elutes from the LC column, it is quantified by the ICP-MS as 78Se.

**Results & Discussion:**

*Parametric Testing of WFGD Absorber Oxidation Air Injection*

Oxidation air flowrate was parametrically changed to three levels: minimum operation, normal operation and maximum flowrate. Slurry dissolved oxygen was measured at each flowrate. Figure 1 shows the averaged DO concentration for each of the different blower capacity settings; the error bars are one standard deviation in length in each direction. Changes were made to Unit A. Unit B results serve as a baseline for comparison. Effectively, the DO content of the slurry was indistinguishable at all conditions tested.

*Figure 1: Average Dissolved Oxygen Concentrations Measured in WFGD Absorber Slurry*

The turndown, approximately 45% of full load, of the oxidation air to the minimum allowable value by the compressor vendor demonstrated no appreciable change in dissolved oxygen. The full load testing of the oxidation air compressor had similar results with no apparent change measured in dissolved oxygen. Since the absorber slurry was operating at the saturation limit for dissolved oxygen, increasing the oxidation airflow merely resulted in more air passing through the system rather than dissolving in the slurry. In fact, results for dissolved oxygen measurements at minimum turndown and at maximum flowrate were indistinguishable (Figure 1), with close averages and falling within the standard deviation of each other. Further, no change in ORP was observed from changes in the oxidation air flowrate.

As the units are burning coal with lower than designed-for sulfur content and operating at lower than designed-for loading, less SO₂ is being dissolved into the absorber slurry per unit time at the same removal efficiency than each absorber is capable of handling. The oxidation air
compressors are sized to provide necessary capacity for slurry oxygenation at constant full load and design sulfur, plus a factor of safety. Unfortunately, compressor turndown capacity is not sufficient to provide the design O:S stoichiometry at the lower sulfur load coming into these WFGD absorbers. This scenario leads to an over-injection of oxidation air. Lack of turndown capacity is the major reason why the adjustment of the oxidation air flow through the range of the compressor did not appear to change the dissolved oxygen. While turndown of the compressors within the range of coals tested did not impact absorber slurry chemistry, implementation of turndown controls could result in power savings. Within the operating ranges tested and considering the current energy prices, the potential savings on compressor turndown may yield up to several hundred thousand dollars a year. Research is ongoing towards options for the potential beneficial use of the oxidation air in locations other than the ART in an effort to offer turndown of the oxidation air flow to the ART to levels below the 45% hard limit.

**Parametric Testing of Upstream Operations**

During the course of this 5-week field test, changes were made to the operation of the ESPs upstream of the WFGD absorbers. This unit burns a low sulfur western coal blend, a major variance from the design basis, making ash collection by the ESP complicated. When this parameter was changed, ash loading to the WFGD was increased and the ORP increased by approximately 300 mV to a level over 500 mV. This increase occurred within one hour. When this parameter was restored to normal operation, ORP slowly decreased until it reached pre-change conditions. This result has been replicated multiple times.

**Impact of WFGD ART Slurry ORP on Selenium**

Selenium is one species of particular concern with regard to wastewater treatment for which the phase partitioning within slurry has been shown to be strongly related to ORP. At low ORP, selenium partitioning will favor the solid phase. As ORP increases above about 300 mV, partitioning will shift and the dissolved-phase selenium increases. Experimental results from this field test exhibit this trend (Figure 2).
Figure 2: Concentrations of Dissolved Selenium and Selenium Associated with the Solids Measured in Absorber Slurry Samples as a Function of ORP

Much of this trend is attributable to the split of the selenium between the two dominant forms in WFGD slurry and wastewater – selenite and selenate. Selenite ion and selenate ion concentrations are charted versus ORP for both Unit A and Unit B WFGD slurry samples in Figure 3. One observes from this data a decrease in selenite ion concentration, and an increase in selenate ion concentration, with increasing ORP.
A shift in the dominant form of selenium within the WFGD absorber slurry was observed as a function of ORP. As ORP increased above about 350 mV, dissolved-phase selenium concentrations also increased and the concentration of selenium in the solid phase decreased. More specifically, the main form of selenium at low ORP was selenite, while selenium was more likely to be found as selenate at higher ORP. Data trends observed are consistent with results reported from other field sites and with theoretical data.

Selenite is removable by many wastewater treatment processes, including physical-chemical processes. However, increasing selenate concentrations can be problematic for many plants, as selenate is more difficult to remove from wastewater. When in the more oxidized state as selenate, selenium is a dissolved ion that requires more specialized treatment options – such as with bioreactors. If the ORP cannot be kept within acceptable levels, sites without more advanced wastewater treatment systems may experience excursion of high selenate concentrations that could potentially cause them to go out of compliance, depending upon the discharge permits of that site.
Impact of WFGD ART Slurry ORP on Mercury

The mercury speciation was observed to change within the absorber slurry, dependent upon slurry electrochemical potential. Slurry total and dissolved mercury concentrations were measured by the methods described in the WFGD Absorber Slurry Sampling and Analysis section. The balance of the total mercury detected, less the dissolved mercury concentration, is thought to be mercury associated with the slurry solids – likely as mercury adsorbed to ash (higher carbon ash from loss on ignition) or the silicate additives not caught by the ESP. Analytical results for the dissolved mercury and mercury associated with the solid phase is given in Figure 4.

