



INSTITUTE OF  
CLEAN  
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**WHITE PAPER:  
PROCESS IMPLEMENTATION  
GUIDANCE FOR POWDERED  
SORBENTS AT ELECTRIC  
GENERATING UNITS**

**INSTITUTE OF CLEAN AIR COMPANIES**

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# Process Implementation Guidance for Powdered Sorbents at Electric Generating Units

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**Abstract:** With the deadline for MATS Compliance quickly approaching, many electric generating units will be installing pollution control systems that utilize powdered sorbents for the removal of mercury. While these applications have been practiced and proven for many years, the number of installations warrants a reminder about best management practices for these powdered materials to facilitate their process integration and safe handling. This paper presents the important characteristics of powders and a basic understanding of how they are applied to handling, transport, and injection. Best management practices are recommended for power plants to safely integrate, operate, and best utilize the applied sorbents and their injection equipment.

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## Introduction

Coal is an abundant source of energy in the United States (US). Over the past decade, this energy source has been highly scrutinized for associated environmental hazards. One such hazard, mercury, has been linked to significant health effects (USEPA, 1997; WHO, 2007). Due to these concerns, the US Environmental Protection Agency (EPA) finalized the Mercury and Air Toxics Standards (MATS) rule in December 2011 to limit mercury emissions from electric generating units (EGUs). The rule was published in the *Federal Register* on February 16, 2012 (77 FR 9304-9513). The MATS rule establishes limits on mercury emission for EGUs to less than 1.2 lb/TBtu (pounds per trillion Btu heat input) on a 30 day rolling average for most coal-fired units with the exception of low-rank coal, such as lignite-fired units, which have a limit of 4.0 lb/TBtu. Individual states also currently regulate mercury emissions from coal-fired EGUs.

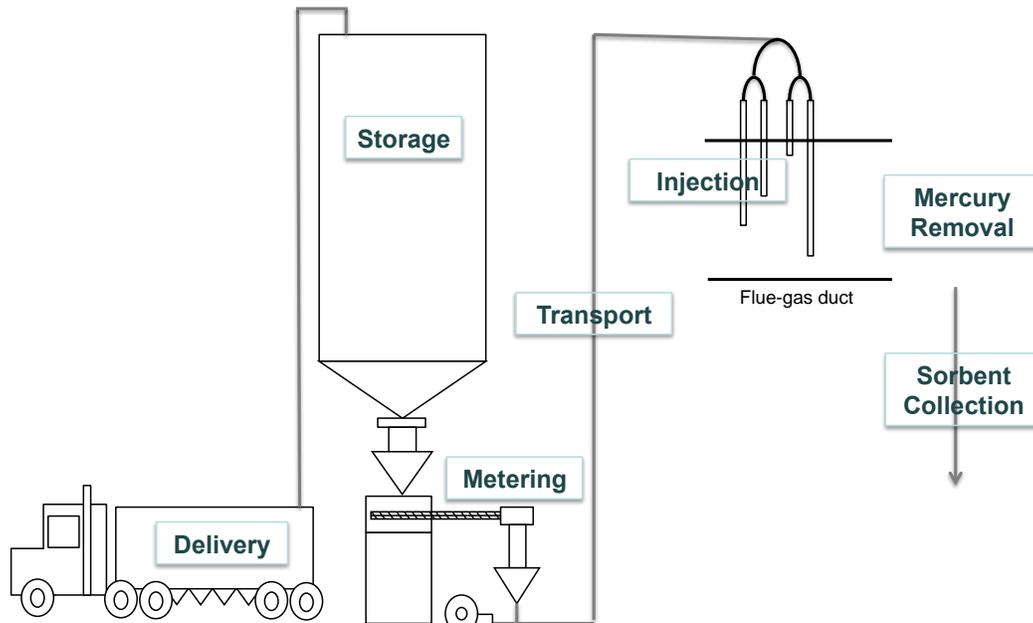
The industry has a range of options available to them to reach compliance levels. One proven control technology to remove mercury is the application of a powdered sorbent to flue gas. Powdered sorbents, in the context of this paper, are materials of a fine particle diameter in the micron range with an appreciable surface area available for adsorption and/or reaction with a target compound. The powdered sorbents being used for mercury control typically fall into two general categories: powdered activated carbon (PAC) and non-carbon based sorbents. Several suppliers now offer a wide range of powdered sorbents with varying material properties that are suitable for adsorption and/or reaction of mercury.

Activated carbon is a widely applied sorbent across many industries. It was originally used to improve the quality of drinking water thousands of years ago and can be applied in the powder or granular forms (Chowdhury et al., 2013). PAC began to be commercially used for gas phase mercury capture at municipal and hazardous waste combustors and medical waste incinerators, in the 1990's to meet EPA regulations for these facilities (USEPA, 1998). Around the same time, PAC started to be developed for EGUs as an active mercury control technology (Pavlish et al., 2003). PAC can be produced from various carbonaceous precursor materials (e.g. coal, wood, coconut, etc.) to produce a porous sorbent. When introduced in the flue gas, PAC physically and chemically adsorbs mercury through the interaction with the pores, functional groups and any additives.

Non-carbon based sorbents have been developed more recently to remove mercury from flue gas. As its name conveys, non-carbon based sorbents are primarily composed of a mineral or other non-carbon base material and can include various additives and/or treatments to encourage the uptake of vapor-phase mercury.

Generally, the application of powdered sorbents for mercury control will include several key steps as depicted below in Figure 1. First, powdered sorbents will be sourced from a supplier and transported to the user's application site. On site, the powdered sorbent will be stored until use. In most large-scale applications, the storage container will be a silo filled from a pneumatic tanker. Powdered sorbent being applied infrequently at low injection rates may alternatively make use of supersacks. The powdered sorbent will reside in its storage vessel until it is metered into transport lines and injected into a flue gas stream at a desired location. The sorbent particles mix with the flue gas where they remove mercury. The flue gas will flow to a particulate control device where the sorbent particles will be collected and separated from the now treated flue gas.

Typical applications utilize an electrostatic precipitator (ESP) or fabric filter (FF) to co-collect sorbents with fly ash particles or as a dedicated secondary particulate control device for the powdered sorbent. Wet scrubber sorbent collection has also been demonstrated, with sorbent injected either into the flue gas or into the scrubber directly.



**Figure 1.** Powdered Sorbent Handling Steps

Mercury capture by powdered sorbents is highly dependent on several factors. These factors include inherent features of the EGU such as coal/flue gas composition, existing air pollution control devices, mercury speciation, available contact time, distribution of the powder in the flowing gas stream, and temperature. An EGU may or may not have control over these factors. Further, the type and supplier of the powdered sorbent (which determines its effectiveness for mercury capture, particle size, and density), application method, and injection rate all have a significant influence on mercury capture success and can be controlled by the EGU. Therefore, it is important to be knowledgeable on the details of these aspects so that the user can be prepared to better operate, maintain, and troubleshoot their powdered sorbent injection systems for effective, safe, and reliable mercury control.

