



## Air-Phase Mercury Removal

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**Author:** Michael Kuznetz

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### Abstract

Controlling mercury emissions from coal-fired power plants and options that may be used to effectively and economically control these emissions have been the subject of intense legislative and regulatory debates and numerous research projects. Presently, activated carbon, silicate-based, brominated and other sorbent injection into the flue gas is one of the most economically feasible mercury control technologies. The purpose of this paper is to present an algorithm that can be used to estimate mercury removal efficiencies for any solid coal-fired electric boiler utility using sorbent injection technologies.

### Introduction

Mercury (Hg) is a hazardous air pollutant that circulates around the globe for a year before depositing back to the earth. It exists in trace amounts in fossil fuels such as natural gas, oil, coal, crustal material and waste products. Through combustion or natural processes, mercury vapor is released to the atmosphere in large amounts. In 1999, mercury emissions from electric power generation sources were estimated by the US EPA to be 48 metric ton/yr, constituting the single largest anthropogenic source of mercury in the US (3). The Clean Air Mercury Rule (CAMR), issued in March 2005, required that a stepwise mercury removal be implemented within the next decade. Mercury removal efficiency is a complex function of several variables including sorbent injection rate, flue gas temperature, the amount of unburned carbon, sorbent adsorption capacity, etc. The U.S. DOE produced an algorithm defining flue gas mercury removal as a function of sorbent injection rate for several U.S. coal-fired plants (3). This paper presents an expanded U.S. DOE algorithm that, in addition to sorbent injection rate,

incorporates the coal combustion process variables, such as flue gas temperature, the amount of unburned carbon, sorbent adsorption capacity, chloride and sulfate contents, type of coal and process configuration, in one general expression. This algorithm, called UMREA, accurately predicts flue gas mercury removal efficiency for a broad range of presently available sorbent injection technologies.

### **1. Hg Removal Efficiencies by Existing Air Pollution Control Devices**

In 1999-2000, the US EPA carried out an Information Collection Request (ICR) to update the mercury emissions inventory for US coal-fired plants. Based on the EPA data gathered and evaluated at that time, the air pollution control devices (APCD) used in pulverized coal-fired utility boilers result in Hg removal ranging from zero to 98 percent (3). The Hg removal efficiencies, calculated by the US EPA, are shown in Table 1. The highest levels of Hg removal are generally obtained by APCD that incorporate fabric filters. Hg removal efficiencies are higher for the plants firing bituminous coals than for either subbituminous coal or lignite. This is attributed to low fly ash carbon contents and the higher relative amounts of elemental mercury ( $\text{Hg}^0$ ), due to low levels of  $\text{Hg}^0$  oxidation, in the flue gas at the plants burning subbituminous coal and lignite.

Table 1. Average Hg removal efficiencies for PC-fired boilers (3).

Post-combustion APCD used for PC		Average Hg removal efficiencies (%) vs coal fired		
		Bituminous	Subbituminous	Lignite
PM control only	CS-ESP	36	3	-4
	HS-ESP	9	6	not tested
	FF	90	72	not tested
	PS	not tested	9	not tested
PM control and spray dryer adsorber	SDA+ESP	not tested	35	not tested
	SDA+FF	98	24	0
	SDA+FF+SCR	98	not tested	not tested
PM control and wet FGD system	PS+FGD	12	-8	33
	CS-ESP+FGD	75	29	44
	HS-ESP+FGD	49	29	not tested
	FF+FGD	98	not tested	not tested

where

AC	Activated carbon
APCD	Air pollution control device
PC	Pulverized coal
CS-ESP	Cold-side electrostatic precipitator
HS-ESP	Hot-side electrostatic precipitator
FF	Fabric filter
SDA	Spray dryer adsorber system
SCR	Scrubber
PM	Particulate matter
PS	Particulate scrubber
FGD	Flue gas desulfurization

The average Hg removal in pulverized coal-fired (PC) utility boilers equipped with cold-side electrostatic precipitators (CS-ESPs) is 35 percent for bituminous coal, 3 percent for subbituminous coal and near zero for lignite. Plants equipped with lime spray dry adsorber scrubbers (SDA-ESP and SDA-FF) showed on the average Hg removal efficiencies ranging from



98 percent for units burning bituminous coals down to 3 percent for units burning subbituminous coals. Plants equipped with only post-combustion PM controls showed average Hg removal efficiencies ranging from 0 to 89 percent.

Average Hg removals in wet FGD scrubbers ranged from 23 percent for one PC-fired HS-ESP+FGD unit firing subbituminous coal to 97 percent in a PC-fired FF+FGD unit firing bituminous coal. Higher Hg removals in the FF+FGD units were attributed to an increased oxidation and capture of Hg in the FF. In units equipped with wet FGD scrubbers, the removal efficiencies were dependent on the concentration of  $\text{Hg}^{2+}$  in the inlet flue gas and PM control device used. In units equipped with spray dry scrubbers and wet limestone scrubbers, a similar level of Hg removal was observed.

