Modeling Mercury Control with Powdered Activated Carbon

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ABSTRACT

Full- and pilot-scale data has been collected on the effectiveness of powdered activated carbon (PAC) injection for control of mercury emissions from flue gas of coal-fired power plants. However, there has been limited modeling work accounting for the removal of mercury by existing equipment as shown by Information Collection Request (ICR) data and by PAC injection, independently of one another.

The mathematical model presented in this paper accounts for both components of total mercury removal at a plant equipped with PAC injection. Algorithms based on recent full-scale demonstrations were developed for PAC injection in plants: (1) firing subbituminous coal and having cold-side electrostatic precipitator (C-ESP), (2) firing bituminous coal and having hot-side ESP (H-ESP) followed by a pulse jet fabric filter (PJFF), and (3) firing bituminous coal and having cold-side ESP (C-ESP).

INTRODUCTION

Injection of Powdered Activated Carbon (PAC) is an approach for controlling mercury emissions that has been developed and tested at the full scale on coal-fired utility boilers. Test programs have been performed on a utility boiler firing subbituminous coal with a downstream cold-side electrostatic precipitator (ESP), on utility boilers firing bituminous coal with a downstream cold-side ESP, and on a utility boiler firing bituminous coal with a Compact Hybrid Particle Collector (COHPAC) arrangement (upstream hot-side ESP with downstream baghouse after the air preheater). Because of these test programs, there are data available for developing performance models of this technology for applications that are similar to these. In this research, performance models were developed. These models are in a form where they can be updated as new information is developed on these applications and for other boiler applications.

MERCURY REMOVAL MODELS

EPA's Information Collection Request (ICR) showed that mercury released from coal combustion may be partly removed from the exhaust gases by existing equipment without additional retrofit technology. The existing equipment may be one or more units that contribute to mercury removal.

If $f_{\text{equipment}}$ is equal to the fraction of mercury removed from the boiler gases by a piece of equipment, then $(1 - f_{\text{equipment}})$ equals the fraction of mercury remaining in the gases after that piece of equipment. The fraction of mercury remaining after n pieces of equipment is equal to

Fraction of mercury remaining after n pieces of equipment is

$$[(1 - f_{\text{equipment 1}}) \times (1 - f_{\text{equipment 2}}) \times (1 - f_{\text{equipment 3}}) \times \ldots \times (1 - f_{\text{equipment n}})] \quad \textbf{Eq. 1}$$

Therefore, the total mercury removal fraction, f_{Total}, is

$$f_{\text{Total}} = 1 - [(1 - f_{\text{equipment 1}}) \times (1 - f_{\text{equipment 2}}) \times (1 - f_{\text{equipment 3}}) \times \ldots \times (1 - f_{\text{equipment n}})] \quad \textbf{Eq. 2}$$

If one of the pieces of equipment is PAC injection, then the total mercury removal fraction is

$$f_{\text{Total}} = 1 - [(1 - f_{\text{equipment 1}}) \times (1 - f_{\text{equipment 2}}) \times (1 - f_{\text{equipment 3}}) \times \ldots \times (1 - f_{\text{PAC injection}}) \times \ldots \times (1 - f_{\text{equipment n}})] \quad \textbf{Eq. 3}$$

where $f_{\text{PAC injection}}$ is the fraction of mercury removed by PAC injection.

If PAC injection is simply added to existing equipment and the removal effects of the existing equipment are combined into one term, then we can represent Equation 3 as

$$f_{\text{Total}} = 1 - [(1 - f_{\text{existing equipment}}) \times (1 - f_{\text{PAC injection}})] \quad \textbf{Eq. 4}$$

where $f_{\text{existing equipment}}$ is the removal fraction of the existing equipment.