This whitepaper will recommend Best Management Practices (BMPs) for utilities using powdered sorbents for mercury control. Additional details pertaining to the important characteristics for mercury sorbents and how they are applied to handling, transport, and injection will be discussed. Key characteristics are described including particle size, tapped density, moisture content, flowability, and safety. Finally, appropriate responses for unusual situations are described. Specifically, the focus will be limited to the use of powdered sorbents applied to the flue-gas system for mercury removal.

## Best Management Practices

Procedures for handling powdered sorbents and operating their handling equipment are important to get the most out of the control technology and maintain a safe working environment. The following BMP guidance is provided to improve work practices for optimal results.

### Safety

Powdered sorbents have been used safely in many industrial applications with prudent operating practices and with properly designed equipment to prevent fire and explosions. Users should be familiar with the characteristics of the specific powdered sorbent to implement BMPs for safe handling. Each type of material used should have appropriate handling procedures for that material.

Workers are the first line of defense in preventing and mitigating work place incidents. If the people closest to the source of the hazard are trained to recognize and prevent those hazards, they can be instrumental in recognizing unsafe conditions, taking preventative action, and/or alerting management. Personnel working with the powdered sorbents and injection equipment should be trained to understand the material they are working with. Some key items that should be communicated to personnel are:

- Be familiar with the material's MSDS/SDS.
- Understand the fire or explosion potential of the powdered sorbent, including how to prevent and mitigate an occurrence (3 conditions for fire; 5 for explosion). Prevention mechanisms include:
  - Ground all transfer and collecting equipment to prevent static discharge.
  - Remove all ignition sources from material handling, transfer, and processing areas where powder dust may be present.
- Understand confined space procedures.
  - Test any enclosed or confined spaces prior to entry for adequate O<sub>2</sub> and sufficiently low carbon monoxide (CO) levels and follow all other confined space procedures.
- Use of respirator (dust masks) and eye protection are recommended if airborne dust is present and inhalation hazards exist.
- Avoid contact with eyes and skin. Use an eye wash station and thoroughly cleanse with water if contact occurs.

### Housekeeping

Good housekeeping is important when handling powdered sorbents due to their tendency to flow easily, accumulate, disperse, and/or potentially become airborne or mixed with storm water. The proper approach is to use good housekeeping for preventative measures. For general housekeeping practices, powdered sorbents should be handled similarly to fly ash and coal dust materials. The risk of these impacts depends on the location and conditions where a leak or buildup occurs.

Any powder that leaks or spills should be promptly cleaned through appropriate techniques. The user should develop procedures to manage the clean-up, referring to the powdered sorbents MSDS/SDS and some guidelines and best practices described below:

- **PAC Spill Clean-Up**

- If the area is enclosed, review and manage any combustible dust hazards, O<sub>2</sub> and CO levels, and select the most appropriate cleanup method. This may include vacuuming or careful sweeping as appropriate.
- Ground all transfer, blending, and dust collecting equipment to prevent static discharge. Remove all ignition sources from material handling, transfer, and processing areas where dust may be present.
- Piles of PACs have the ability to self-heat, particularly when partially wetted and subsequently dried. When conditions are unknown, evaluate activated carbon piles for potential temperature deviations prior to any agitation or cleanup effort (e.g., use of infrared (IR) imaging or a temperature probe).
  - **If no temperature deviation is observed**, vacuuming or careful sweeping techniques can be used. A dedicated vacuum system designed to handle combustible dust is the preferred method. If a vacuum system is not available, material can be carefully swept into piles with brooms and cleaned up.
  - **If temperature deviations are observed**, perform a job safety analysis with appropriate levels of smoldering mitigation while pile is carefully cleaned. Separate any smoldering areas from the remaining carbon and extinguish. Monitor remaining carbon for any additional smoldering by IR scan or temperature probe monitoring before final collection.
- Once all piles are swept up and clean, if there is process drainage, a wash down of the area can be done.
- Collected PAC can be disposed of into a proper dumpster or placed into normal handling systems if available to be reclaimed. Be sure to follow all locally required disposal regulations and requirements.

- **Non-Carbon Based Sorbent Spill Clean-Up**

- Vacuuming or careful sweeping techniques can be used. If a vacuum system is not available, material can be carefully swept into piles with brooms and cleaned up and placed into proper dumpster for disposal (be sure to follow all locally-required disposal regulations and requirements).
- Once all piles are vacuumed and/or swept-up and clean, if there is process drainage, a wash down of the area can be done.
- Collected sorbent can be placed into normal handling systems if available to be reclaimed.

## Operating Procedures

The following sections recommend specific operating procedures that pertain to powdered sorbent application at an EGU to encourage safe and effective material handling.

### *Delivery*

Powdered sorbent products used for mercury capture are typically delivered via truck to the plant site and unloaded pneumatically into an onsite silo. Upon crossing the fence line onto the plant site, the driver must follow all plant safety procedures and protocols applicable to the work.

Each facility should have its own safety procedures that must be followed but some important considerations for a driver unloading a product are:

- Be familiar with the MSDS/SDS for the product.
- Have the ability to see the off-loading line and the silo; if vision is obscured then plant personnel must assist the driver in off-loading. Full-time communication is needed, and the driver should remain with the truck.
- Wear all appropriate personal protective equipment, including, without limitation, hardhat, safety glasses with side shields, safety footwear, suitable hand protection (gloves), and hearing protection.
- Secure the truck and trailer from movement.
- Secure all transfer hose couplings with banding or strapping material to prevent movement and/or accidental release.
- Electrically ground the trailer utilizing grounding cables.
- Walk the entire transfer area including the silo and truck to ensure they are prepared for off-loading to begin.
- Do not pressurize the trailer in excess of the amount specified by the manufacturer.
- After fill and disconnect, conduct a safe walk around of the truck and trailer and ensure both are prepared for movement.

Operators should unload the sorbent within the design standards so that no leakage occurs when filling. The storage and the transport systems should have a handful of parameters to monitor (and log) that will indicate whether the operation is within normal range or not. These parameters include:

- Silo level monitor (high and low) – tied to alarms and permissives to fill.
- Vent filter differential pressure – tied to alarm and permissive to fill.
- Motive air pressure and temperature.
- Optional for carbon based sorbent silos: CO and/or temperature in the airspace above the high level indicator inside the silo and/or manual temperature screening (thermal imaging) on the outside of the silo wall.

Some small applications will utilize supersacks delivered via truck and would require different handling protocols.