Figure 4: Concentrations of Dissolved Mercury and Mercury Associated with the Solids Measured in Absorber Slurry Samples as a Function of ORP

The relationship between ORP and the mercury within the scrubber slurry becomes more apparent when one views the ratio of dissolved to total mercury as a function of ORP. The field test results are charted in this manner in Figure 5. At ORP below about 400 mV, mercury is more likely to be associated with the slurry solids. At higher ORP, the mercury seems to favor the dissolved phase.
A relationship between ORP and the speciation of mercury within the absorber slurry was observed. As ORP increased, less mercury was associated with the solids and the concentration of mercury in the dissolved phase increased. At low ORP, mercury was detected primarily with the absorber slurry solids. In contrast, at high ORP, the mercury was mainly found in the dissolved phase. This observation should be considered when predicting the effects of sorbent species for mercury removal. Based upon these results, one possible explanation may be that at low ORP, mercury adsorption to slurry solids is likely to be maintained and could even be favorable to occur within the solution, while at high ORP (above about 500 mV), the high oxidative potential could cause the mercury to desorb from the slurry solids. This hypothesis warrants further testing.

**System Tuning**

The tuning of the WFGD and WWT systems to achieve a predictable phase-partitioning is possible, but requires a substantial shift to a more holistic control scheme. Currently, many utilities will burn coal based primarily on coal cost, without including impacts upon downstream operations such as SCR catalyst life, air heater corrosion, ESP functionality, WFGD impacts and/or the effect(s) on WWT within the cost analysis. To meet new regulations in a cost effective manner, system integration from combustion to wastewater treatment may be beneficial. While currently no complete integration systems are available, new research is
yielding links between factors such as boiler O\textsubscript{2} levels and manganese scaling, and SCR life versus selenium speciation.

One variable in many WFGD systems is oxidation air. When adequate turndown is available, this has been shown to afford some control over ORP.[4] However, this is more useful as a fine tuning, similar to a fine adjustment on a microscope, for ORP levels which are approximately 80 mV above the operating set point. While other methods are being developed for ORP control, either positive or negative, the system tuning is not limited to ORP.

Further testing and research has shown the potential saving in SO\textsubscript{2} removal by adjusting the ball mill limestone grind and density. A finer grind, or higher percent passing 325 mesh, potentially increases the rate of dissolution and should allow for an uptick in SO\textsubscript{2} interaction with the CaCO\textsubscript{3}. While this change impacts the WFGDs with absorber trays or perforated plates, this change may have a greater impact on the open spray tower designs. Tuning this parameter may allow a lower L/G ratio, potentially resulting in economic savings by allowing intermittent removal of an absorber recycle pump from service. Other future tuning parameters may result in mitigation strategies for scale growth control in the WFGDs as well as consistent gypsum quality with lower inert and unused carbonate content.[9]

All of these changes will require a control system to oversee the upstream changes to the coal supply or furnace control and a feedback response change in either the WFGD or the WWT system. While the nature of the WFGD and the parasitic power loss that results may never change, system tuning and optimization should allow for a more responsive system to upstream conditions as well as the potential savings in power, chemicals and maintenance costs.

Conclusions:

Parametric changes to oxidation air had no effect upon slurry ORP and DO content. One infers that, once the slurry has reached saturation with oxidation air, addition of more air will not appreciably increase ORP. Over-injection of oxidation air is, therefore, not the cause of high ORP within WFGD absorber slurries. Further, results showed that blower turndown is insufficient to provide a method for decreasing ORP at some sites under some conditions.

Parametric changes to upstream operational parameters effected significant change upon slurry ORP. When the ESP operation was changed to lower particulate removal, ORP dramatically increased from about 250 mV to above about 500 mV over the course of an hour, and the ORP remained steadily high during this operational setting. When the ESP was returned to normal operation, the WFGD ART slurry ORP declined slowly, eventually returning to baseline values. Therefore, upstream operations have been shown to have significant impact upon WFGD slurry chemistry.

Selenium oxidation state and phase were impacted by slurry ORP. At ORP levels below about 300 mV, selenium exists predominantly in the +4 oxidation state as selenite. Selenite occurs
with slurry solids and is easily removed by many wastewater treatment methods, including physical-chemical treatment methods. As slurry ORP increases above about 300 mV, selenium shifts to the +6 oxidation state to form selenate. Selenate is a dissolved species that passes through some wastewater treatment systems, causing concern for compliance with effluent limitations.

Changes in slurry ORP caused a pronounced effect on the fraction of mercury within the absorber slurry. When the ORP was under about 500 mV, slurry mercury was observed to partition predominantly with the solids, likely adsorbed to solids within the absorber slurry. As ORP increased to levels above 500 mV, most of the mercury was detected as a soluble ion within the slurry filtrate. In absence of additives that may sequester mercury as a sulfide compound, high ORP levels may cause mercury to be removed from association with slurry solids. Specifically, one infers that highly oxidative environments may cause mercury to dissociate from sorbents to which mercury had adsorbed, when in an aqueous environment. Further testing of this finding is warranted.

References:


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