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Reducing Mercury Emissions by  
Improving Total PM Control

*Beaumont Environmental Systems*

Willard Goss  
Beaumont Environmental Systems  
108 Lintel Drive  
McMurray, PA 15317  
Phone 724 941-1743  
Willgoss@adelphia.net

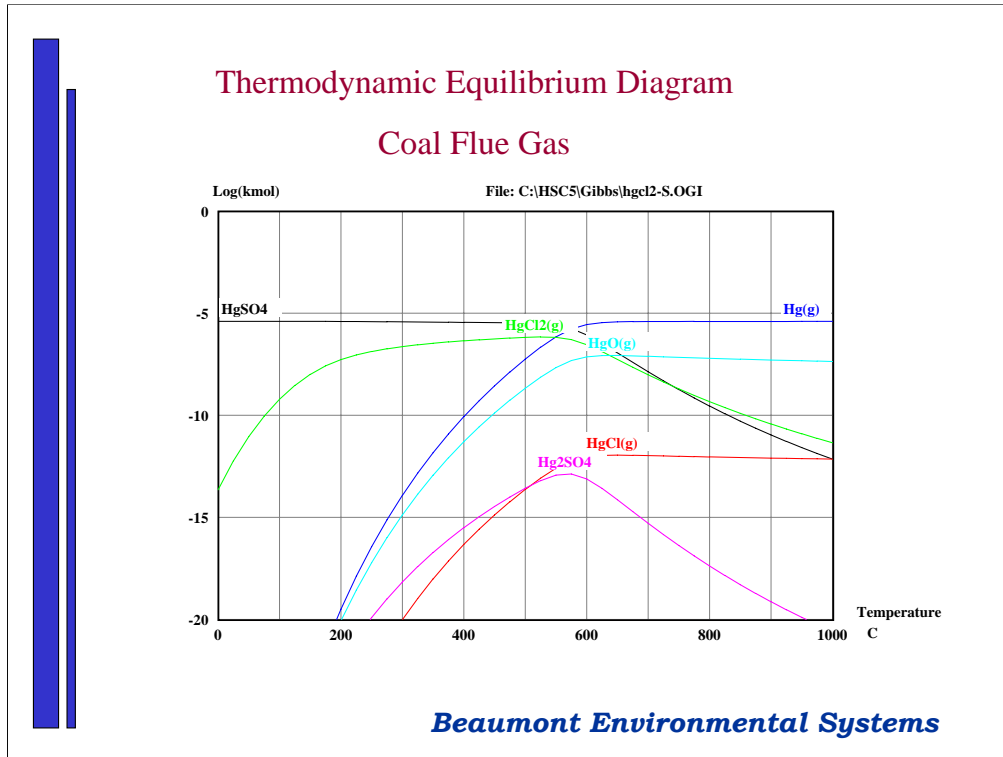


## Mercury Uptake

- Flue Gas Acids
  - SO<sub>2</sub>, SO<sub>3</sub>/H<sub>2</sub>SO<sub>4</sub>, HCl, NO<sub>2</sub>
  - HCl and Carbon (Oxidation & Binding) Have been Studied
- H<sub>2</sub>SO<sub>4</sub>
  - Role is starting to be studied
  - Appears Combined with Cooling to be Important using existing carbon and SO<sub>3</sub>.

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Acids needed to oxidize mercury; HCl and LOI carbon only goes so far, gas cooling and conditioning with SO<sub>3</sub>/H<sub>2</sub>SO<sub>4</sub> can get you beyond 90% control without adding more carbon to mix.



(1) Cooling favors mercury vapor oxidation and the preferred compounds as gas is cooled in the PM collection regime are (1) mercuric sulfate and mercuric chloride. Meaning both chlorine and H<sub>2</sub>SO<sub>4</sub> are potential promoters of mercury vapor oxidation; and oxidation is necessary for capture.



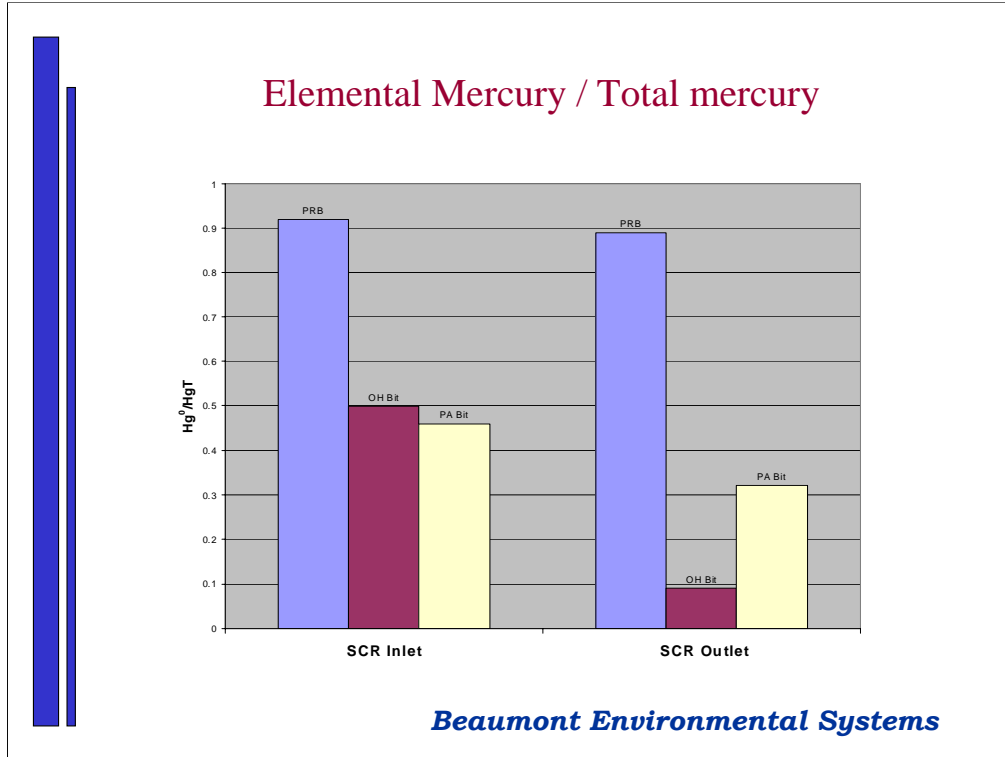
## Improving Mercury Uptake

- Improved Oxidation By Cooling
  - 350 F –  $\text{SO}_3 + \text{H}_2\text{O} = \text{H}_2\text{SO}_4$  Vapor
  - 250 F  $\text{H}_2\text{SO}_4$  to Liquid Droplets
- Adsorption to Particles
  - On Alkaline Particles – Downstream
  - Lime most cost effective
- Collectable as PM – Also  $\text{H}_2\text{SO}_4$

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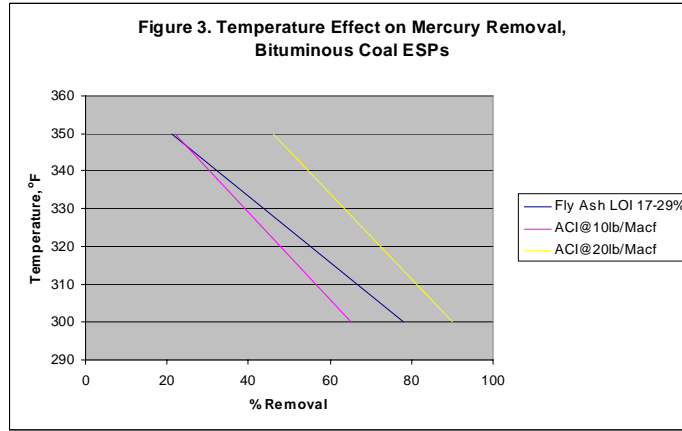
After oxidation is maximized by adsorption/and or condensation of  $\text{H}_2\text{SO}_4$  onto fly ash, carbon or alkaline solids will bind the oxidized mercury; the cooler the better. Lime, as shown in a table of potential sorbents in the paper, is the most cost-effective sorbent of oxidized Hg, and neutralizes excess acidity entering the PM collector.