### *Storage*

Once the powdered sorbent has been transferred to the storage vessel, some general principles of storage should be followed:

- Keep the material dry. Most powdered sorbents used for mercury control are not hygroscopic so simple care should be taken to not introduce water to the storage or conveying equipment. It is not necessary to use instrument air for processes such as conveyance or silo aeration as long as the air source is substantially dry.
- General combustible materials or strong oxidizers should not be stored near the powder.
- Keep ignition and heat sources away from storage and transport areas, and electrical sources properly grounded.
- Maintain stringent housekeeping in process areas.
- Avoid elevated temperatures.

In a confined space such as a storage silo, oxygen will be depleted over time. Personnel should not enter the confined space without allowing oxygen to be replenished and appropriate monitoring, or use of appropriate safety gear.

### *Self-heating*

During storage, the material can be at the risk of self-heating (specific details of self-heating properties are described in more detail in the Environmental, Health, and Safety characteristics below). Self-heating of powder sorbents (primarily PAC) can be tracked with CO and temperature monitoring. These conditions are extremely rare, but if elevated conditions occur, it could be an indication that a self-heating issue is arising. To provide an example, the general approach is given here. Each facility should develop site- and sorbent-specific protocols by working with its sorbent supplier. The appropriate temperature set points and thresholds will vary by material.

It is important to note that a high CO or high temperature measurement on its own does NOT necessarily indicate a smoldering heat-up situation within a PAC bed. A combination of both high CO and a high temperature does indicate that a smoldering heat-up is probable. If a user intends to utilize CO as an indication of potential smoldering within a PAC storage bin, it is suggested the following metrics be developed:

- The LEL for CO is 12.5% or 125,000 ppm. General guidance indicates that CO levels should stay below 10% of this value (1.25% or 12,500 PPM) to allow for an appropriate response time before any explosive limits are reached, while not causing false CO alarms.
- If a high CO reading is encountered, it is also important to validate the product temperature. It is suggested that each facility work with their supplier to develop threshold temperature guidance using thermal imaging of the outside of the storage silo (taken through the silo side-wall) or directly of a bed using one or more thermocouples or direct thermal imaging as the temperature monitoring point(s).

If both a high CO reading and a high temperature are measured, indicating a potential heat-up condition, a continuous purge of either CO<sub>2</sub> or N<sub>2</sub> is the best means of extinguishing any smoldering material. Once the inert gas is injected, the temperature should be monitored until the material is adequately cooled. This process can take up to several days. After it is

completely cooled, air can then be slowly reintroduced into the bin to re-passivate the sorbent particle surface with oxygen. The slow reintroduction of air is critical and should be done while monitoring temperature. Each site needs to develop further site-specific guidance on re-passivation in conjunction with the supplier.

It is NOT recommended to utilize water to quench a smoldering carbon heat-up inside a storage silo. It is far easier and safer to utilize an inert gas injection (CO<sub>2</sub> or N<sub>2</sub>) to extinguish any potential hot spots than to try and quench the entire carbon bed with water. In addition, most PAC storage bins are not designed structurally to hold large quantities of water, nor are they equipped with a water quench system as they were never intended to be filled with liquid.

### *Powder Transport and Injection*

After the injection system is in place, it should be monitored and maintained to ensure smooth operation. This would include:

- Monitoring powdered sorbent feed rate and blower pressures for irregularities.
- Regular inspection of the transport lines and injection points for any deterioration signs.
- Inspection and possible clearing of injection lances during scheduled downtimes to maintain proper particle flow.

Clear lances are especially important to maintain effective mercury removal and for optimal operational safety. Lance pluggage can be identified by flow or pressure drops. Sensors can be specifically installed in each lance or in the leg to the lance for early detection. Prompt cleaning of the lances should be scheduled if pluggage occurs.

### *Sorbent Collection*

The use of some mercury sorbents, primarily PAC, will increase the carbon content of the fly ash mixture. In typical systems this is a small increase on the order of one percent. In polishing baghouse systems such as EPRI's TOXECON configuration, the carbon can be the majority of the solids captured. As the carbon becomes the dominant component within the high-temperature process environment, the potential for self-heating of accumulated solids can also increase (Darenne & Stewart 2009). This phenomenon has been addressed in detail in a previous ICAC publication (ICAC, 2007) and a summary of the resulting best practices is provided here. Increasing the frequency of hopper emptying prevents material buildup and therefore circumvents potential issues. Frequent cleanouts are key to maintaining safe collection and disposal transport of collected solids. In addition to maintaining low solids accumulation in the hoppers, keeping a low temperature profile for the ash mixture by removing or limiting hopper heaters will also prove advantageous.

If operating protocols do not improve solid removal, several mechanical retrofits can be pursued to improve hopper emptying and ensure clear transportation. The following includes a highlight on some of the techniques that are available:

- Apply liners or coatings to reduce wall friction and improve movement of particles.
- Add a mechanical force to break cohesive forces or agglomeration and move material.

- Acoustic horns are recommended over vibrators to improve flow and prevent solidifying the ash particles. This becomes more important with PAC/ash mixtures as they tend to be more cohesive and adhesive than ash alone.
- Air cannons are a viable addition to eliminate buildup and dead stock, thus preventing caking and enabling solids flow. The volume of air introduced should be controlled to not introduce significant amounts of oxygen or create a dust cloud that could re-entrain sorbent or ash particles.
- Fluidizing air can be added to prevent plugging of the hopper discharge air.
- Monitoring methods such as temperature monitoring, CO detectors, and level switches can also be installed to alert the user of ash buildup or self-heating issues.

## Mercury Sorbents

Several characteristics of powdered sorbents will have a strong influence on mercury removal performance and dictate materials handling needs. Sorbent vendors provide product specifications to describe the typical characteristics for each particular sorbent and equipment suppliers will utilize these characteristics to design the handling systems. This section describes these typical specifications in detail to promote a better understanding of what they are, how they relate to the BMPs, and how to identify and troubleshoot potential deviations from normal operation.

### Particle Size

Particle size is an important powdered sorbent parameter that plays a role in every aspect of the powdered sorbent handling steps. Size affects the powder flow (delivery, storage, metering, transport, injection, and collection), and in some cases, mercury removal performance.