In 1999, 72 percent (890 units) of the coal-fired electric utility boilers in the U.S. used post combustion controls that consisted only of PM controls. This data is shown in Table 2. This included 791 units using either CS- or HS-ESPs and 80 units that used FF baghouses. This translates into the fact that 64 percent of all coal-fired electric utility boilers in the U.S. in 1999 had mercury removal efficiency ranging from 0 percent to 36 percent.

Table 2. Number of coal-fired utility boilers equipped with PM control only (3,6).

PM Control	Number of Units
CS- or HS-ESP	791
Two ESPs in series	2
FF	80
ESP+FF	6
PS	5
ESP+PS	4
Mechanical collector	2

Since AC and other sorbent injection into the flue gas is still the most economically feasible option for mercury removal and the APC technologies have not drastically changed, the volume of Hg-laden AC has increased tenfold due to implementation of CAMR. It is obvious that much of this AC ends up in fly ash and other coal combustion residues (CCR) since complete AC generation is impractical. As a result, fly ash disposed of in landfills, monofills and structural fills has higher Hg contents.

## **2. The U.S. DOE NETL's Mercury Removal Efficiency Algorithm**

As part of the Mercury Control Performance and Cost Model, the U.S. DOE NETL has developed Hg removal efficiency models for seven coal-fired power plants (6). These models were based on available pilot- and full-scale data fits using basic curve-fitting algorithms. The algorithms calculate the activated carbon injection rate required to achieve specified Hg removal efficiency for a particular control method such as, for example, AC injection upstream of an existing ESP. The performance predictions were made for individual facilities and based solely on control method, flue gas temperature and coal type.

The general form of the algorithms for the seven electric coal-fired power plants tested is as follows (6):

$$R = 100 - \frac{a}{ACI + b} \quad (1)$$

where  $R$  - percent of total Hg removal, inlet to outlet

$ACI$  – activated carbon injection feed rate, 0-5 lb/MMacf (0 – 80 kg/MMacm)

$a, b$ – numerical coefficients related to chlorine and sulfur coal contents and the air

pollution control process configuration. Table 3 compiles the coefficients  $a$  and  $b$ .

Table 3. Hg removal efficiency coefficients  $a$  and  $b$  for a range of flue gas temperature (6).

Set No.	Coefficient	Flue gas temperature, °F									
		225	230	240	250	275	280	285	300	330	345
1	$a$	55.54			159.3	494.6					
2		128.7			371.0	1219					
3			1373.1				247.8		296.7		319.6
4				51.04				159.4			
5				118.7				370.7			
6					4.28		27.56		148.0		
7			266.1			23.2				28.0	
1	$b$	1.44			3.684	11.55					
2		1.43			3.694	12.14					
3			32.11				3.39		4.29		3.66
4				1.32				3.56			
5				1.32				3.56			
6					0.048		0.313		0.92		
7			11.13			0.43				0.32	

The coefficients for data sets 1, 2, 4 and 5 and 3, 6 and 7 were developed for bituminous and subbituminous coals, respectively. The relationships between the coefficients  $a$  and  $b$  and flue gas temperature are shown in Figure 1.

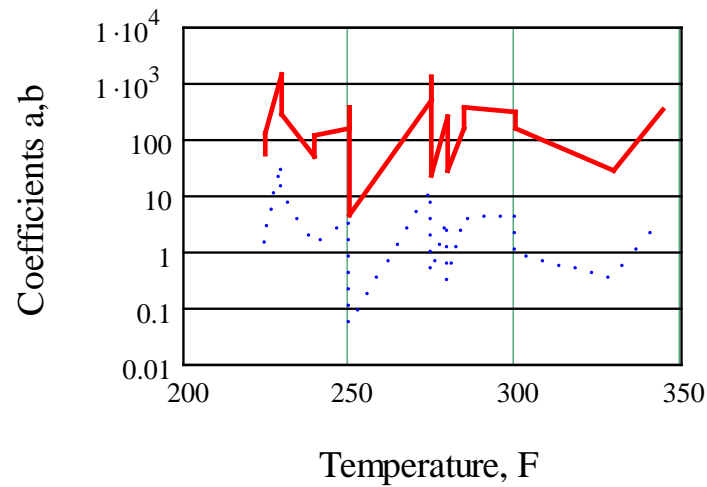


Figure 1. Coefficients  $a$  and  $b$  (dotted line) as functions of flue gas temperature  $T$  (°F).

No good correlation between  $b$  and  $T$  was found. The correlation coefficient between  $b$  and  $T$  is -0.255. Similarly, there is no correlation between  $a$  and  $T$  (correlation coefficient 0.094). However, there is a strong positive correlation between  $a$  and  $b$  (correlation coefficient equals 0.884). As follows from Figure 2,  $a \approx 100b$ , i.e.