**IMPORTANT - THIS ACTION ALSO CONVERTS ALL  $\text{H}_2\text{SO}_4$  TO FILTERABLE PM, WHICH ELIMINATES VISIBLE PLUMES AND LOWERS TOTAL PM EMISSIONS TO THE FILTERABLE CAPABILITY OF THE PM COLLECTOR, EXCEPT POSSIBLY FOR VERY SMALL ESPs.**



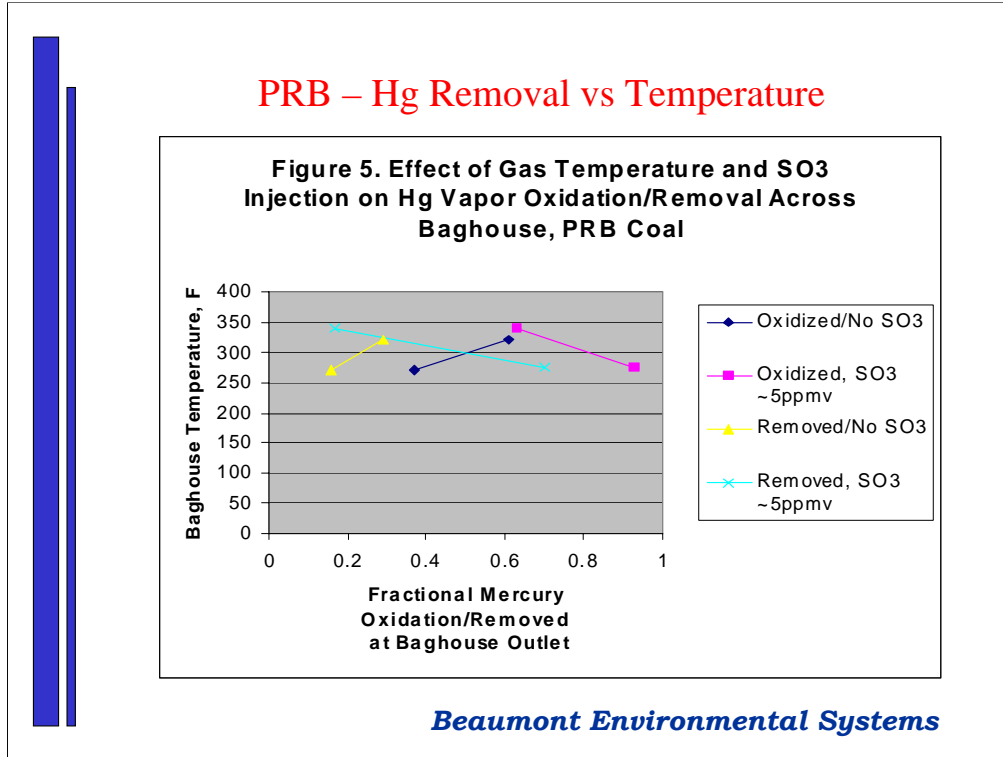
Alkaline fly ash and low chlorine content (PRB, lignites) result in low mercury oxidation in the flue gas, while bituminous coals generally have high mercury oxidation levels..

## Temperature Effect using Carbon



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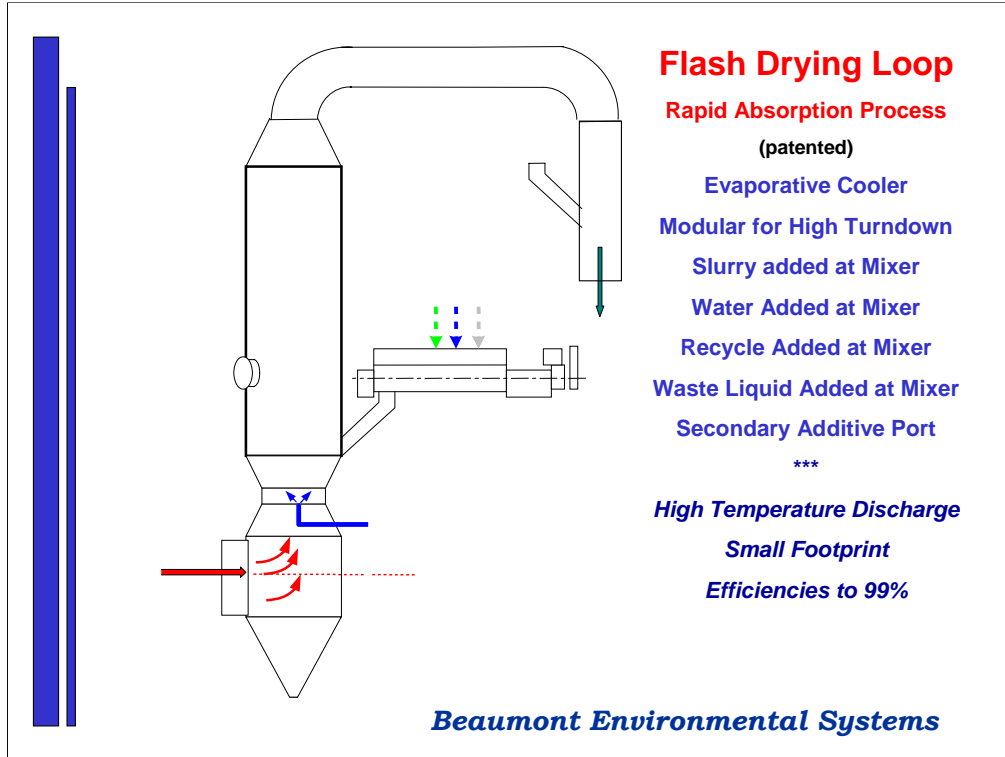
Mercury removal by carbon within the temperature range shown always improves with gas cooling, whether LOI carbon or externally supplied AC, and the effect is rather pronounced. If carbon content is very low, other mechanisms may still be used with proper conditioning to improve mercury oxidation and capture.



If carbon is low.