#### What it is:

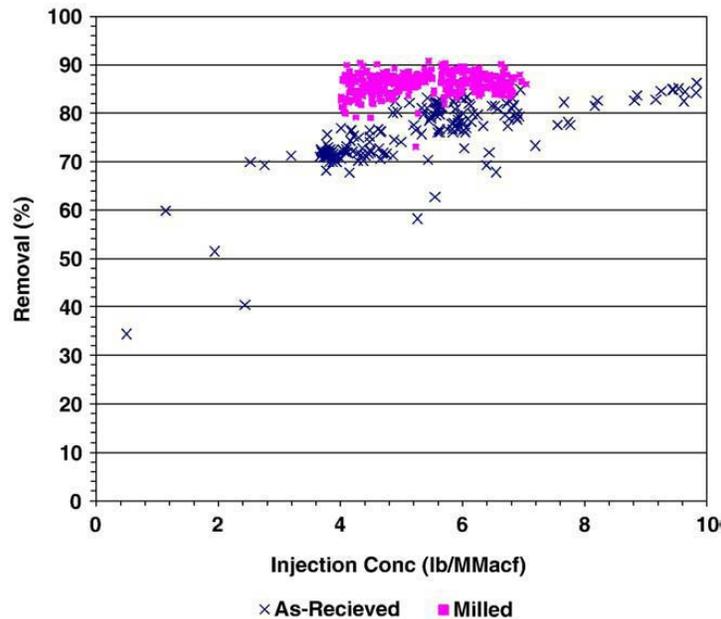
Particle size for powdered sorbents is used to reference an approximate particle diameter assuming a nearly spherical shape. Powdered sorbents contains a range of particle sizes. For sorbent injection applications, particle size will commonly be measured as percent passing a mesh size or as a full distribution. Table 1 below shows the typical reference methods used to determine particle size. A sizing specification of 95% or greater passing through 325 mesh is typical for powdered sorbents associated with mercury removal. This mesh size corresponds to particle size that could pass through a 44  $\mu\text{m}$  gap (i.e. greater than 95% of the particles will have a diameter smaller than 44  $\mu\text{m}$  and the remaining fraction will have larger diameters). At this percentage, the particle size distribution will range from about 1 to 100  $\mu\text{m}$ . Alternatively, a more detailed analysis using laser light scatter can provide specific particle sizes across the size range. The particle size distribution can be characterized by a mean size, typically the mass mean diameter (MMD), or by a cumulative size, typically the percentage of the particles less than a specific value (e.g.  $d_{95}$ ). The MMD varies by product and can be obtained from the supplier. The MMD of PAC have been cited between 15 and 25  $\mu\text{m}$  (Sjostrom, 2014). Fine grind can have a smaller MMD.

**Table 1.** Reference methods for particle size measurement

Typ. Method Label	Method Description	Reference Method No.
Passing through 325 mesh	Standard Test Method for Determination of Particle Size of Powdered Activated Carbon by Air Jet Sieving	ASTM D5158 - 98(2013)
Particle size distribution	Particle Size Distribution by Laser Light Scattering	ASTM D4464 - 10 ASTM B822 - 10

Why it matters:

Observations of duct injected PAC show some trend toward greater **mercury removal** with decreased particle size when PAC is injected upstream of an ESP. The benefit of maintaining a small particle size has been demonstrated both theoretically and in testing demonstrations (Chen, Rostam-Abadi & Chang, 1996; Chang, 1998; Pavlish et al., 2003; Sjostrom et al., 2009; Clayton, Lowring & Wong 2014). For example, a study was conducted at a 630 MW<sub>e</sub> unit with activated carbon injection (ACI) upstream of an ESP. As received standard PAC was compared to PAC that was milled on site to reduce the particle size. Figure 2 illustrates how the smaller particle size showed an incremental improvement in mercury removal percentages (Sjostrom et al., 2009).



**Figure 2.** Mercury removal vs. injection concentration for larger (as-received) and smaller (milled) particle size PAC (Sjostrom et al., 2009).

There are a number of explanations put forth for this improvement. Solely from the sorbent perspective, mercury removal will depend on mass transfer from the flue gas to the particle surface, reactivity, and sorption capacity. Any of these factors can affect the mercury removal potential. Decreasing particle size relates to an improvement in mass transfer (Chen, Rostam-Abadi, Chang, 1996; Pavlish et al., 2003). Another contributing factor is that for a given mass of sorbent, a decrease in particle size will increase the number of particles. This increase allows for

a more thorough coverage of the gas stream, which increases the likelihood of mercury particle interactions and thereby mass transfer. An increase in the number of particles also increases the external surface area for adsorption of mercury relative to the treatment volume, which also increases mass transfer by decreasing the necessary diffusion distance. (*Note: this is contingent upon the metering of sorbent into the gas stream using gravimetric (loss in weight) feeders to control the feed on a mass basis, which is the most common technique employed in ACI systems.*) In the dynamic flue gas environment upstream of an ESP, which has limited contact time and low concentrations of mercury, mercury removal by PAC will often be mass-transfer limited making particle size an important property. In emission systems with long sorbent/flue gas contact times, mass diffusion limitations and contact probability become less of an issue, and sorbent particle size becomes less of a factor.

The material handling during **delivery, storage, metering, transport, and injection** of powdered sorbents will vary somewhat depending on their particle size, but as a general rule, a sorbent injection system designed for standard sized sorbents will also handle fine grind (i.e. smaller diameter than the typical ranges presented above) sorbents. If the particle size and/or particle size distribution deviate from the design specification, the user should verify with the equipment provider if any changes to the feed system such as fluidization demands are required to accommodate the smaller size particles. It is observed that powdered sorbents trend toward greater fluctuation in bulk density with lower particle size. The fluctuation in bulk density affects equipment or processes where the sorbent is not settled (e.g. in aeration zone of silos, rotary valves, and screw feeders). While there will be variations in effect between different equipment configurations, as a general observation, the affect of fine grind sorbents on a standard sorbent injection system in the zones mentioned above may result in increased flowability, greater tendency for surging of flow or flushing, and decreased steady-state feed rates. All of these issues can be addressed with adequate equipment design. When filling trucks, fine grind sorbents may need more time or an additional mechanism to settle in order to maintain full transport weights. Powder **injection** equipment can be designed to counteract agglomeration effects and promote particle distribution for in-duct reactions.