$$R = 100 \left( 1 - \frac{b}{ACI + b} \right) \quad (2)$$

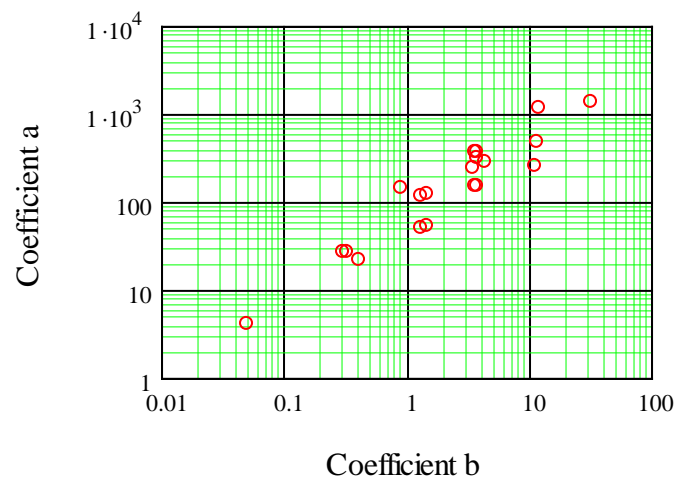


Figure 2. Coefficient  $a$  as a function of coefficient  $b$ .



From Equation (2), Hg removal efficiency is simply a function of  $ACI$  and is independent of flue gas temperature if  $b$  is small compared to  $ACI$ . When  $b$  equals  $ACI$ , the maximum removal is only 50 % which is lower than required to be able to comply with CAMR. If  $ACI$  is zero or negligible with respect to  $b$ , the mercury removal is zero according to Equation 2.

### **3. The Universal Mercury Removal Efficiency Algorithm**

The following discussion presents an algorithm that the author developed in 2006 to supplement the US DOE algorithm given by Equation (2). The new algorithm fits the Hg removal efficiency data for solid coal-fired electric utilities boilers and is not applicable to the units firing gasified coal. It was developed based on the following data and assumptions:

1. Flue gas temperature has a profound effect on the mercury removal efficiency. The removal efficiency sharply decreases with increasing flue gas temperature and vice versa.
2. The amount of AC injected in the flue gas stream upstream of the APCD and the AC adsorption capacity are the most important variables affecting the removal. Removal efficiency sharply increases in response to an increase in the AC injection rate and adsorption capacity.
3. The amount of unburnt carbon, coal chlorine and sulfur contents and the APC process configuration do affect the removals but to a lesser degree than temperature and ACI rate. Removal efficiency increases with increasing the amount of unburnt carbon and coal chlorine and sulfur contents and vice versa. The amount of unburnt carbon in fly ash can be determined by LOI (Loss on Ignition) Method. Coal chlorine and sulfur contents represent the type of coal and is introduced as a single variable for convenience. After the initial

percentage of Hg reduction across the APCD for a certain type of coal has been determined, it can be adjusted. Online flue gas chlorine, sulfur and mercury analyzers can be used to correlate the ACI rates.

4. Hg removal efficiency depends on the APC process configuration. This variable is introduced in the algorithm as a single coefficient. This coefficient can be adjusted for a given coal-fired plant. In the graph below, this coefficient, for example, is adjusted for a pulverized bituminous coal and CS-ESP process and the value assigned to it is 100. The Hg removal efficiency decreases when this coefficient increases. The most common process configurations are listed in Table 1.
5. The algorithm describes total Hg removal. Hg speciation in flue gas is a complex function of temperature, oxidizing agents and the type of APCD. Therefore, if the precise speciation is available, the fractions of  $\text{Hg}^0$ ,  $\text{Hg}^{2+}$  and particle bound  $\text{Hg}_p$  can be incorporated into the algorithms as shown in the followings part.
6. Flue gas temperature is in the range 32 to 1000 °F with the mean value centered around 250 °F at sampling port locations. This value is discussed in the section titled “Vapor Phase Mercury Concentration Derivation”.
7. No mercury desorption from the adsorbent occurs.
8. Hg removal efficiency is not a linear function of ACI rates.
9. The algorithm is an exponential function having upper and lower limits of 100 percent and 0 percent, respectively.
10. Relative humidity and its variations in flue gas have no significant impact on the adsorption capacities of the AC and unburned coal carbon.

11. Hg adsorption capacities of the commercially available activated carbons do not vary significantly (the average specific surface area is around 600 m<sup>2</sup>/g AC).
12. Specific surface area of unburnt carbon in fly ash is significantly lower than that of AC (10-100 m<sup>2</sup>/g).
13. The removal (adsorption) capacity of AC ranges from 0.1 to 1 percent by weight. Figure 4 is based on a 0.5 percent (wt/wt) adsorption capacity (Norit Americas AC).
14. Amount of smectite minerals in fly ash is negligible and the clay is mostly kaolinite (specific surface area equals 10 -20 m<sup>2</sup>/g).
15. Adsorption capacity of clay present in the fly ash is negligible compared to that of unburnt carbon.
16. All removed Hg is incorporated into AC and unburnt coal carbon.
17. Pressure is 1 atm.

Then an algorithm describing total Hg removal efficiency at coal-fired power plants can be presented in the following form:

$$RE = 100 \left( 1 - e^{\frac{-H \cdot M}{G} \cdot \frac{398}{T^2 + 273} \cdot \frac{L^2 + A}{B}} \right) \quad (3)$$

where

RE – total Hg removal efficiency, percent

H - activated carbon injection rate, kg AC/Mm<sup>3</sup> (standard dry air-flue gas)

M - total Hg adsorption capacity of activated carbon, g Hg<sub>T</sub>/kg AC

G - concentration of total Hg in flue gas,  $\mu\text{g}/\text{m}^3$  of standard dry air-flue gas

L - amount of unburnt carbon in coal, percent by wt.