In this research, data from full-scale tests of mercury reduction were used to formulate models for mercury reduction from existing equipment and from PAC injection. Full-scale data for mercury removal by existing equipment are available from the ICR data. Full-scale testing results of mercury reduction from PAC injection are available from the Department of Energy's field testing programs at Southern Company's Gaston Plant, Wisconsin Electric Power Company's Pleasant Prairie Power Plant (PPPP), and at PG&E Corp. National Generating Group's Brayton Point and Salem Harbor Plants. [1]

MERCURY REMOVAL BY EXISTING EQUIPMENT, $f_{\text{existing equipment}}$

Through statistical analysis of the ICR data, Reference 2 shows that mercury reduction is a function of emission control equipment configuration, of chlorine content of the coal, and (in some cases) of the SO_2 emissions level from the boiler. Reference 2 provides algorithms to estimate mercury capture as a function of the plant configuration, the coal chlorine content, and the SO_2 emissions. These algorithms are:

Algorithm 1 (cold-side ESP):

$$f_{existing\ equipment} = C_1 \times \ln [(\text{coal Cl, ppm})/(SO_2, \text{ in lb/MMBtu})] + C_2 \qquad \textbf{Eq. 5}$$

Algorithm 2 (all other categories):

$$f_{existing\ equipment} = C_1 \times \ln (\text{coal Cl, ppm}) + C_2 \qquad \textbf{Eq. 6}$$

There are minimum and maximum allowable values that set the allowable range for the results of Equations 5 and 6. These are shown with C_1 and C_2 in Table 1 for hot- and cold-side ESP conditions.

According to this model (Eqs. 5 and 6), the mercury reduction efficiencies of existing equipment for conditions at Gaston, PPPP, Brayton Point, and Salem Harbor are estimated in Table 1.

Table 1. Collection of mercury by air pollution control equipment, predictions using correlation of Reference 2.

					Gaston	**PPPP**	**Brayton Point**	**Salem Harbor**
	Chlorine, % by weight in coal				0.03	0.0015	0.08	0.03
	Coal Chlorine, ppm				300	15	800	300
	Flue Gas SO_2, lb/MMBTU				0.650	0.360	0.820	0.500
	C_1	C_2	Min	Max				
ESPc	0.1233	-0.3885	0.0%	55.0%		**7.1%**	**46.0%**	**40.0%**
ESPh	0.0927	-0.4024	0.0%	27.0%	**12.6%**			

ESPc = cold-side ESP
ESPh = hot-side ESP

Gaston fires bituminous coal and has a hot-side ESP followed by an air preheater and then a low-pressure pulse-jet fabric filter (PJFF) for a COHPAC arrangement.[1,3,4] Reference 2 did not include algorithms for facilities with this arrangement. One might expect that the mercury reduction without PAC might correspond approximately to the predicted mercury reduction in Table 1 for a hot ESP (ESPh). Under the conditions at Gaston, this equals 12.6%. However, tests at Gaston showed negligible mercury removal, but the difference may be reasonable considering the range of variability in the possible results. However, this demonstrates that this algorithm will give reasonable estimates but not precise values.

At the PPPP, a facility firing PRB coal with a cold-side ESP, the test results showed about 5% actual mercury removal from existing equipment compared to about 7% as estimated by the algorithm of Reference 2 (Eq. 5) for the same conditions at PPPP, and shown in Table 1.[1,5] Therefore, this is approximately in the same range. The chlorine content of the coal used at PPPP (15 ppm, which is much lower than those of most other PRB sites) probably contributes to the low removal by existing equipment. With chlorine content more typical of a PRB coal, around 100 ppm or more, the algorithm predicts that mercury would be reduced by a greater amount.

For Brayton Point, a facility firing bituminous coal and equipped with a cold-side ESP, the algorithm of Reference 2 (Eq. 5) produces an estimated mercury reduction by existing equipment of about 46% (see Table 1) versus an actual measured removal efficiency of 32%.[1] These values, which are in about the same range, further illustrate that the algorithm of Reference 2 is not exact, but approximate, at estimating mercury removal by existing equipment.