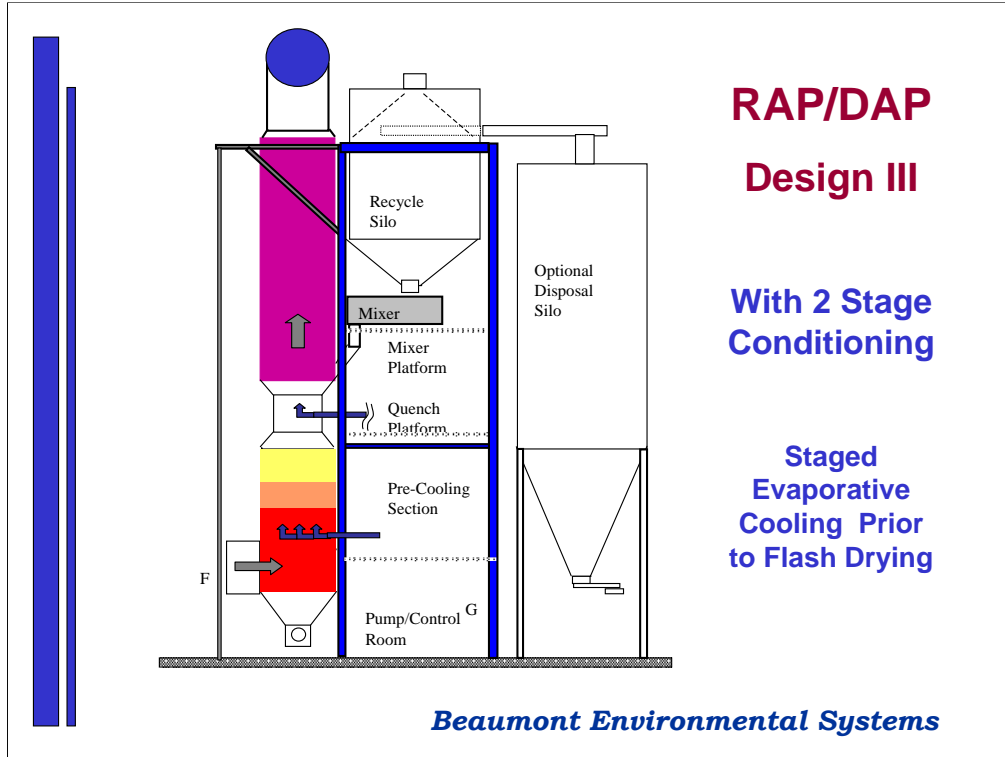
In the above plot this PRB coal has less than 1% LOI carbon, but with SO<sub>3</sub> conditioning and gas cooling upstream of a fabric filter dramatically improved both mercury oxidation (about 60% at baghouse outlet at 330F with no SO<sub>3</sub> to >90% at 275F with SO<sub>3</sub> conditioning) and removal (30% at 320F no SO<sub>3</sub>, vs >70% at 275F with SO<sub>3</sub>). Also point out that without SO<sub>3</sub> the low LOI coal actually showed less mercury oxidation and capture with gas cooling, which may explain why systems with PRB have seen less mercury control with spray dryer baghouses than with baghouses alone. Our system allows full FGD and optimized mercury capture where a standard semi-dry FGD will not..

ALSO while this only shows slightly better than 70% capture with conditioning + cooling, this was achieved using existing ductwork and not using a reactor designed to optimize both oxidation and capture of mercury. A reactor would have allowed staged cooling with more SO<sub>3</sub> injection followed by lime addition, both increasing the oxidized mercury (which already exceeded 90% at the modest conditions above) as well as capturing all oxidized mercury (as opposed to ~75% with a cooled and conditioned baghouse only).

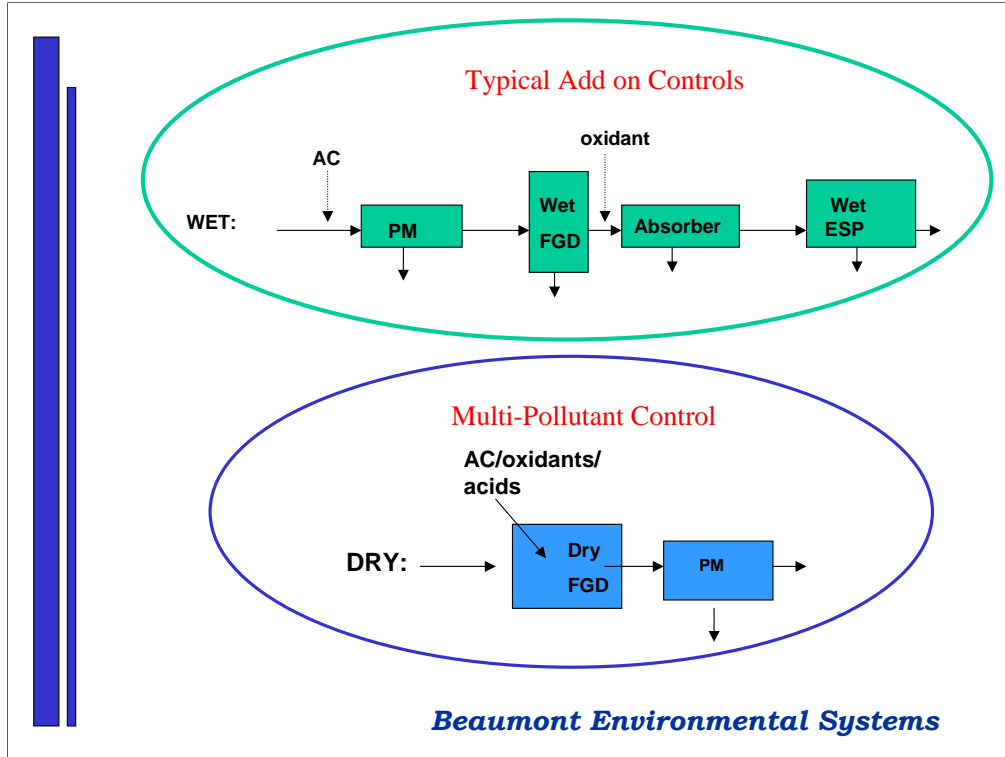


The latest in the evolution of dry/semi-dry systems uses the patented flash drying process.

The above features were added and patented to improve the older reactor type semi-dry system. In addition to the many improvements, the flash drying concept has improves efficiency, utilization of lime and allowed a higher outlet temperature.

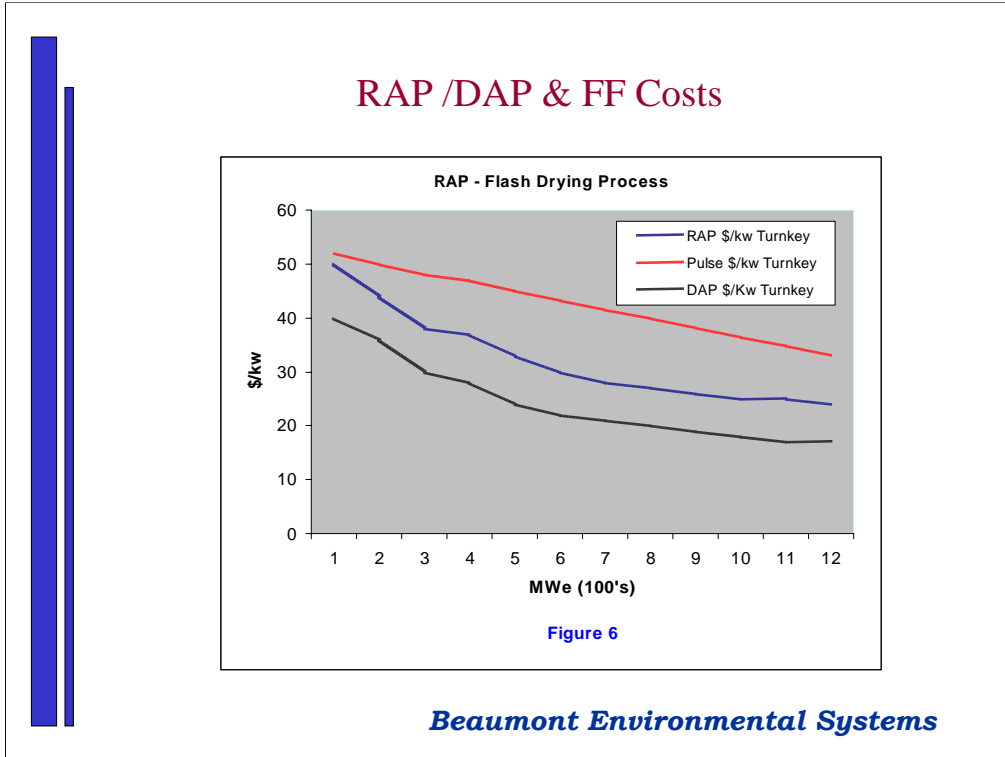


To enhance Mercury control with bituminous coals we can pre-condition the incoming flue gas and ash. We attempt to overcome the lack of acid ( $\text{SO}_3$ ) in the flue gas of lower-sulfur fuels for elemental mercury removal. Added acid can be absorbed on ash acts as a landing zone for elemental Mercury.