T - temperature, °C

A - coefficient reflecting chlorine and sulfur coal contents, dimensionless

B - coefficient related to the APC process configuration, dimensionless.

The average value for A and B is 100.

A plot of Hg removal efficiency in Eq. 3 as a function of ACI rate is shown in Fig. 3.

The plot entails the following conditions:

G = 25  $\mu\text{g}/\text{m}^3$  of standard dry air-flue gas

T = 50 °C

M = 5 g Hg<sub>T</sub>/kg AC

L = 5 percent

A = B = 100.

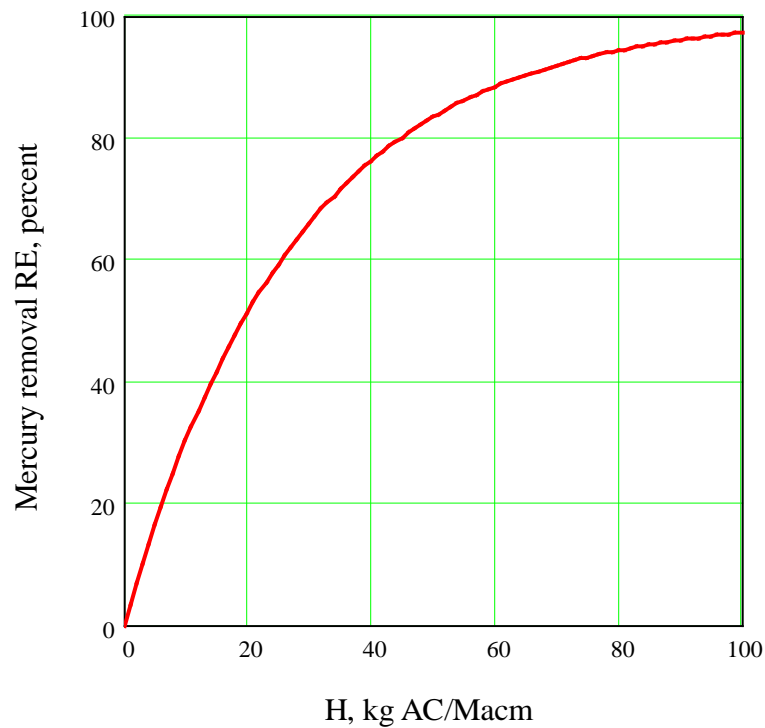


Figure 3. Plot of Universal Mercury Removal Efficiency Algorithm (Eq. 3).

Figure 4 compares the shapes of the Universal Mercury Removal Efficiency Algorithm (UMREA) and the DOE NETL Mercury Removal Algorithm as functions of ACI rates at different G-values and temperatures. The range of field operating flue gas temperatures is, according to Table 3, from 225 °F (107 °C) to 345 °F (174 °C) with the average of 276 °F (135.5 °C). The range of removal efficiencies, calculated by UMREA, is defined by vertical step bars in Fig. 4 which shows the results for the following boundary conditions:

H = 0-100 kg/Macm (0-6.25 lbs/Macf)