Another consideration of sorbent particle size is any effect it may have on powdered sorbent **collection** and, therefore, particulate emissions from the plant when it is injected into the flue gas stream. While decreasing particle size can have some benefits, it is important to keep in mind that the particles still must be captured with high efficiency by the particulate control device. With the given size parameters discussed above, PAC injection has had more than 10 years of success in controlling mercury in this manner without increasing the PM emission (often measured as percent opacity) of most plants. The particulate control devices, either ESPs or fabric filters or combination of these technologies (i.e. TOXECON™), in coal combustion plants are designed for >99% to >99.99% efficiency of fly ash collection. Fly ash typically falls in the particle size range of 0.01 µm to 100 µm. As discussed, most powdered sorbents will have a substantially larger minimum diameter than fly ash, which provides successful removal with a FF. Removal in an ESP will be determined by the sorbent properties (primarily particle size and conductivity) in combination with ESP operating features (e.g. rapper schedule, rapper intensity, specific collection area, design velocity, etc.) and the preexisting fly ash characteristics. In general, high PAC collection efficacies resulting in little to no change in opacity been observed at typical sorbent injection rates (Starns et al., 2003). An improvement in ESP efficiency due to

use of brominated PAC injection has even been observed in some full-scale test programs in the US. Improved collection levels were attributed to a conductivity increase due to bromination (Landreth, 2008). The addition of non-carbon based sorbent has also been reported to result in an increase in ESP collection efficiency due to a marked reduction in bulk fly ash resistivity (Gale & Butz, 2014). It is noted that with the coming of the MATS rule, utility boilers will add measurement systems for particulate mass measurements. While it is not expected that sorbent injection will create compliance excursions with the MATS particulate mass limit of 0.03 lb/MMBtu, less mass emission data has been gathered to verify this assertion. It is recommended that plants investigate their particulate emission with sorbent injection operating at the required rate before their MATS compliance deadline.

Additional considerations when dealing with any fine size powdered material are health, safety, and environmental impacts. These aspects will be discussed in sections that follow.

#### What to do:

Work with your equipment and sorbent vendors to ensure compatibility. Understand the specification for the selected powdered sorbent particle size. Make sure design requirements match with your equipment specifications.

### **Tapped Density**

Particle tapped density is a characteristic that depends on the sorbent make-up, size, and inter-particle voids. It will play a role in the delivery, storage, and transport aspects of the sorbent handling.

#### What it is:

Tapped density is a typical property of powdered sorbents found in specifications. It is defined by ASTM as the bulk density of a powder (or granular solid) after consolidation/compression prescribed in terms of "tapping" the container of powder a measured number of times, usually from a predetermined height. Tapped density is reported in terms of mass per unit of volume. In the US, the typical unit for tapped density is pound per cubic feet (lb/ft<sup>3</sup>). The ASTM reference method for tapped density is ASTM D7481 – 09. This method is labeled as Standard Test Methods for Determining Loose and Tapped Bulk Densities of Powders using a Graduated Cylinder. A laboratory instrument is manufactured to perform the ASTM method, with accurate and repeatable results easily produced using these instruments. *(Note: Tapped density is sometimes confused with apparent density. The latter is the mass per unit volume of loose fill material. Apparent density is not a good reference method for powdered sorbents because powdered sorbents display more variation in bulk density due to the ability to settle in a bed.)*

#### Why it matters:

This property is important to powdered sorbent users because it provides the measure of mass per unit volume required to calculate the weight capacity of tankers, silos, supersacks or other vessels for **delivery** or **storage** of the sorbent. A measure of sorbent weight is more useful to users than measures of volume because sorbents are sold on a weight basis and typically metered on a mass basis (gravimetrically). Mass rate metering is based on either a mass per unit of time

(e.g. lb/hr.) or on a mass rate calculated from boiler conditions such as pound of sorbent per million actual cubic feet of flue gas (e.g. lb/MMacf) or mass per unit of boiler load (e.g. lb/MW).

Tapped density of a powdered sorbent, when used for design purposes such as feeder screw sizing, typically produces inaccurate results. This is due to the characteristic of powders to hold air pockets within a bed. In moving or mixing beds of powdered sorbent, actual bulk density is dependent upon its stress and strain history, temperature, moisture content, and particle size. Due to changes in these variables, the actual bulk density can be as much as 50% lower than the tapped density value. Therefore, the appropriate density range must be considered during the design of the equipment, especially where the powdered sorbent is not settled or air pockets exist in the bed (i.e. where the bulk density will have a tendency to be significantly lower than the tapped density). Bulk density can be measured using uniaxial compression of a loosely packed bulk material.

#### What to do:

Working with your equipment and sorbent vendors, understand the specification for the tapped density. Make sure the equipment and powdered sorbent specification are mutually compatible. If the powdered sorbent density deviates from the design specification, the user should verify if any changes to the feed system are required to accommodate the change.

## Moisture Content

The ability of a powdered sorbent to take up and hold water affects how much effective sorbent is being used and will determine handling methods for storage and distribution.

#### What it is:

Most powdered sorbents will typically contain moisture on the surface and in their pore structure. A portion of the water making up the moisture content is normally physically adsorbed. This moisture is loosely bound and will easily be dispelled by elevating the temperature to around water's evaporation point. The other portion of water in PAC is tightly bound to oxygen functional groups. This moisture is not easily removed but is typically a low percentage. Moisture content is measured by ASTM Method D2867.

#### Why it matters:

In typical concentrations (e.g. <10%), moisture content of powdered sorbents does not detract from (may even enhance) mercury performance. High moisture may start to affect the flowability of powdered materials in the **storage, metering, transport, and injection** of powdered sorbents. Particles high in moisture may start to have a higher tendency for agglomeration and clogging, resulting in mass flow issues and reduced mercury removal.

#### What to do:

During the selection of your sorbent vendor, understand the specification for the moisture content and ensure that equipment design can accommodate these requirements. Follow the BMPs to properly store the powdered sorbent to limit excessive moisture uptake.

## Flowability characteristics

The flow characteristics of bulk solids are critical for the design of storage, transport, and injection systems to deliver powdered sorbent. The overwhelming majority of powdered sorbent injection for mercury control will utilize a large storage silo connected to a pneumatic conveying system. A blower located near the injection system will provide the motive air to transport sorbent particles from either an eductor or rotary valve into the transport line where they are conveyed as a dilute phase mixture to the injection point. Pneumatic conveying design will vary by supplier. While this whitepaper highlights critical aspects, more detailed technical information on the design parameters is available in another ICAC whitepaper, “Bid Specification Information Requirements and Bid Evaluation Form for Activated Carbon Injection Systems” (ICAC, 2010), pages 19-26. Keep in mind that the reference paper is from 2010 and may not reflect the state-of-the-art equipment design in total today. But, it is relevant in general for PAC. Proper design for other sorbents needs to be evaluated based on differences in moisture, flowability properties, density, and other parameters.

### What it is:

Certain powder properties are critical to the design of material handling equipment. Multiple test laboratories are available to perform measurements for these properties<sup>1,2,3</sup>, which are described below:

<b>Property</b>	<b>Utility</b>
Cohesive strength	Used to determine discharge outlet dimensions to avoid ratholes.
Compressibility	Provides bulk density as a function of consolidating pressure. Consideration must be given to using the proper value for such calculations as silo loads, silo capacity, and feed density.
Wall friction	Sets the hopper wall angles. Walls must be steep enough and have sufficiently low friction to allow material to reliably flow along them.
Permeability	In a silo with fixed discharge port dimensions, gas permeability sets the critical steady state discharge rate achievable with the material.
Fluidization	Fluidization behavior of a material is utilized in proper design of a silo bottom if an air assisted discharge design is utilized.
Saltation point	Transition point between dilute and dense phase transport.