Updating a wet FGD system may require up to three additional control devices, three wet discharge points, and one dry discharge point.

A Multi-Pollutant dry system has two controls, one dry discharge point.



The above chart shows the cost for mercury only and combined mercury with SO<sub>2</sub> controls.



## Conclusions

1. Controls for mercury alone do not make economical nor engineering sense.
2. Total PM control is coming and mercury control can be integrated within an approach of upstream particle cooling, condensing, and agglomeration.
3. Acid addition may be necessary for 90% mercury control on very low sulfur, low chlorine or alkaline ash fuels.
4. A vertical reactor is more appropriate than a horizontal duct for hosting gas-solid mixing and chemical reactions on solid surfaces.
5. Upstream and downstream activities for pollution control are either unaffected or complimented by the cooling/conditioning reactor; e.g. an upstream cooling reactor makes both PM and FGD controls work better.
6. The reactor with upgradeable features sans PM collector can be installed for typically \$20-30/kW<sub>e</sub>; with fabric filter added for another \$35-\$50/kW<sub>e</sub>. It can easily be upgraded to a full semi-dry FGD system for additional SO<sub>2</sub> and NO<sub>x</sub> control.
7. Total PM emissions will be ~0.01 lb/MMBtu and mercury removal ~90% for a reactor +fabric filter ; reactor+ESP+wet FGD performance will depend upon size of ESP.

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The paper reaches the following conclusions.

# **Reducing Mercury Emissions by Improving Total PM Control**

**Charles B. Sedman, Consultant**

P O Box 1123

Hillsborough, North Carolina 27278

and

**Willard L Goss, Director**

Sorbent & Particulate Systems

Beaumont Environmental Systems

108 Lintel Drive

McMurray, Pennsylvania 15317

## **ABSTRACT**

Recent field development efforts have focused on reducing mercury emissions from coal fired utility boilers by either introducing a sorbent into flue gases specifically for sequestering mercury vapor or adding/enhancing flue gas desulfurization (FGD) to remove mercury concurrently with acid gases. With future regulations and permits requiring control of several emissions, including both condensable and filterable particles (total PM), as well as mercury, a logical approach is to apply controls for total PM that either increase mercury uptake on collected particles or increase mercury oxidation in the PM collector that allows high efficiency removal in the scrubber.

Beaumont has developed a staged gas cooling and conditioning system combined with advanced particle collection that both promotes high efficiency total PM control and separates the mercury oxidation and binding mechanisms, allowing optimization of both processes. The result is high efficiency combined PM and mercury control, without addition of special sorbents and contamination of marketable fly ash, that can be implemented with or without FGD. With this approach, improving NO<sub>x</sub> controls upstream generally promotes mercury removal, such that all major pollutants are synergistically controlled. The remainder of the paper discusses specific application hardware and estimated costs based on recently proposed commercial retrofits for both sub-bituminous and bituminous coals.

## **INTRODUCTION**

In 1971, the US Environmental Protection Agency (EPA) promulgated the first New Source Performance Standards (NSPS) for coal-fired utility boilers. The regulations included test methods and reporting requirements for sulfur dioxide (SO<sub>2</sub>), nitrogen oxides (NO<sub>x</sub>), and particulate matter (PM); the PM standard required only reporting the

mass per heat input of filterable particles at stack conditions, though the test method required measuring of both filterable and condensable particles. This effectively allowed uncontrolled condensable particles (primarily condensed sulfuric acid for coal and oil boilers) to be emitted from utility boilers. Some states have since required compliance with combined filterable and condensable PM (hence total PM), and most states have indirectly regulated total PM emissions through stack opacity regulations. In spite of this, the regulations have not prevented seasonal acid plume problems from wet FGD-controlled boilers, particularly the higher sulfur applications with SCR NOx controls.

In June 2002, EPA issued major source reporting requirements (which include many coal-fired utility boilers) that mandate periodic stack testing and reporting of total PM.<sup>1</sup> Within the next year, all major EPA studies on PM<sub>2.5</sub> will have been completed. States will then be required to submit plans within three years (2006-2008) that comply with new PM<sub>2.5</sub> air quality standards.<sup>2,3</sup> At that time it is expected that all PM standards will be effectively revised to account for total PM, especially since practically all condensable particles from utility boilers are emitted as PM<sub>2.5</sub>.

Coupled with pending state and perhaps revised NSPS for mercury emissions, an opportunity for synergistically reducing both total PM and mercury emissions now exists. The remainder of this paper describes the physical and chemical interactions, equipment, and estimated costs for one approach for a combined PM and mercury control scheme that integrates well with existing SO<sub>2</sub>, NOx and PM controls, and is flexible enough to meet future requirements with minimal additional space and capital expenditures.

## **Controlling Condensable Particles for Total PM Control**

The first (and only) SO<sub>3</sub> Symposium was held in 1998 to discuss plume opacity/sulfuric acid mist formation and control, and is summarized as follows.<sup>4,5</sup>

- SO<sub>2</sub> to SO<sub>3</sub> conversion in the boiler averages about 0.6% for bituminous coal, less for sub-bituminous;
- SO<sub>3</sub> is sorbed by fly ash as gas is cooled; hence PM controls remove some SO<sub>3</sub> as sorbed sulfate;
- One wet FGD system reported about 15% reduction in SO<sub>3</sub>;
- SCR increases SO<sub>2</sub> to SO<sub>3</sub> conversion by another 1% or so, more than doubling SO<sub>3</sub> flue gas concentrations for most sources;
- Below about 178°C, SO<sub>3</sub> combines with water in the flue gas to form H<sub>2</sub>SO<sub>4</sub> vapor;
- H<sub>2</sub>SO<sub>4</sub> dew points range from 120-130°C for most coal-fired flue gases; this means that cooling gas below 120°C (248°F) converts nearly all free H<sub>2</sub>SO<sub>4</sub> vapor to liquid droplets. In a dust-free environment, these droplets are <0.1 micrometers in diameter.

Given these parameters, several approaches are commercially available to abate condensable PM emissions without resorting to lower-sulfur fuel:

- addition of alkaline material, including ammonia, immediately upstream of the PM collector to absorb  $\text{H}_2\text{SO}_4$  (this would include semi-dry FGD installation)
- addition of alkaline material to furnace
- addition of wet ESP after wet FGD
- increase pressure drop across wet FGD

While all of these approaches would reduce total PM, they generally are not capable of significantly reducing mercury emissions, as described in the following discussion of mercury emissions and control.