G = 1-35  $\text{g}/\text{m}^3$  of standard dry air-flue gas

T = 107-174 °C

$M = 15 \text{ g Hg}_T/\text{kg AC}$

$L = 5 \text{ percent}$

$A = 200$

$B = 50.$

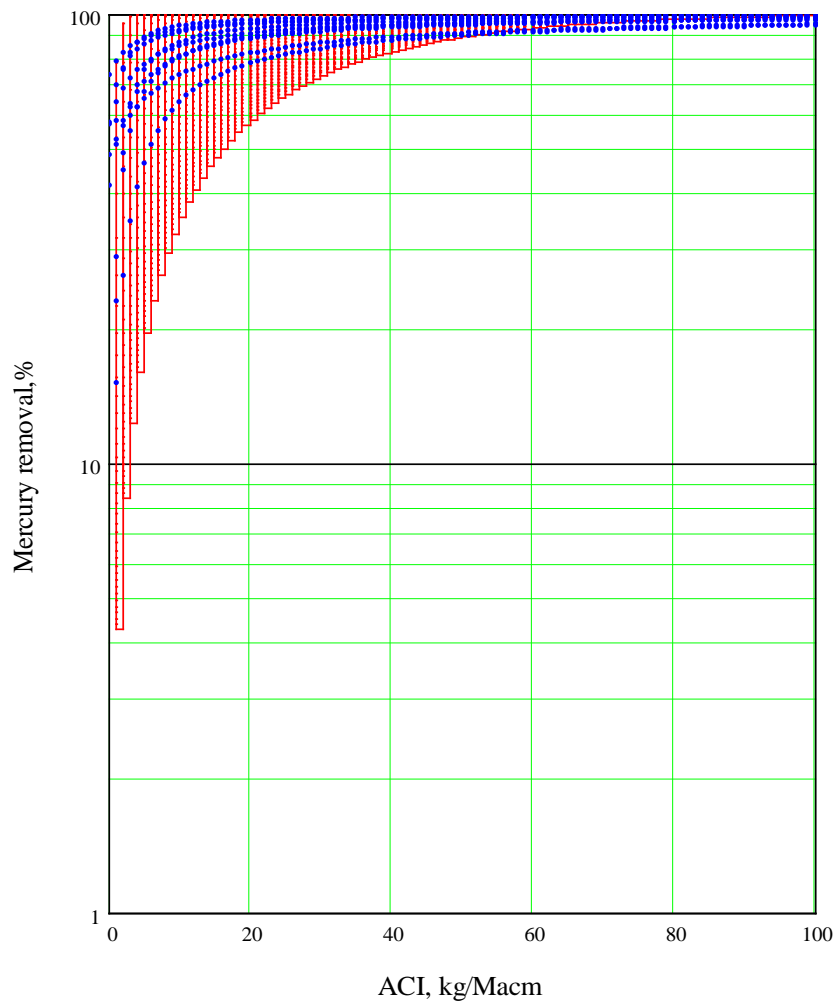


Figure 4. Comparison of the Universal Mercury Removal Efficiency Algorithm

and the DOE/NETL Mercury Removal Algorithm at various T- and G-values.

Mercury removal efficiency predicted by UMREA is shown as vertical bars. Figure 4 clearly shows that the DOE/NETL Mercury Removal Algorithm (shown as blue dotted lines) predicts optimistically high mercury removal efficiencies even without injection of activated carbon (AC). This is demonstrated in Figure 5 that compares the results of the both algorithms with the mercury removal data from other studies. Figure 5 entails the following boundary conditions:

$H = 0-100 \text{ kg/Macm}$  (0-6.25 lbs/Macf)

$G = 5-40 \text{ g/m}^3$  of standard dry air-flue gas

$T = 100-180 \text{ }^\circ\text{C}$

$M = 25 \text{ g Hg}_T/\text{kg AC}$

$L = 2-5 \text{ percent}$

$A = 100$

$B = 100.$

The range of mercury removals predicted by UMREA is shown as a series of vertical step bars. The thick solid line represents the average removal efficiency predicted by the DOE/NETL Mercury Removal Algorithm. The thin dashed and thick dash-dotted lines reflect the data obtained for the Pleasant Prairie and Salem Harbor plants, respectively, when Norit Darco AC was used (1). The thick dash-dotted line is also a good fit for the results of tests from LOS 1 using AC injection (2). The thin dotted line shows the average data for B-PAC and AC injection studies at Great River Energy Stanton Station (4). The thin solid line represents the mercury removal data in the St. Clair Plant for Norit Darco AC injection (4). The thick dashed line shows a

fit of the mercury removal data obtained in a Sorbent Technologies' 40-acfm duct-injection pilot study employing proprietary brominated AC sorbents (4).

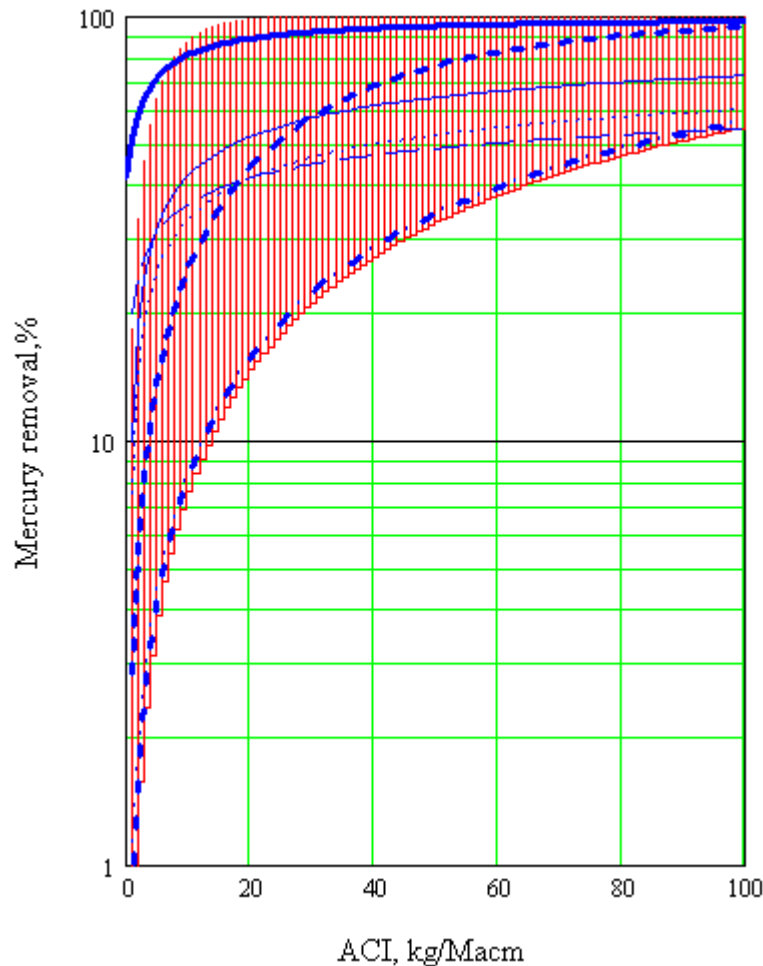


Figure 5. Various data set fits by the Universal Mercury  
Removal Efficiency Algorithm

A- and B-coefficients of 100 produce the best fit of all data cited above as compared to A = 200 and B = 50 that fits only the DOE/NETL algorithm. Figures 4 and 5 show that the shape of a curve describing mercury removal by flue gas fly ash and adsorbents including AC follows the



shape of a non-linear adsorption isotherm. For  $A = (50-200)$ ,  $B = (50-150)$  and the rest of the variables kept within their normal operating ranges, Eq. 3 can be used to predict mercury removal by any of the presently commercially available sorbent injection technologies.