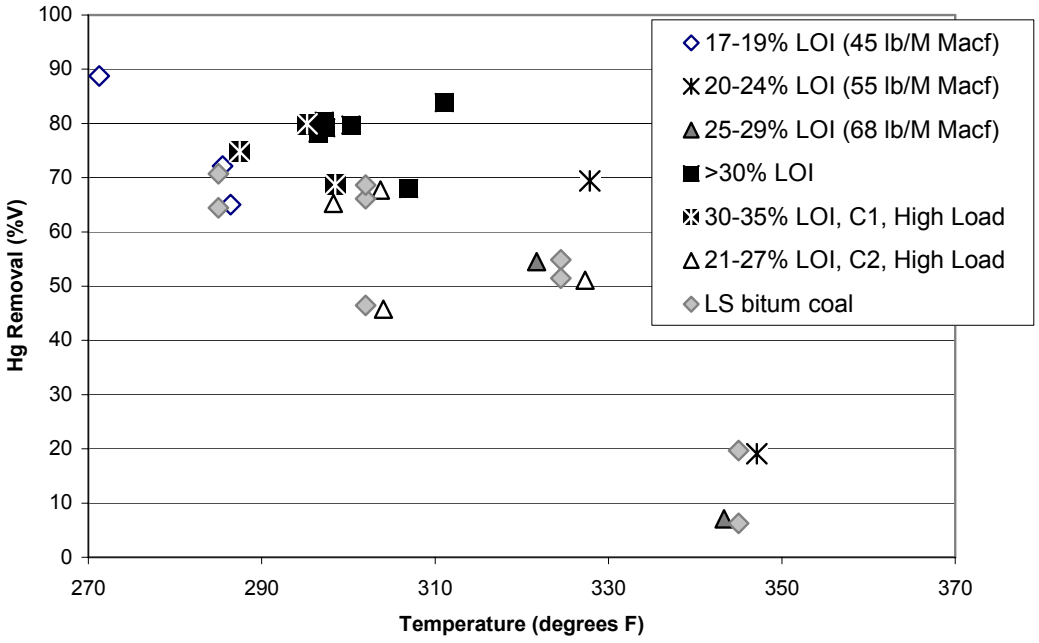
At Salem Harbor, a facility firing bituminous coal and equipped with a cold-side ESP, 87% mercury reduction from existing equipment was measured.[1] This compares to about 40% estimated from the algorithm of Reference 2 (Eq. 5) and shown in Table 1. Salem Harbor operates with fly ash loss-on-ignition (LOI) in the range of 25%-35%. According to Reference 6, this is approximately equivalent to a carbon loading of 60-84 lb/MMacf in the exhaust stream – a much higher carbon loading than one would typically inject PAC. So, the carbon in the ash likely contributed to the very high intrinsic capture of mercury.

The capacity of PAC to absorb mercury is so great that it should not be limiting except at temperatures of about 350 ºF or more, which is greater than the gas temperature at the exit of most air preheaters. So, cooling usually has little or no beneficial effect on mercury absorption by PAC. However, the ability of fly ash and unburned carbon in the fly ash to absorb mercury is far less than that of PAC and may be enhanced by cooling. Therefore, while spray cooling may enhance mercury absorption by fly ash and downstream capture in the ESP or fabric filter, spray cooling is not expected to enhance mercury capture by PAC.

The importance of temperature on intrinsic capture is demonstrated by test results at Salem Harbor. Because Salem Harbor has the ability to increase its ESP inlet temperature through operation of steam heaters, parametric tests of intrinsic mercury removal as a function of temperature could be performed. Figure 1 shows the results of that testing under various firing conditions along with data taken from another test using low sulfur (LS) bituminous coal (not the baseline coal). The trend is quite clear that increasing temperature reduces intrinsic mercury capture from as much as 90% down to around 10%.

Because a facility's mercury reduction by existing equipment may be significantly different than what the algorithm of Reference 1 determines, this algorithm should be used with care and only for making estimates. As the measurements at Salem Harbor clearly indicate, LOI (or other ash qualities) and gas temperature can have a very significant impact on the level of mercury being removed by existing equipment and may be worth including as parameters in this algorithm at some future date when more information is available. Therefore, the algorithm of Equation 6 and Reference 1 may provide reasonable estimates in many cases. But, there is a chance that actual mercury capture may differ significantly from what Equation 6 predicts. For any specific facility, actual measurements of mercury removal, if available, should be used.