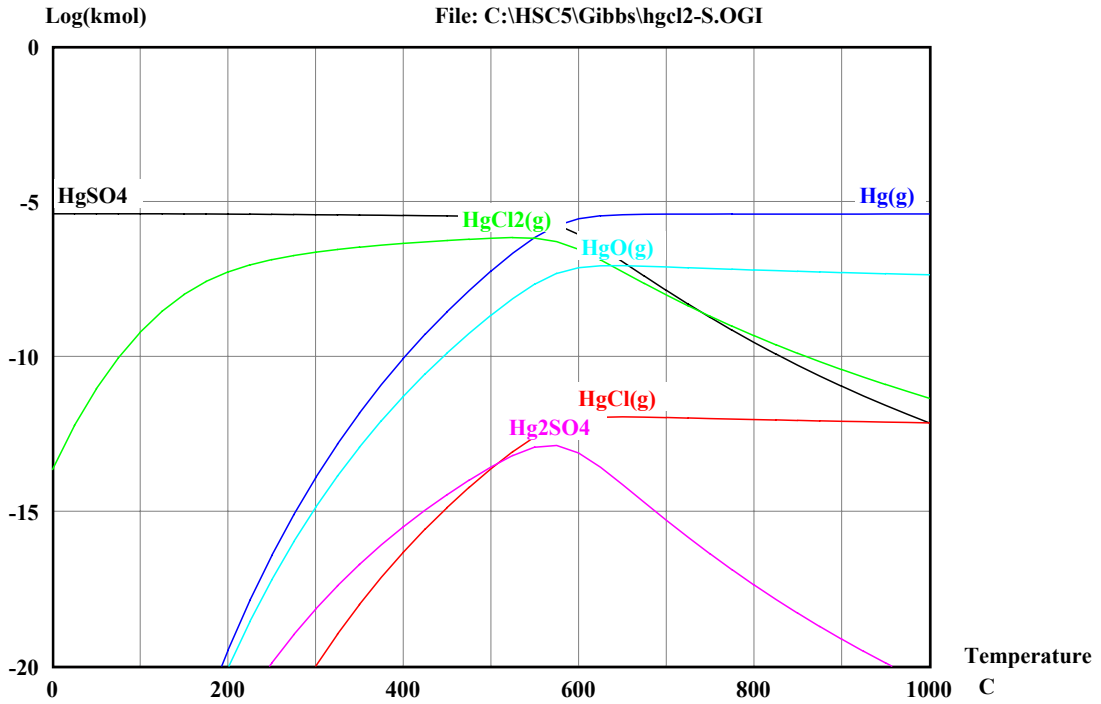
## Mercury Emissions and Control

Mercury is emitted from coal combustion in two distinct forms (1)  $\text{Hg}^0$  or elemental mercury, insoluble in water and generally inert, and (2) oxidized mercury ( $\text{Hg}^{++}$ ), water-soluble and reactive, especially toward alkaline materials. Much has been written on mercury control, but the essential task is to convert as much  $\text{Hg}^0$  as possible to  $\text{Hg}^{++}$  prior to an absorption/adsorption mechanism, or to combine oxidation and sorption using special sorbents such as activated carbon. The two most popular concepts are oxidation in conjunction with wet scrubbing or activated carbon injection upstream of the PM collector. While these concepts are valid for mercury control, they are counterproductive to improved PM control, especially that of condensable PM.

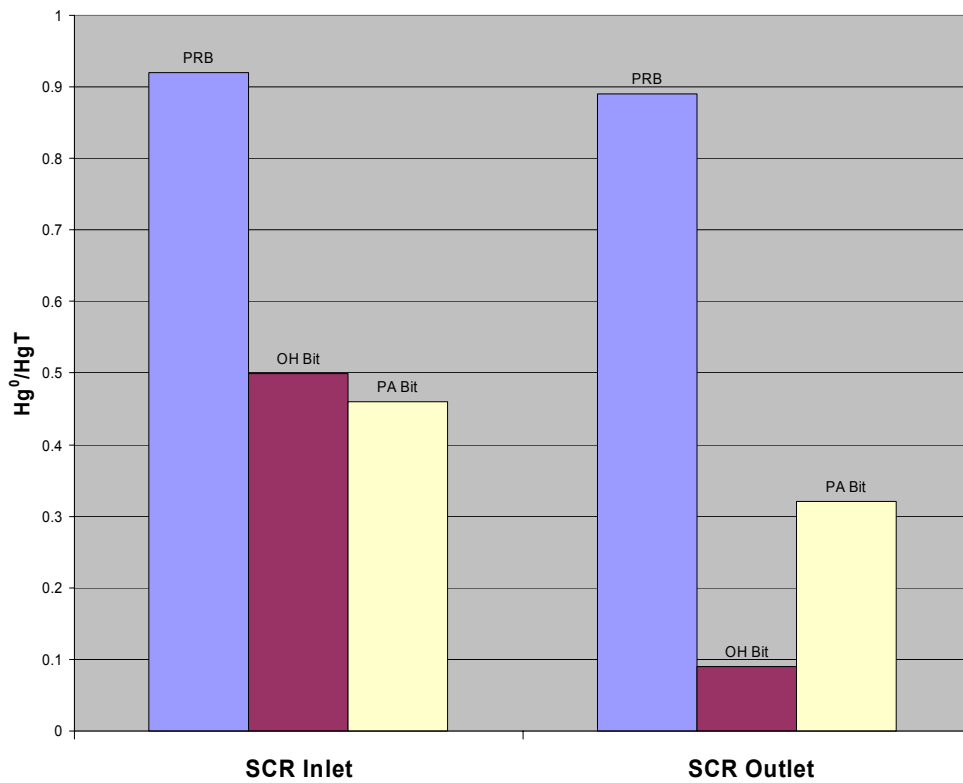
Smaller-scale research by DOE and EPA has identified the role of Lewis base sites and flue gas acids on fly ash and carbon surfaces in promoting surface  $\text{Hg}^0$  oxidation and  $\text{Hg}^{++}$  uptake.<sup>6-8</sup> Flue gas acids include  $\text{SO}_2$ ,  $\text{SO}_3/\text{H}_2\text{SO}_4$ ,  $\text{HCl}$  and  $\text{NO}_2$ . In particular, the role of chlorine as an oxidant and carbon as an oxidation/binding host have been studied and are the basis for many ongoing and planned mercury reduction research projects. Little is known thus far about the role of  $\text{H}_2\text{SO}_4$  in mercury chemistry, primarily because of the difficulty in measuring  $\text{H}_2\text{SO}_4$ . EPA and EPRI are both initiating mercury research projects that include and account for  $\text{H}_2\text{SO}_4$ , but data is not yet available. Circumstantial evidence indicates that  $\text{H}_2\text{SO}_4$  may be important, especially when combined with gas cooling.

Figure 1 is a thermodynamic equilibrium diagram for coal flue gas.<sup>9</sup> It clearly shows that for temperatures above  $400^\circ\text{C}$ ,  $\text{Hg}^0$  is the preferred state for mercury vapor. Below that, both  $\text{HgSO}_4$  and  $\text{HgCl}_2$  are preferred forms, with  $\text{HgSO}_4$  more preferred at equilibrium. But gaseous mercury reactions below  $400^\circ\text{C}$  are quite slow, and bench, pilot, and full scale studies all support the dominant role of heterogeneous or surface-catalyzed reactions in  $\text{Hg}^0$  oxidation at lower temperatures.<sup>10,11</sup>  $\text{HCl}$  supplies  $\text{Cl}^-$  for  $\text{HgCl}_2$  formation;  $\text{SO}_2$  (indirectly) and  $\text{SO}_3$  (directly) supply the  $\text{SO}_4^{=}$  for  $\text{HgSO}_4$ . Since bituminous coals have ample chlorine and sulfur, we would expect  $\text{Hg}^{++}$  to be the dominant form in post-air heater flue gas, and most full-scale studies confirm this. Lower-rank coals have less chlorine and sulfur and also have alkaline ashes that neutralize surface acids, so one would similarly expect that  $\text{Hg}^0$  is dominant for these coals. Figure 2 shows measurements from an earlier DOE study that support these premises.<sup>12</sup>