### 4. Vapor Phase Mercury Concentration Derivation

The U.S. EPA Hg emissions data for coal power plants in the U.S. for 1999 (3,6) is shown in Table 4.

Table 4. Hg speciation in the flue gas at U.S. electric power coal-fired utilities in 1999.

Hg <sub>T</sub>	Hg <sup>0</sup>	HgCl <sub>2</sub>	Hg <sub>p</sub>	Hg <sup>0</sup> / HgCl <sub>2</sub>	(Hg <sub>p</sub> + Hg <sup>0</sup> )/ HgCl <sub>2</sub>
M. Tons	M. Tons	M. Tons	M. Tons		
48	26.1	20.41	1.48	1.279	1.351

Based on Table 4, un-oxidized Hg (i.e. Hg<sup>0</sup>) amounts to about 54 percent of the total Hg emitted in 1999. Most likely, particulate Hg<sub>p</sub> is Hg<sup>0</sup> since Hg<sup>0</sup> is a smaller than HgCl<sub>2</sub> molecule and, therefore, more readily adsorbed onto particulate matter (7). The following calculations were performed to test this assumption.

Molecular weight (MW) of Hg<sup>0</sup> = 200.59 g

Molecular weight of HgCl<sub>2</sub> = 271.5 g

Volume of 1 mole of air at 25°C = 24.46 L

1 ppm<sub>v</sub> = 10<sup>-6</sup> atm = 760(10<sup>-6</sup>) mm Hg

Concentration of species X can be estimated in the following manner (5):

$$C_x (\mu g / m^3) = N \cdot ppm_v \cdot \frac{1 \mu mol}{24.46 \mu L} \cdot \frac{MW_x (\mu g)}{\mu mol} \cdot \frac{1000 L}{m^3} \quad (4)$$

where N = number of ppm<sub>v</sub>.

Substituting the molecular weights in the above expression and dividing by each other gives the following relationship:

$$\frac{C(Hg^0)}{C(HgCl_2)} = 0.739 \cdot \frac{N_1 \cdot ppm_v(Hg^0)}{N_2 \cdot ppm_v(HgCl_2)} \quad (5)$$

Equation (5) indicates that the ratio of concentrations of the Hg species in the flue gas differs from the ratio of their partial pressures by a factor of 0.739. The reciprocal of 0.739 is 1.353, i.e.

$$1.353 = 0.739 \cdot \frac{N_1 \cdot ppm_v(Hg^0)}{N_2 \cdot ppm_v(HgCl_2)} \quad (6)$$

This value is very close to the value of 1.351 in Table 4, i.e. practically all elemental mercury is in the vapor form or adsorbed onto the flue gas fly ash:

$$Hg^{El} = Hg^0 + Hg_P \text{ and } Hg_{Total} = Hg^{El} + HgCl_2$$

From Eq. 6,

$N_1 = 1.83(N_2) ppm_v$ , i.e. almost all of the vapor phase Hg is elemental mercury rather than oxidized  $HgCl_2$  mercury.

Vapor pressure of  $Hg^0$  can be found using Antoine Equation (6):

$$\log P_{Hg^0} = A - \frac{B}{T + C} \quad (7)$$

For  $Hg^0$ ,  $A = 7.975756$  (5)

$B = 3255.61$  (5)

$$C = 281.988 (5)$$

T – temperature, °C

Figure 6 shows a plot of  $\text{Hg}^0$  vapor pressure as a function of flue gas temperature using Equation (6).