There are multiple equipment design firms quite capable of designing systems that can reliably feed the variety of mercury control reagents currently on the market. These manufacturers use the properties above in the system design and often provide internal proprietary design guidance that is derived from engineering practice. When commissioning a system, it is important to note that flexibility should be considered on the front end of the design process such that the system that is installed will be capable of reliably feeding an appropriate range of products.

### Why it matters:

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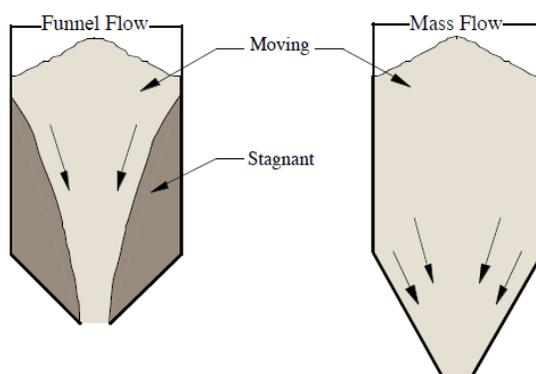
<sup>1</sup>Jenike & Johanson, [www.jenike.com](http://www.jenike.com)

<sup>2</sup>Solids Handling Technologies, [www.solidshandlingtech.com](http://www.solidshandlingtech.com)

<sup>3</sup>Mercury Scientific, Inc. [www.mercuryscientific.com](http://www.mercuryscientific.com)

### *Storage and metering*

The first stage of a powdered sorbent handling system is a storage vessel that reliably removes bulk solids from storage into a feed metering device. Powdered sorbents will flow through a silo with funnel flow or mass flow, as seen in Figure 3. In the left-hand flow pattern in Figure 3, called funnel flow, an active flow channel forms above the outlet, with stationary material at the periphery. As the level of the material in the hopper decreases, layers of the non-flowing material may or may not slough into the flowing channel. The right-hand flow pattern, called mass flow, occurs when all of the material contained in the silo is in motion whenever any is withdrawn from the hopper at the bottom. Material from the center as well as the periphery moves uniformly toward the outlet. Dry sorbent silos should be designed to operate under mass flow as they provide a first-in/first-out flow sequence, eliminate stagnant material, and provide a steady discharge with a consistent bulk density and a uniform, well-controlled flow.



**Figure 3.** Illustration of flow patterns in a silo.

In some small applications, bulk supersacks could be used for storage instead of silo systems. These sacks can also encounter the flow problems as described above and their handling system should include design aspects to protect against it. If the powdered sorbent is not leaving the storage vessel as expected, the equipment vendor and sorbent supplier should be contacted to address potential flow problems (e.g. bridging, rat-holing, caking, etc.) that could be a result of the design or material properties.

Sorbent should flow from the storage vessel into a metering device. As mentioned above, gravimetric metering systems are highly preferred to volumetric metering system. The weight of the sorbent can be accurately and continuously measured using the gravimetric mode thereby avoiding the potential for inconsistent sorbent conveyance. Reliable metering is critical to understand performance metrics and to efficiently utilize the sorbent.

### *Transport and Injection*

After powdered sorbent leaves the storage vessel and metering device, the flowability properties will also impact the material movement through the transport lines and injection lances. As material is conveyed along a transport line, a minimum volumetric flowrate is necessary to achieve a velocity high enough to keep the particles above their saltation point. This keeps the particles moving through the line so they do not deposit and cause blockages.

After the sorbent particles have been successfully transported from the storage location to the flue gas duct where they will be introduced, the location and mode of injection will have a significant effect on the performance of the sorbent. Sorbents are typically injected downstream of the economizer and upstream of a particulate control device. The injection location will be plant specific and should be selected based on properties of the powdered sorbent, temperature, contact time, space, particulate control device, interaction of other additives (such as dry sorbent injection, conditioning agents, oxidizing agents, etc.) and other flue gas chemistry considerations. The injection system will vary with suppliers but ultimately the same goals are being pursued: (1) optimized particle size (or reduced agglomeration) and (2) high degree of particle dispersion in the flue gas duct, commensurate with flue gas flow distribution. These goals can be achieved through changing the powdered sorbent, injection lance design, lance location and orientation, duct modifications, inclusion of static in-line mixers, etc.

In addition to particle size, particle distribution is critical to maximizing the performance of the sorbent. Computational fluid dynamic (CFD) or other flow modeling can be a useful tool to ensure the sorbent is injected at the best location in the flue gas duct, particularly for injection upstream of ESPs, where it is critical to achieve good mixing in a relatively short residence time. Various lance designs and fixed features that can be added to the duct system are also available to improve sorbent distribution and mixing with the flue gas. It is important to ensure that proper attention has been dedicated to the injection design so that sorbent is being efficiently utilized.

### *Collection*

After injection and reaction with the flue gas, the particulate control device of the unit will collect sorbent particles. As discussed above, this typically entails separation of the particles from the flue gas in an ESP or FF, or sometimes a wet scrubber. Collected particles are directed to hoppers that are emptied to transport the solids to their final disposal location.

### What to do:

Pneumatic powder conveyance is a widely applied technique with standard practices that equipment vendors will follow. A few adaptations and optimal design considerations particular to the use of mercury sorbents are presented here.

To improve **storage** and **metering** of powdered mercury sorbents, silo air is often added. A variety of air injection valves are commercially available to be incorporated into the silo design. These devices can often allow adaptation of a given silo design for the storage and feeding of materials with different flow properties. Further, they can be utilized to overcome flow stoppages due to bridging and/or rat-holing. The number, location, preferred design, and operating protocol for these devices is best decided in consultation with the device manufacturers or equipment suppliers noted earlier. The operating protocol consists of the pulsing sequence, pulse duration, and interval between pulses, which can most reliably be developed during field commissioning of the system.