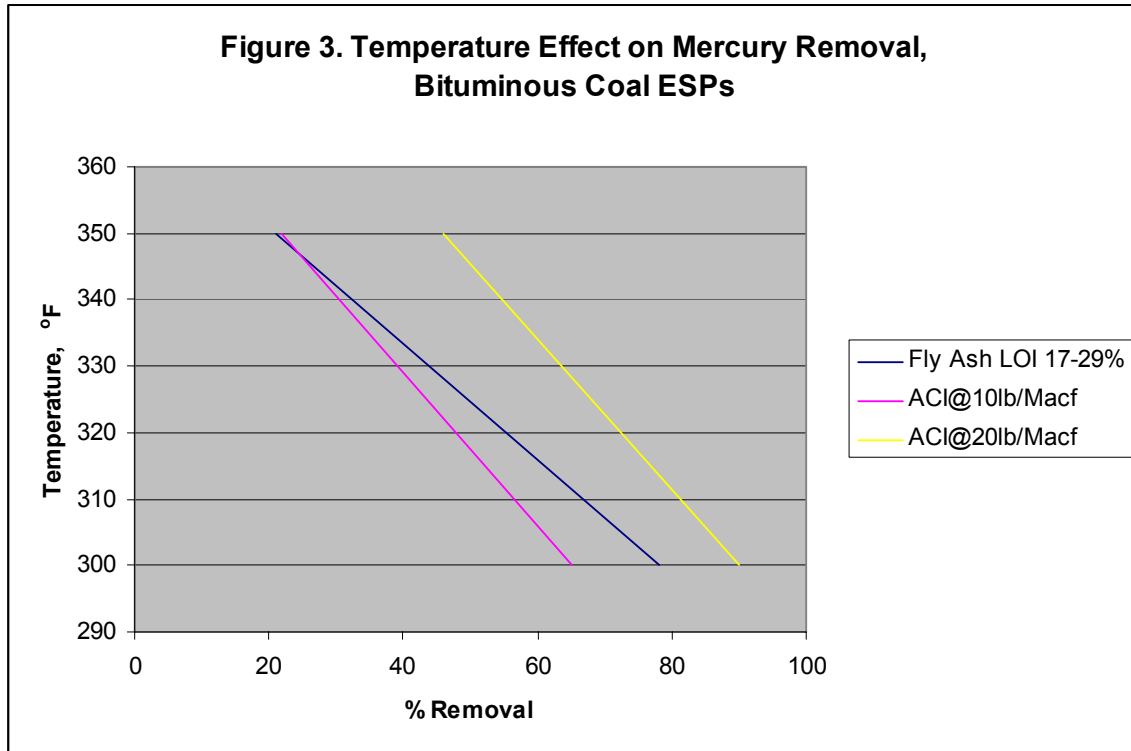
**Figure 1. Thermodynamic Equilibrium Mercury Speciation**



**Figure 2. Mercury Speciation Across SCR**



For bituminous coals, DOE field studies have suggested a strong temperature effect on mercury removal for both high carbon fly ash and carbon sorbents, as shown in Figure 3.<sup>13</sup> However, for lower-rank coals, gas cooling with carbon injection has had no discernible effect in DOE full-scale studies,<sup>14</sup> and even has shown a negative effect with fly ash in one DOE pilot study.<sup>15</sup>



ACI – Activated Carbon Injection

### ***Mercury Oxidation***

The key elements in heterogeneous mercury oxidation appear to be the abundance of acid sites and the degree of gas-solid mixing. Acid sites are implicated for both carbon and fly ash surfaces. For example, Dunham, et al.<sup>16</sup> found that removing carbon from bituminous coal ash had no effect on the heterogeneous oxidation of  $Hg^0$ , but had a profound effect with sub-bituminous coal ash. Their observation was that subbituminous ash carbon was more reactive than bituminous ash carbon. Another interpretation is that both acids and reactive sites are essential for  $Hg^0$  oxidation; bituminous coal flue gas has ample acid gases and both carbon and non-carbon catalytic sites for producing more acids (e.g.  $NO$  to  $NO_2$  and  $SO_2$  to  $SO_3/SO_4^-$ ) while sub-bituminous coal flue gas is acid limited and catalytic sites are hampered by the presence of alkalinity at the particle surface that will neutralize acids formed. Therefore, in an acid deficient environment, carbon may be important in both producing and hosting surface oxidants. [UNDEERC notes that HCl is not an oxidant, but can react with carbon surfaces to produce an acid site that oxidizes mercury.]<sup>6</sup> EPA research similarly shows that fly ash with no carbon can oxidize  $Hg^0$  in

the presence of HCl, NO, or SO<sub>2</sub>, presumably by catalytically producing the Cl<sup>-</sup>, NO<sub>3</sub><sup>-</sup> or SO<sub>4</sub><sup>=</sup> surface groups necessary.<sup>7,8</sup>

The importance of gas-solid contact is easily observed by the degree of Hg<sup>0</sup> oxidation observed across baghouses compared to that observed across ESPs.

### *Mercury Capture*

It is important to make the distinction, as UNDEERC does, in the mechanisms of Hg<sup>0</sup> oxidation and capture. All fundamental research indicates that oxidation is a prelude to capture, so that the role of carbon is a dual role of oxidant by creation of acid sites and binding to those sites. For fly ash (without carbon) to both oxidize and bind it must, too, create surface acids and either bind those acids or have nearby alkaline sites that react with Hg<sup>++</sup>. EPA research has clearly established that once Hg<sup>0</sup> is oxidized to Hg<sup>++</sup>, alkaline solids and salt hydrates are both effective in binding and removing Hg<sup>++</sup> from flue gases, especially as temperature is decreased. Table 1 illustrates the binding capacities for various alkaline materials at 60, 100, and 140°C (q<sub>60</sub>, q<sub>100</sub>, q<sub>140</sub>).<sup>17</sup>

**Table 1. Sorbent Properties and HgCl<sub>2</sub> Capacities**

Sorbent	pH	BET Surface Area (m <sup>2</sup> /g)	Avg. pore diameter (Δ)	D <sub>50</sub> (μm)	Porosity (unitless)	Surface Basicity (mmoles/m <sup>2</sup> )	HgCl <sub>2</sub> Capacity (mg HgCl <sub>2</sub> /g)		
							q <sub>60</sub>	q <sub>100</sub>	q <sub>140</sub>
Ca(OH) <sub>2</sub>	11.95	14.510	248	6.25	0.156	0.033	0.4469	0.2020	0.0800
CaO	11.95	4.525	5840	7.01	0.065	0.017	0.4471	0.0538	0.0153
CaCO <sub>3</sub>	9.64	0.9042	4130	23.69	0.006	n/a	0.4594	0.0509	0.0111
CaSO <sub>4</sub> ·xH <sub>2</sub> O	7.4	6.605	198	29.09	0.069	n/a	0.3595	0.1152	0.0039
NaHCO <sub>3</sub>	8.35	14.305	500	53.9	0.161	n/a	0.2416	0.1467	0.0358
Na <sub>2</sub> CO <sub>3</sub>	10.98	0.9582	221	300	0.006	0.032	0.2814	0.0551	0.0188
NaOH	12.01	0.2546	252	300	0.001	2.530	0.0000	0.0978	0.0085
Na <sub>2</sub> SO <sub>4</sub>	6.65	0.2031	74.4	88.94	0.001	n/a	0.1847	0.0424	0.0090
K <sub>2</sub> CO <sub>3</sub>	10.98	0.5718	111	300	0.003	0.124	0.4102	0.0409	0.0090
K <sub>2</sub> SO <sub>4</sub>	7.37	0.4448	110	30.64	0.002	n/a	0.2047	0.0253	0.0028
Mg(OH) <sub>2</sub>	10.21	10.91	315	9.61	0.152	0.002	0.2900	0.0370	0.0024

The concept of having both acids and alkalinity intimately together is difficult to achieve in practice and is one reason that mercury removal for low-chlorine and sulfur coals has been observed to decrease when alkalinity is added and gases are cooled. Cooling tends to increase the sorption of acids to particle surfaces, but if the surfaces are alkaline, this is generally counterproductive to oxidation, and hence capture, of Hg<sup>0</sup>.