Figure 1. Salem Harbor Mercury Romoval Without PAC Injection (Ref. 6)



MERCURY REDUCTION BY PAC INJECTION, $f_{\text{PAC injection}}$

Reference 7 has algorithms developed from pilot-scale data for mercury reduction on boilers equipped with PAC injection. In this work, we have made the following model improvements:

1. The algorithms of Reference 7 were developed from pilot-scale tests and characterize total mercury reduction from both PAC injection and existing equipment as a function of PAC injection concentration. When using the algorithms of Reference 7, it is necessary to have a different PAC injection algorithm for each type of equipment configuration, including upstream equipment. These PAC injection algorithms may have to be updated as new information regarding mercury control from existing equipment becomes available. In the research described in this paper, the mercury reduction from PAC injection was isolated from that of the other equipment. Therefore, as we gain more information on reduction of mercury from equipment other than PAC injection, it should not be necessary to perform new regressions on the PAC injection models, and it will also be possible to assess the fate of mercury in equipment that is either upstream or downstream of the PAC injection system.

2. The algorithms of Reference 7 are of a form in which it is possible to approach 100% mercury removal by injection of very high concentrations of PAC. As will be shown, experience at PPPP showed that, under some circumstances, it is not

possible to achieve such extremely high reduction of mercury emissions with PAC injection. Therefore, the algorithm for mercury reduction from PAC injection was modified to permit an upper limit to mercury removal that may be less than 100%.

3. Because the algorithms of Reference 2 are based on the full-scale ICR data, it is desirable to use them to characterize mercury reduction from existing equipment. However, it is not possible to integrate the algorithms of Reference 2 into the approach used in Reference 7. By treating the mercury reduction from PAC injection independently from mercury reduction from other equipment, it is possible to use the algorithms of Reference 2 to characterize mercury reduction from existing equipment.

In the case of PPPP, PAC injection test results demonstrated that mercury reduction behaved asymptotically with a maximum achievable mercury reduction from PAC that is well below 100%, regardless of PAC injection rate. For this reason, the equation that is used in Reference 7 to characterize the relationship between mercury reduction and PAC injection

$$\% \text{ reduction} = \eta = 100 \times f_{\text{from PAC injection}} = 100\text{-}[A/(M+B)^C] \qquad \textbf{Eq. 7}$$

where M is the mass injection rate of PAC (in lb/MMacf) so that

$$M = \{[A/(100 - \eta)]^{(1/C)}\} - B \qquad \textbf{Eq. 8}$$

has been modified to be

$$M = \{[A/((100*D) - \eta)]^{(1/C)}\} - B \qquad \textbf{Eq. 9}$$

Where D is the fraction of mercury reduction that is asymptotically approached.

A set of constants A, B, C, and D are specified for a given plant configuration and gas temperature. At this time, these constants can only be derived for full-scale applications similar to the conditions where full-scale data exists. For some other boiler configurations, there are test data available from pilot-scale tests that can be used until full-scale data become available. For configurations where neither full-scale nor pilot-scale data exists, the constants can be developed as data becomes available from future tests.

PAC INJECTION MODELS DEVELOPED FROM FULL-SCALE DATA

For the purpose of modeling, we are interested in estimating the necessary PAC injection rate to achieve a specified level of mercury control. Therefore, we developed algorithms of PAC injection rate as a function of desired mercury reduction by PAC. So, rather than plotting mercury reduction versus PAC injection concentration, as is done in References 5, 3, and 4, we have reversed the axes from what is shown in these references.

In these tests several different PAC sorbents were tested. The different PAC sorbents will be designated on the legends of the figures. Since specific information regarding the properties of the tested sorbents was not available, the impact of these properties on mercury removal performance was not evaluated. However, effects of sorbent choices on mercury capture performance are noted.