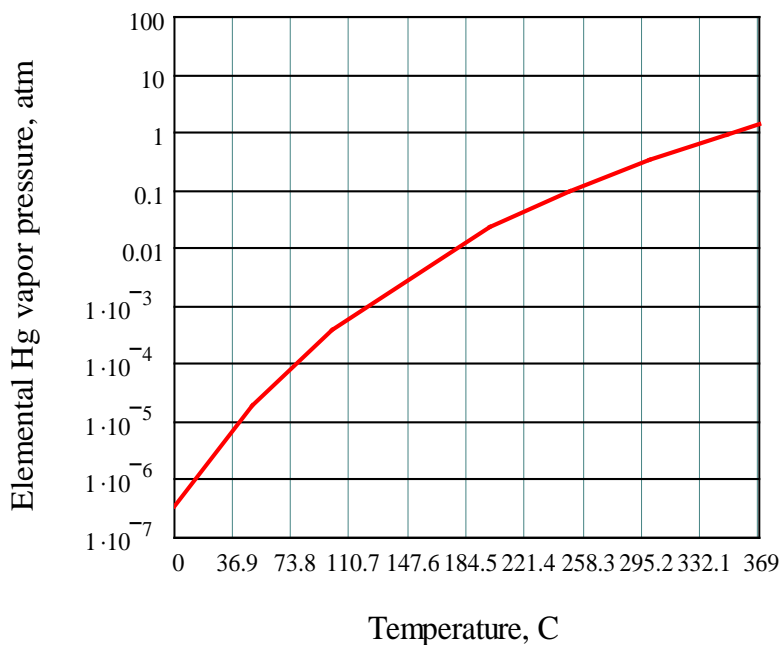


Figure 6.  $\text{Hg}^0$  vapor pressure as function of flue gas temperature.

Table 5 lists  $\text{Hg}^0$  and  $\text{HgCl}_2$  vapor pressures as functions of temperature, the ratios of vapor pressures and the ratio of expected concentrations in the flue gas derived using Equation (8).

Table 5. Ratio of  $\text{Hg}^0$  to  $\text{HgCl}_2$  concentrations in the flue gas vs. temperature.

Flue gas temperature, °C	$\text{Hg}^0$ vapor pressure, atm.	$\text{HgCl}_2$ vapor pressures, atm.	Ratio vapor P. $\text{Hg}^0/\text{HgCl}_2$	Ratio concert. $\text{Hg}^0/\text{HgCl}_2$
0	$3.5 \cdot 10^{-7}$	$2 \cdot 10^{-8}$	17.5	12.92
16	$1.32 \cdot 10^{-6}$	$2.5 \cdot 10^{-7}$	15.3	11.3
46	$1.31 \cdot 10^{-5}$	$4 \cdot 10^{-6}$	5	3.7
50	$1.9 \cdot 10^{-5}$	$4 \cdot 10^{-6}$	4.75	3.5
80	$1.32 \cdot 10^{-4}$	$7 \cdot 10^{-5}$	1.9	1.4
100	$3.73 \cdot 10^{-4}$	$2 \cdot 10^{-4}$	1.87	1.38
125	$1.32 \cdot 10^{-3}$	$2 \cdot 10^{-3}$	0.66	0.49
185	$1.32 \cdot 10^{-2}$	$4.5 \cdot 10^{-2}$	0.33	0.24
200	$2.2 \cdot 10^{-2}$	$7 \cdot 10^{-2}$	0.31	0.23
250	$9.4 \cdot 10^{-2}$	0.4	0.24	0.18
262	$1.32 \cdot 10^{-1}$	0.7	0.19	0.14
300	0.32	2	0.16	0.12
350	0.88	7	0.14	0.1
369	1.32	9	0.13	0.096

A plot of the ratio of  $\text{Hg}^0$  to  $\text{HgCl}_2$  concentrations in the flue gas vs. temperature is shown in

Figure 7.

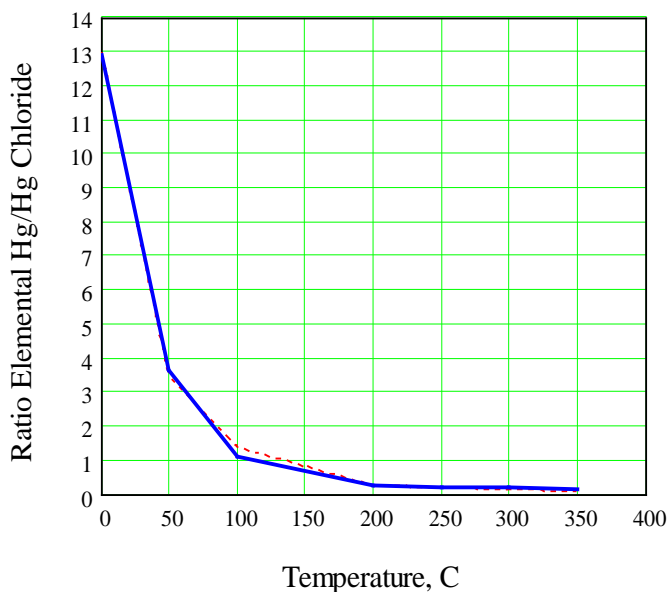


Figure 8. Ratio of  $\text{Hg}^0$  to  $\text{HgCl}_2$  concentrations in the flue gas vs. temperature.

The solid blue and dashed red lines in Figure 7 are an exponential fit of the data and data in Table 5, respectively.

An exponential data fit of the function  $f(x)$  in Figure 8 can be described as

$$f(x) = a \cdot e^{b \cdot T} + c \quad (8)$$

where  $a = 12.753$

$$b = -0.026$$

$$c = 0.167$$

$T$  – temperature, °C

It should be noted that at  $T = 120^\circ\text{C}$  ( $250^\circ\text{F}$ ), which is the average flue gas temperature at sampling ports (200-300 °F),  $f(x) = 0.731$  which is close to the coefficient 0.739 in Eq. (5).