During powder **transport** and **injection**, several recommendations should be considered for optimal sorbent utilization:

- Optimize the air velocity - The velocity should be greater than the saltation velocity (the minimum air velocity to maintain the particles in suspension) through the entire pipeline length to ensure that particles do not settle out and clog the lines. Increasing the air velocity too much, however, will increase the particle impaction at the bends thereby increasing the wear on the system as well as the propensity for impact agglomeration. Therefore, a good air velocity will be around 3 to 4,000 ft/min with pressures around 5 – 14.7 psig.
- Minimize bends – reducing the number of bends will reduce pressure loss due to friction in the transport pipeline. Lower pressure drops will help maintain the solids velocity over the distance of the transport pipeline.
- Utilize long radius elbows – at pipeline bends, particles will collide with the pipe walls disturbing the velocity and causing wear to the pipe material. Over time these bends will lose their integrity and be potential sources of particle leaks. Decreasing the bend angle, utilizing ceramic lined/backed pipe, and/or addition of sacrificial metal on the outside of the pipe bend will maintain the particle velocity and reduce pipe attrition and extend pipe life.
- Have balanced splits and equal line distance – sorbent particles will flow from one source to several injection lances. The pipeline and lance system should be balanced so that the pressure profiles are similar in all lines to promote uniform particle flow and injection into the flue gas.
- Install smooth transitions – as the particle flow is split and transitioned from one section to the next, particle build up and clogging can occur. Ensure that these transitions are smooth to promote particle transport and minimize block-ups.
- Consider the necessary design range - the blower and eductor should be sized such that the operation can pneumatically convey a wide range of injection rates that would cover the range of the mercury removal needs for each specific application.
- Include access to the transport lines and injection lances for maintenance.
- Carry out CFD modeling to determine the optimum locations of the lances to maximize sorbent dispersion at the inlet to the particulate control device.

For the **collection** system, proper bin shape and construction will promote reliable mass flow. The introduction of sorbents to the typical solids collected (i.e. fly ash) could necessitate a change in the solids removal procedures to maintain mass flow similar to the storage silos described above in the BMPs. Additionally, detailed design concepts can be reviewed in a previous publication by ICAC (ICAC, 2007).

### **Environmental, Health and Safety characteristics**

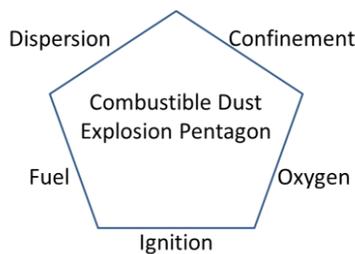
While powdered sorbents have been in industrial use for decades, safety knowledge and procedures should continually be refreshed and followed to maintain their safe application. Key focal points are housekeeping, personnel protection, environmental protection, good equipment design and operations training that is mindful of the properties of the powdered material. Discussed below are the specific hazards of dust explosion and fire.

What it is:

### *Dust Explosions*

As discussed above, the powdered sorbents being utilized for control of gas-phase mercury at EGUs are typically finely divided powders that exhibit particle sizes in the sub-100 um range. In this size range, there can be a potential for dust explosions based on the chemical make-up and reactivity. The National Fire Protection Agency (NFPA) defines a combustible particulate as “a combustible particulate solid that presents a fire or deflagration hazard when suspended in air or some other oxidizing medium over a range of concentrations, regardless of particle size or shape” (NFPA 654-2006). Combustible dusts are further defined by the Occupational Safety and Health Administration (OSHA) as containing particle size of less than 420 microns (in comparison, table salt has an average particle size of 100 microns and Human hair is 40-300 microns) that present a fire or explosion hazard when dispersed and ignited in air.

Combustible dusts constitute a small portion of particulate solids but are present in many industrial settings. For a dust explosion to occur, five components are required and can be represented with a pentagon as shown in Figure 4. Eliminate any one component and the dust explosion cannot occur.



**Figure 4.** The dust explosion pentagon. Eliminate any one condition and the dust explosion cannot occur.

The ease of ignition and the severity of a combustible dust explosion are influenced by particle size, volatile matter content, moisture content, ambient humidity, oxygen available for combustion, the shape of dust particles, and the concentration of dust in the air. The most common way to determine if a given material is susceptible to exploding is to subject the material to the Standard Test Method for Explosibility of Dust Clouds (ASTM E1226). Testing services for this method are readily available from vendors such as Chilworth Technology, Inc., Fike, and Fauske & Associates. Tests are conducted in a standardized 20-liter spherical apparatus wherein a small sample of dust is suspended in the vessel and subjected to an ignition source in the form of 10 J chemical igniters. The pressure in the test apparatus is recorded as a function of time. The maximum pressure observed is denoted as  $P_{max}$ .  $K_{st}$ , the dust deflagration index, is derived from the maximum rate of pressure increase recorded during testing. The two indices are used in the design and selection of equipment and components for explosion venting, suppression, and containment. Some example materials and their dust explosion class ratings are given in Table 2 below. For mercury control powdered sorbents, commercial PACs would be considered mildly explosible (Class 1), similar to sugar, and non-carbon based sorbents may be categorized as not explosible (Class 0).

**Table 2.** Dust Explosion Class Ratings<sup>4,5</sup>

Dust explosion class	$K_{st}$ (bar.m/s)	Characteristic	Typical Material
St 0	0	No explosion	Silica
St 1	>0 and $\leq 200$	Weak explosion	Powdered milk, charcoal, sugar
St 2	>200 and $\leq 300$	Strong explosion	Cellulose, wood flour
St 3	> 300	Very strong explosion	Aluminum, Magnesium

Reducing the explosion hazard includes eliminating at least one of the five ingredients: fuel, oxygen, an ignition source, dispersion of the dust in sufficient quantity and concentration, and/or confinement of the dust. For example, keeping silos free from ignition sources by monitoring wall temperatures routinely, as well as addressing and avoiding other potential ignition sources, can prevent the five criteria from being met. These areas were addressed more specifically in the BMP section.

### *Fire Potential*

Even if a combustible dust does not have all of the conditions to satisfy the explosion pentagon, there still may be a fire risk. For a fire to occur, three required components or conditions must be present: (1) fuel, (2) oxygen, and (3) ignition (heat). They are sometimes referred to as the fire triangle. **Eliminate one required component of the fire triangle and a fire cannot occur.**

### *Self-Heating*

Some powders may exhibit a characteristic known as self-heating. There are conditions under which PAC can undergo self-heating, which can be managed to avoid fire risks. With proper storage and handling no issues of self-heating should occur. However, when storage conditions allow the rate of heat generation to be greater than the rate of dissipation, heat accumulates and self-heating can occur (ICAC, 2007).

Studies indicate that self-heating in activated carbon is predominantly due to the chemical oxidation of carbon. The primary source of oxidation is through chemisorption of oxygen. This oxidation is relatively slow at ambient temperature but the process is exothermic, i.e. generates heat. If not dissipated, the temperature of the stored material increases as does the rate of oxidation. If the self-heating is unabated, the minimum ambient temperature for self-ignition can be approached. Cameron and MacDowall (1972) tested a range of carbons and found that the critical ignition temperature is typically in the 250 – 480 °C temperature range, well above ambient conditions for a typical storage silo. Once this critical temperature is reached the material may start to smolder or even freely combust. PAC tends to smolder slowly, sometimes without producing smoke or a flame. Combustion will continue as long as adequate oxygen, heat, and fuel (discussed above as the fire triangle) are present. In addition, most PAC producers

<sup>4</sup> OSHA CPL 03-00-008 (Combustible Dust National Emphasis Program)

<sup>5</sup> NFPA 68 (Standard on Explosion Prevention by Deflagration Venting)

have introduced passivation steps in their manufacturing processes to minimize the possibility of carbon self-heating.