Gaston

Figure 2a shows mercury collection results measured from an on-line mercury analyzer during testing conducted at Gaston. Data is plotted as PAC injection concentration versus mercury reduction percent. Data includes results with several different sorbent types.[8] Figure 2a also shows a curve developed in the form of Equation 9 to approximately correspond to the results achieved at Gaston. The coefficients for the algorithm are listed in Table 2. It is notable that, at Gaston, the choice in sorbent appeared to have little or no impact on performance. It is also notable that, at mercury removal rates in the range of 92%-96%, mercury reduction is less sensitive to changes in PAC injection rate. Figure 2b shows the data for 92%-96% mercury reduction in greater detail. The enclosed region on Figure 2b includes the estimated 95% confidence range for this mercury reduction data.[a] Figure 3, a plot of deviation of the predicted and measured PAC injection rate,[b] demonstrates this in another way. For most mercury reduction levels, the deviation between model and actual PAC injection rates is only about 10%. For mercury reduction in excess of 90%, however, the deviation is higher on a percentage basis. While Figure 3 shows that, expressed as a percent of predicted level, at high removal rates the deviation between the model and measured value is –30% to +40%, in fact this only corresponds to a range of under ±1 lb/MMacf. The high percentage in the deviation is due to the actual values being relatively small at Gaston.

Table 2. Coefficients For Curvefit Algorithms

Plant	Algorithm	A	B	C	D
Gaston		53	0.1	2	1.00
PPPP	a	150	5	1	0.72
	b	140	1	1	0.69
	c	145	3	1	0.705
Brayton	a	300	3	0.8	1.13
	b	300	0	0.8	1.05
	c	300	1.5	0.8	1.09

a. 95% confidence range for Hg reduction and for PAC injection concentration are determined by ±2 standard deviations from the arithmetic mean, with correction for sample size.
b. Calculated as (actual rate – predicted rate) / predicted rate and expressed in percent