The data in Table 5 shows that at this temperature, the ratio of  $\text{Hg}^0$  to  $\text{HgCl}_2$  concentrations in the flue gas equals 1.0. It is now obvious that at lower than  $120^\circ\text{C}$  temperatures  $\text{Hg}^0$  will dominate the vapor phased and at temperatures above  $120^\circ\text{C}$   $\text{HgCl}_2$  will be the dominating Hg species. If the average flue gas temperature is around  $120^\circ\text{C}$  ( $250^\circ\text{F}$ ), then the ultimate ratio for Hg speciation is

$$\frac{C(\text{Hg}^0)}{C(\text{HgCl}_2)} \cong 1.0 \quad (9)$$

This ratio is independent of the APC process design and Hg removal efficiency provided chlorine in coal is always in excess of Hg.

From Eq. 3 and Eq. 8 follows:

$$G = \text{Hg}^0 \cdot (1 + 1/R) \quad (10)$$

$$G = \text{HgCl}_2 \cdot (1 + R) \quad (11)$$

where

$$R = \left[ 12.753e^{-0.26T} + 0.167 \right] \quad (12)$$

$$M = M_1 + M_2 \quad (13)$$

$M_1$  -  $\text{HgCl}_2$  adsorption capacity of activated carbon or other adsorbent, g  $\text{HgCl}_2$ /kg AC

$M_2$  -  $\text{Hg}^0$  adsorption capacity of activated carbon or other adsorbent, g  $\text{Hg}^0$ /kg AC

The G and M values in Eq. (10) and (13) can be incorporated in Eq. (3) as follows:

$$RE = 100 \left( 1 - e^{\frac{-H \cdot (M_1 + M_2)}{G} \cdot \frac{398}{T^2 + 273} \cdot \frac{L^2 + A}{B}} \right) \quad (14)$$

where

RE – total Hg removal efficiency, percent

H - activated carbon injection rate, kg AC/ $\text{Mm}^3$  (standard dry air-flue gas)

M - Hg adsorption capacity of activated carbon, g  $\text{Hg}_T$ /kg AC, Eq. (13)

G - concentration of total Hg in flue gas,  $\text{g}/\text{m}^3$  of standard dry air-flue gas, Eq. (10)

L - amount of unburnt carbon in coal, percent by wt.

T - temperature,  $^{\circ}\text{C}$

A - coefficient for chlorine and sulfur coal contents, dimensionless

B - coefficient related to the APC process configuration, dimensionless.

The average value for A and B is 100.

Due to difficulties associated with continuous monitoring of  $\text{HgCl}_2$ , the use of Eq. (10) in Eq. (14)

is strongly recommended.

## **5. Conclusion**

The US EPA Clean Air Mercury Rule issued in 2005 required that a stepwise mercury removal be implemented within the next decade. Presently, not all of the existing coal-fired electric power plants and utility boilers are equipped to meet the new Maximum Achievable Control Technology limit for mercury. The sorbent injection technologies along with the process retrofit are the most economically feasible technologies for mercury removal from flue gas. Mercury removal efficiency is a complex function of many variables including the sorbent injection rate, flue gas temperature, amount of unburned carbon, mercury flue gas concentration, sorbent adsorption capacity, and APCD process configuration.

This paper makes a first attempt to incorporate the major variables affecting mercury removal from coal-fired electric power plant flue gas in one general expression, called UMREA, to define the amount of mercury that can be captured by any of the presently commercially available sorbent injection technologies. UMREA (Eq. 14) is an expanded and a more flexible version of the US DOE Mercury Removal Efficiency Algorithm. UMREA predicts flue gas mercury removal for a broad range of commercially available adsorbents. It can be used by various industries since mercury is emitted from a number of industrial processes beyond coal and oil combustion such as municipal and medical waste combustion and thermal treatment of hazardous materials.

### 6. References

1. Bland, A., L. Johnson, F. Guffey, K. Sellakumar, G. Walling, D. Steen, E. Klunder. (2004). Mercury control at low rank coal-fired power plants by a pre-combustion thermal treatment process. 2004 Western Fuels Symposium. Billings, Montana.
2. Chang, R., S. Sjostrom, T. Starns, and C. Richardson. (2004). Full-scale evaluation of mercury control options for western coals. 2004 Western Fuels Symposium. Billings, Montana.
3. Keating, M.H., Maxwell, W.H., Driver, L., and Rodriguez, R. (1997) Mercury Study Report to Congress; EPA-452/R-97-010. U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards. Washington, DC.
4. Nelson, S. Jr., R. Landreth, Q. Zhou, and J. Miller. (2004). Brominated mercury sorbents and evaluations of concretes containing mercury sorbents. 2004 Western Fuels Symposium. Billings, Montana.
5. Noll, K.E. (1993). Fundamentals of Air Quality Systems. Design of Air Pollution Control Devices. AAEE. Annapolis, MD.
6. U.S. Environmental Protection Agency. (2002). Research and development. Control of mercury emissions from coal-fired electric utility boilers: Interim report including ERRATA. EPA-600/R-01-109. Washington, DC.
7. Sappey, A.D. *et al.* (2014). A Continuous Emissions Monitor for Total, Elemental, and Total Speciated Mercury. ADA Technologies, Inc. Englewood, CO.