## COMBINING TOTAL PM AND MERCURY CONTROL

A suggested approach is to combine gas cooling and conditioning, so that the following occurs:

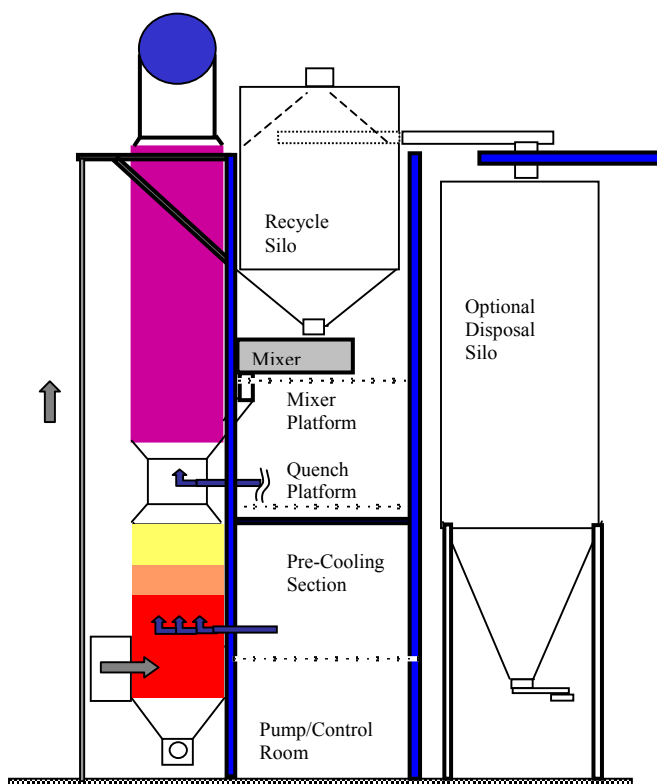
1.  $\text{H}_2\text{SO}_4$  is sorbed and condensed on supermicron fly ash particles upstream of the PM collector and collected as a particle;
2. Mercury vapor is mixed in a turbulent contact zone with these acid particles to promote surface-catalyzed oxidation;
3. An alkaline material is added downstream of the contact zone, but upstream of the PM collector to adsorb  $\text{Hg}^{++}$ ; alternatively if a wet FGD system is downstream of the PM collector, the FGD absorber may collect  $\text{Hg}^{++}$  that is not sorbed on fly ash.

Figure 4 shows the Beaumont reactor designed for all three steps - a staged vertical duct reactor section with water spray cooling zone beneath and a venturi-assisted turbulent zone above. A recycle silo, mixer, and injection chute are optional for recycle of solids and/or addition of sorbent for multi-pollutant control.<sup>18</sup> Costs and other considerations will be discussed later. The important features are:

1. Acids are condensed in a turbulent particle-rich environment such that particle collisions and gas-particle interactions are maximized in a relatively short (<0.5 sec) time, allowing particle growth and minimizing spontaneous nucleation of ultrafine acid mist. Oxidation of  $\text{Hg}^0$  to  $\text{Hg}^{++}$  takes place in this stage.
2. A second mixing stage allows introduction of binding agents such as additional carbon and lime that will both sequester free acids that could cause downstream corrosion of internals as well as bind  $\text{Hg}^{++}$  in the flue gas to solid particles. For most applications only lime will be needed as a mercury binding agent.
3. The larger particles and cooled gas both provide for better filterable PM collection in the PM collector, whether ESP or baghouse.
4. The condensable PM, primarily  $\text{H}_2\text{SO}_4$ , has been essentially converted to filterable PM by condensation on fly ash and neutralization with sorbent.
5. Mercury is essentially all converted to  $\text{Hg}^{++}$ , and is mostly bound to sorbent and fly ash in-flight by the turbulent contact with sorbent.

The PM collector is also important in that a longer solid residence time will ensure nearly complete collection of unbound acids and  $\text{Hg}^{++}$ . For this reason a baghouse is preferred over an ESP. Use of an electrostatically enhanced fabric filter available from Beaumont will allow even longer filtering cycles, as well as reducing total PM emissions by another order of magnitude.<sup>19</sup>

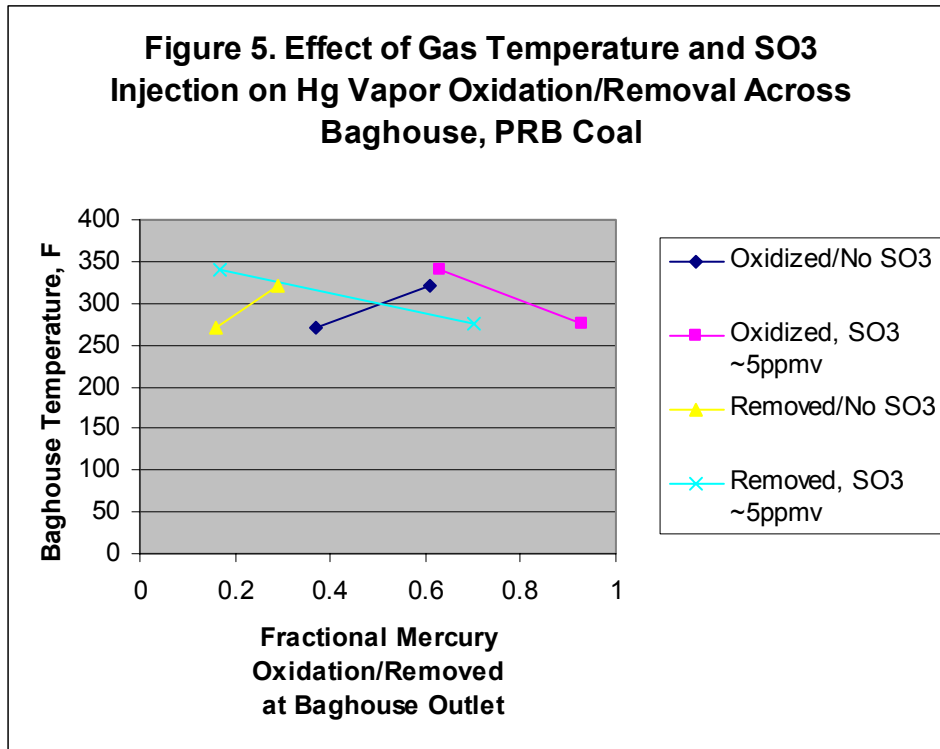
**Figure 4. Reactor with 2-Stage Evaporative Cooling/Flash Drying**



For higher-sulfur bituminous coals, especially where SCR is used for NO<sub>x</sub> control, sufficient H<sub>2</sub>SO<sub>4</sub> and HCl are already present in the flue gas to drive the mercury oxidation reactions. For lower-sulfur coals, especially those with alkaline ash, supplemental acid may be added to promote Hg<sup>0</sup> oxidation via either oxidation catalysts, SO<sub>3</sub> gas conditioning, or H<sub>2</sub>SO<sub>4</sub> added with cooling water.