Figure 2a. Gaston Testing

Data from reference 8

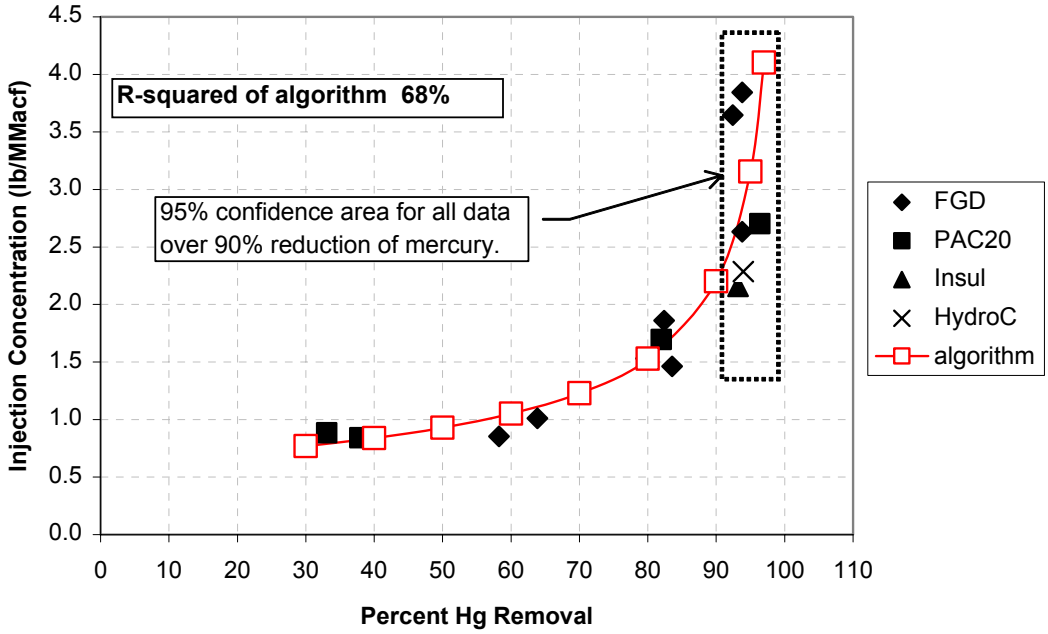


Figure 2b. Gaston Testing

Data from reference 8

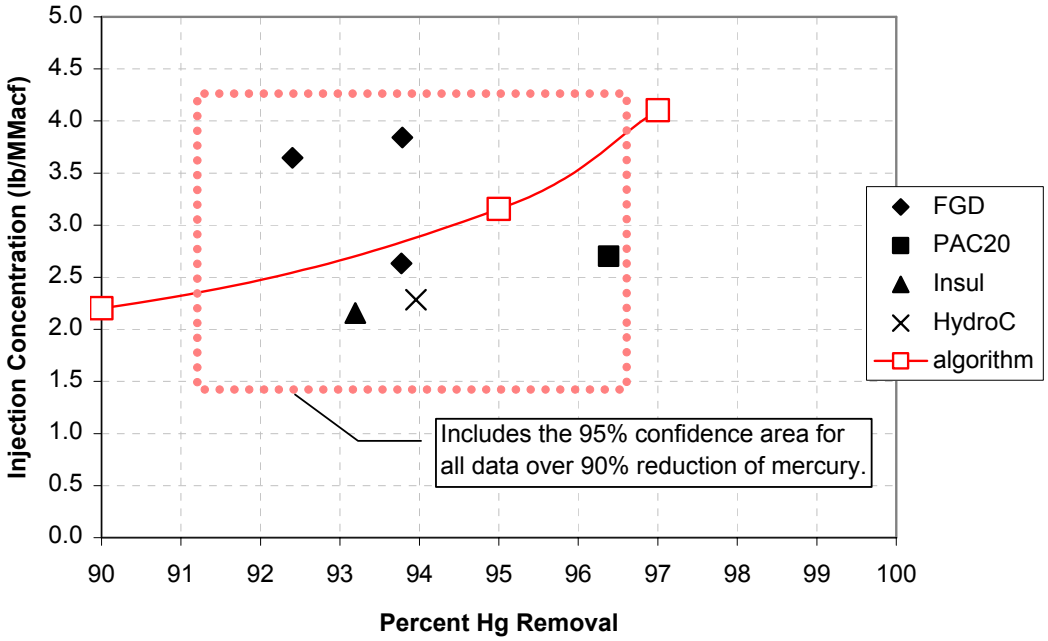
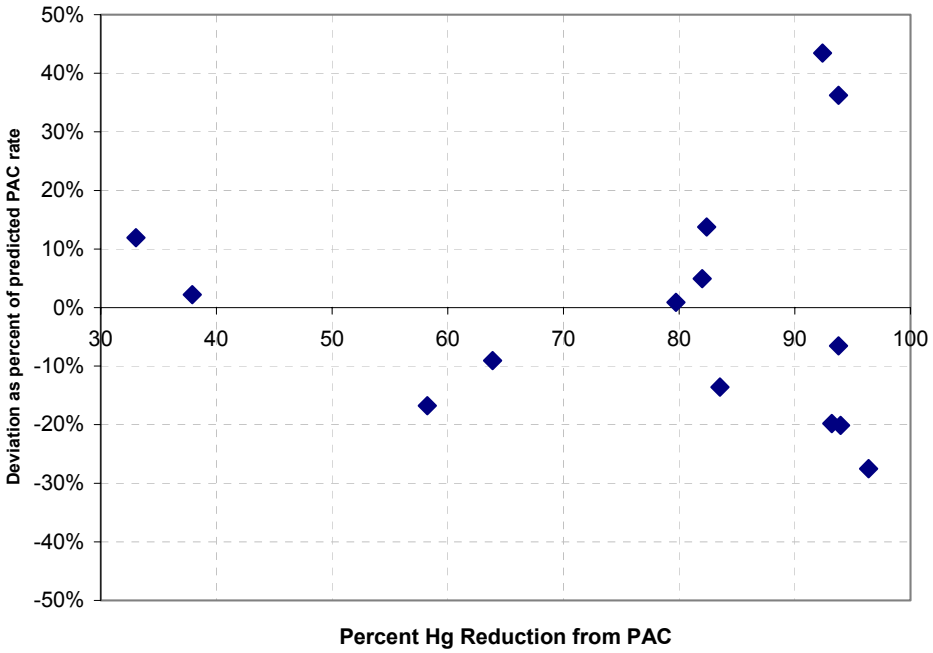