As described in the UN Manual of Tests & Criteria, Section 13.6 Test 3(c), there is a standard test available to determine the self-heating potential for a material (UN, 2009). The test protocol compares the thermal response of a sample of material vs. an inert reference. Both samples are placed into glass tubes in an oven controlled at 75 °C. A thermocouple is placed in the material in each tube. The material is held at 75 °C for 48 hours or until the sample explodes or ignites, whichever occurs first. If the sample explodes or ignites the test result is designated “+”. Further, if a temperature differential of 3 °C or greater is noted, the result is “+”, i.e., the material is considered self-heating.

#### Why it matters:

The explosivity, flammability, and self-heating characteristics of your applied sorbent must be taken into account for the design of the **delivery, storage, metering, transport, injection, and collection** systems to mitigate potential safety issues.

#### What to do:

Proper design in concert with best management practices will result in safe and reliable handling of powdered sorbents. Equipment and structures that are exposed to powdered sorbent should have the proper electrical and fire safety ratings. BMPs for personnel safety and housekeeping, such as those discussed above, are key to maintaining a safe workplace.

## **Concluding Remarks**

In summary, powdered sorbents are a reliable and safe mercury control technology EGUs can apply for MATS compliance. As with any control technology, sorbents should be integrated into the process and safety management practices to ensure their safe and effective use. Sorbent and equipment vendors are readily available to provide the appropriate solution to meet your needs, upgrade systems to meet necessary changes, and troubleshoot process or performance issues.

PAC has been used safely in many industrial applications with prudent operating practices for personnel protection and with proper fire and explosion preventing equipment (e.g. use of proper PPE, monitoring silo CO and temperature, avoidance of large-volume deposits in the process by continuous and monitored discharge from the hoppers to avoid fire risks, and good housekeeping for spill cleanup). Each material will require its own appropriate handling specifications. Thus, users should be familiar with the characteristics of the specific powdered material selected to ensure safe handling guidelines are followed.

## References

- Cameron, A., & MacDowell, J.D. (1972). The self heating of commercial powder activated carbons. *Journal Applied Chemistry and Biotechnology*. 22 (9), 1007-1018.
- Chen, S., Rostam-Abadi, M., & Chang, R. (1996). Mercury removal from combustion flue gas by activated carbon injection: mass transfer effects. *Preprint Paper - American Chemical Society, Fuel Chemistry*. 41 (1), 442-446.
- Chang, R. (1998). *Development and Evaluation of Low-Cost Sorbents for Removal of Mercury Emissions from Coal Combustion Flue Gas*. Interim Report TR-110532. September 1998.
- Chowdhury, Z., Summers, R., Westerhoff, G., Leto, B., Nowack, K., & Corwin, C. (2013). *Activated Carbon Solutions for Improving Water Quality*. American Water Works Association (AWWA). Denver, CO.
- Cayton, R., Lowring, J. & Wong, J. *Designing Advanced Activated Carbons for Enhanced Mercury Capture*. 2014 AIChE Annual Meeting, Atlanta, GA.
- Derenne, S., & Stewart, R. (2009). *Toxecon retrofit for mercury and multi-pollutant control on three 90-MW coal-fired boilers*. Final Report: Project Performance and Economics. DOE Cooperative Agreement No. DE-FC26-04NT31766, Report No. 41766R23. December 2009.
- Gale, T., & Butz, J. (2014). *Powder-Sorbent Alternatives to SO<sub>3</sub> for ESP Conditioning*. Energy, Utility & Environment Conference. Phoenix, AZ. February 3 - 5, 2014
- Institute of Clean Air Companies (ICAC). (2007). *Design and Operation of Fabric Filter and Electrostatic Precipitator Hoppers with High-Carbon Ash*. Publication Prepared by the Mercury Control Division. October 2007.
- Institute of Clean Air Companies (ICAC). (2010). *Bid Specification Information Requirements & Bid Evaluation From for Activated Carbon Injection Systems*. Publication ICAC-HG-1. March 2010.
- Landreth, R. (2008) *Gas-Phase Brominated PAC for ESP Performance Improvement*. Energy, Utility & Environment Conference. Tucson, AZ. January 27 -30, 2008
- Pavlish, J., Sondreal, E., Mann, M., Olson, E., Galbreath, K., Laudal, D., Benson, S. (2003). Status review of mercury control options for coal-fired power plants. *Fuel Processing Technology*. 82. 89-165.
- Public Health and Environment, World Health Organization (WHO). (2007). *Exposure to Mercury: A Major Public Health Concern*. WHO Document Production Services, Geneva, Switzerland, 2007.

- Sjostrom, S., Dillon, M., Sonnelly, B., Bustard, J., Filippelli, G., Glesmann, R., Orscheln, T., Wahlert, S., Chang, R., & O'Palko, A. (2009). Influence of SO<sub>3</sub> on mercury removal with activated carbon: full-scale results. *Fuel Processing Technology*. 90. 1419-1423.
- Sjostrom, S. (2014) Activated Carbon Injection, in *Mercury Control : for Coal-Derived Gas Streams* (eds E. J. Granite, H. W. Pennline and C. Senior), Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim, Germany. doi: 10.1002/9783527658787.ch18
- Starns, T., Bustard, J., Durham, M., Martin, C., Schlager, R., Sjostrom, S., Lindsey, C., Donnelly, B., Alfonso, R., Chang, R., & Renninger, S. (2003). *Results of Activated Carbon Injection Upstream of Electrostatic Precipitators for Mercury Control*. MEGA Symposium. Baltimore, MD. 2003.
- United Nations (UN). *Classification procedures, test methods and criteria relative to explosives of Class I*. Copyright 2009.  
[http://www.unece.org/fileadmin/DAM/trans/danger/publi/manual/Rev5/English/01en\\_part1.pdf](http://www.unece.org/fileadmin/DAM/trans/danger/publi/manual/Rev5/English/01en_part1.pdf) (accessed October 2013)
- United States Environmental Protection Agency (USEPA). (1997). *Mercury Study Report to Congress. Volume V: Health Effects of Mercury and Mercury Compounds*. EPA-452/R-97-007. December 1997.
- United States Environmental Protection Agency (USEPA). (1998). *Study of Hazardous Air Pollutant Emissions from Electric Utility Steam Generating Units*. Final Report to Congress. EPA-453/R-98-004a, February 1998.