As evidence that this approach works for control of mercury emissions from the more difficult sub-bituminous coals, Figure 5 shows new pilot data of mercury removal by fabric filters with and without SO<sub>3</sub> conditioning of fly ash, as a function of temperature. In these cases cooling and conditioning were accomplished by injection of SO<sub>3</sub>, indirect gas cooling, and no ductwork modifications, and therefore represent proof of concept without the added benefits of a reactor to provide mass transfer and additional solids residence time for H<sub>2</sub>SO<sub>4</sub> and Hg vapor sorption/oxidation/binding reactions. Figure 5 shows that cooling was counterproductive in both mercury oxidation and capture for the low-carbon PRB fly ash (LOI <<1.0%); when ~5ppmv SO<sub>3</sub> was introduced, mercury

oxidation increased from less than 40% to 95% at 270°F, and capture from less than 20% to 70%, with no external carbon added. Future work will examine the addition of a reactor, further gas cooling, and additional SO<sub>3</sub>/H<sub>2</sub>SO<sub>4</sub> addition, all of which should increase mercury oxidation and capture.



### Commercial Application of Combined Total PM/Mercury Controls

Beaumont had previously patented a flash dry FGD reactor<sup>20</sup> that was easily adapted to meet the new requirements for gas cooling and conditioning for synergistic acid condensation and mercury oxidation, as shown previously in Figure 4. This reactor can be employed in three ways: (1) and 2 as methods of conditioning and cooling gas upstream of a fabric filter for total PM and mercury control, or conditioning and cooling gas upstream of an ESP and wet scrubber for condensable PM removal and mercury vapor oxidation upstream of the scrubber (called Dry Adsorption Process or DAP), and (3) as a method of increased mercury oxidation as an integral part of a flash-dry FGD system (denoted as Rapid Absorption Process, or RAP).

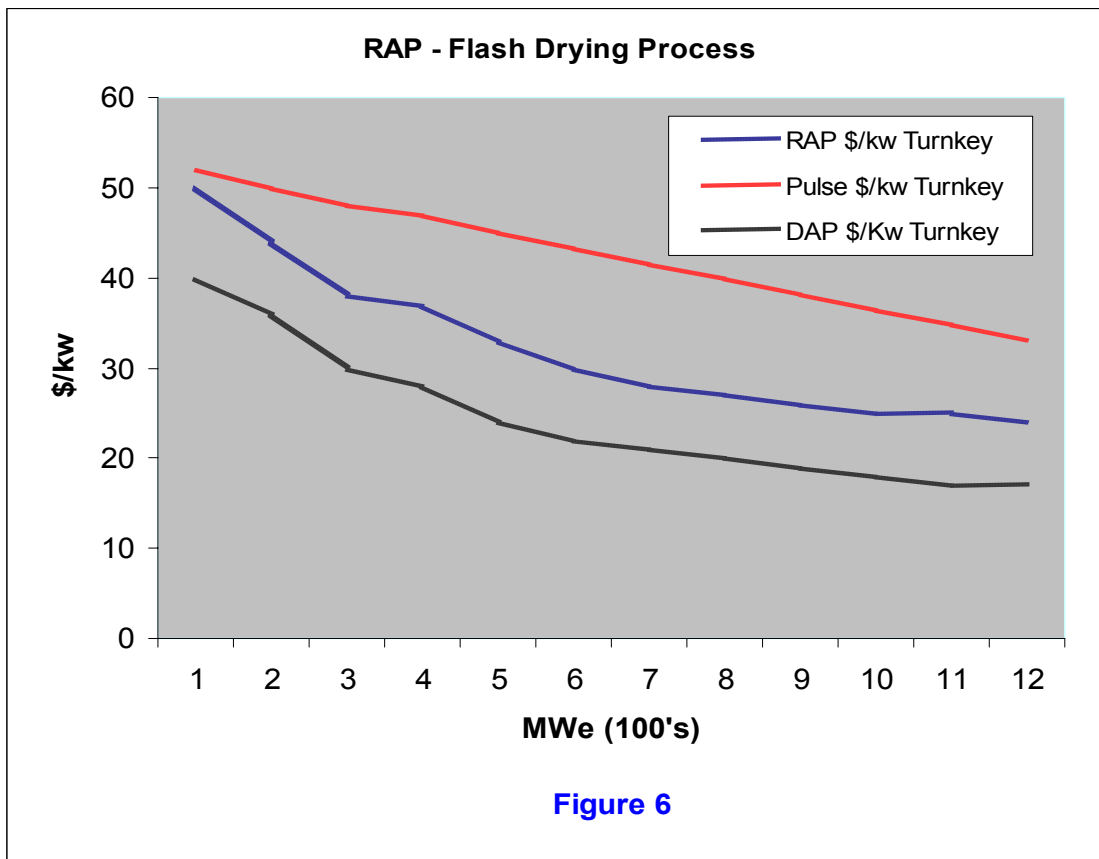
Another aspect of the reactor is that excellent gas-solids mixing is promoted by a venturi section and uses gravity opposed to vertically upward gas flow that induces additional internal mixing so that fly ash surfaces are fully utilized. The same principles would also ensure good sorbent utilization that is lacking with duct injection systems, should one choose to add special sorbents to achieve very low emissions.

Several commercial bids have been prepared recently that allow a good estimate of capital costs for a reactor system as in (1) and (2) above; and as a fully integrated semi-dry FGD system with baghouse as in (3) above. Figure 7 illustrates these systems applied to coal utility boilers. Since reactor dynamics require gas flow velocities between 3 and 12 m/sec (10-40 ft/sec), multiple reactors on larger boilers are recommended to maintain flow during load swings; therefore larger applications require more reactors. In Figure 7, costs are based upon 1 reactors up to 250 MWe, 2 reactors up to 500 MWe, 4 reactors up to 1,000 MWe and 6 reactors up to 1,500 MWe.

## COST DISCUSSION

In the following figure we have included costs for (1) Material Handling, (2) Controls, (3) Electrical, (4) Erection, (5) Tower Steel, (6) Enclosure for RAP but not (A) Booster Fans, (B) Demolition, or (C) local productivity factors.

The design is for (a) 90 to 95% SO<sub>2</sub> removal rate, (b) 90% nominal mercury control, (c) 320°F inlet, (d) 200 to 210°F outlet and (e) 12 to 13 inches system pressure drop (SP).



In the above figure we have provided pricing for a reactor (DAP) which is used for conditioning the incoming flue gas by cooling and optional acid addition for mainly PM and mercury emissions control. This is the lower curve in Figure 7.

The middle curve prices a reactor for gas conditioning and SO<sub>2</sub> control by Flash Drying. DAP is converted to RAP by adding a feed mixer plus material handling/solids recycling equipment and enclosing the support tower.

The top curve shows the cost of the pulse type fabric filter. This unit is sized to allow high recycle rates and therefore high inlet grain loadings.

By combining a RAP reactor with a fabric filter we have a multi-pollutant device to meet current and future control regulations (other than NO<sub>x</sub>), with a small footprint

## CONCLUSIONS

- 1. Controls for mercury alone do not make economical nor engineering sense.**
- 2. Total PM control is coming and mercury control can be integrated within a total PM control approach of upstream particle cooling, condensing, and agglomeration.**
- 3. Acid addition may be necessary for 90% mercury control on very low sulfur, low chlorine or alkaline ash fuels.**
- 4. A vertical reactor is more appropriate than a horizontal duct for hosting gas-solid mixing and chemical reactions on solid surfaces.**
- 5. Upstream and downstream activities for pollution control are either unaffected or complimented by the cooling/conditioning reactor; e.g. an upstream cooling reactor makes both PM and FGD controls work better.**
- 6. The reactor with upgradeable features sans PM collector can be installed for typically \$20-30/kW<sub>e</sub>; with fabric filter added for another \$35-\$50/kW<sub>e</sub>. It can easily be upgraded to a full semi-dry FGD system for additional SO<sub>2</sub> and NO<sub>x</sub> control.**
- 7. Total PM emissions will be ~0.01 lb/MMBtu and mercury removal ~90% for a reactor +fabric filter ; reactor+ESP+wet FGD performance will depend upon size of ESP.**

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