Figure 3. Deviation of the Gaston PAC Algorithm

deviation = (actual PAC rate minus predicted PAC rate) divided by predicted PAC rate



Pleasant Prairie Power Plant (PPPP)

Figure 4 shows mercury collection results measured from an on-line mercury analyzer during testing conducted at PPPP. Data includes results with several different sorbent types.[8] Figure 4 also shows a data point for the total mercury removal as measured by the Ontario Hydro method. The Ontario Hydro method shows a somewhat higher, but nevertheless similar, mercury removal as the on-line mercury analyzer used for the testing. Curves were developed in the form of Equation 9 to correspond to specific sets of data and are plotted on Figure 4. The coefficients of these algorithms (A, B, C, D) are listed in Table 2. Unlike the results at Gaston, at PPPP the choice of sorbent has a significant effect. This may be a result of the fact that, at Gaston, there is a downstream fabric filter, which provides improved sorbent-gas contact, while at PPPP all of the mercury absorption had to occur in the duct. Figure 5 is a plot of deviation of the predicted and measured PAC injection rate.[c] Had one algorithm been used for all of the sorbents, the deviations would have been very high in some cases. Nevertheless, there is enough scatter in some of the data that, even with different algorithms for each sorbent, deviation can be on the order of 40%. Note that the one data point with very high percent deviation (over 70%) was actually at a low removal rate, and the absolute difference between the algorithm results and measured results was quite small. It is recommended that, for other plants with conditions similar to those at PPPP, some consideration should be made for the sorbent type. Since the choice of sorbent affects performance, a different algorithm may be necessary to accurately model the performance for each sorbent.

c. Calculated as (actual rate – predicted rate) / predicted rate

Figure 4. PPPP Testing

Data from reference 8

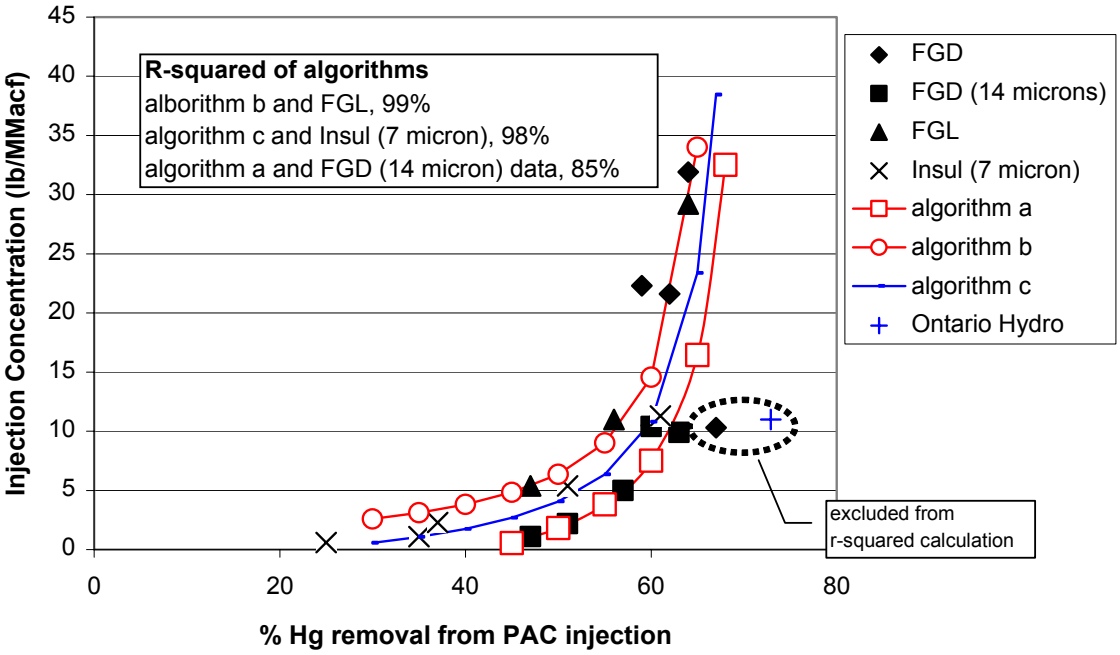
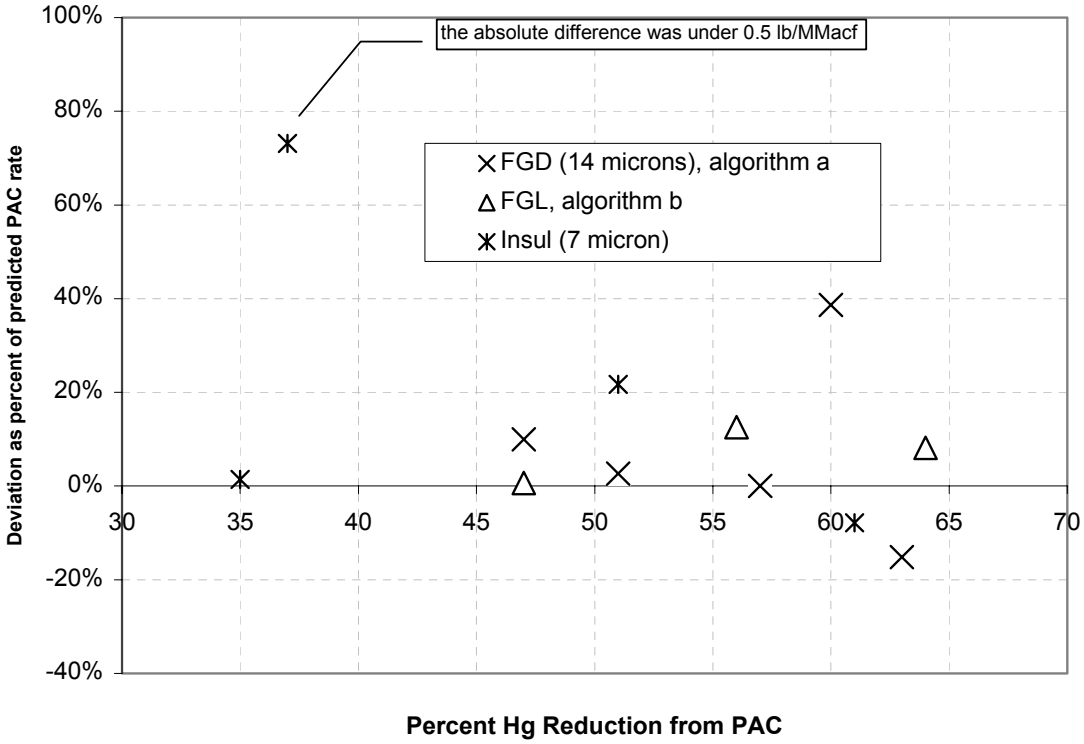


Figure 5. Deviation from the PPPP PAC Algorithms

deviation = (actual PAC rate minus predicted PAC rate) divided by predicted PAC rate



Brayton Point

Figure 6 shows results of testing at Brayton Point. Data includes results with several different sorbent types.[8] Figure 6 also shows curves developed in the form of Equation 9 that correspond to specific sorbent types. The coefficients of these algorithms are listed in Table 2. Like PPPP and unlike the results at Gaston, at Brayton Point the choice of sorbent appears to have a significant effect on performance. When considered with the PPPP results, this provides further evidence that the sorbent choice may have a greater impact when a downstream fabric filter is not installed. While good correlation is possible for all data with algorithm c (R^2 = 77%), improved correlation was possible by using different correlations for different sorbents, as demonstrated by the higher correlations of algorithms a and b with the sorbents indicated on Figure 6. Figure 7 shows that the predictive accuracy of the algorithms across a broad mercury removal range does not change much. However, Figure 7 shows that improved accuracy will result if the algorithm is tailored to the sorbent. For algorithm c, maximum deviation ranges –60% to +50%. But, by tailoring the algorithm to the sorbent, as shown for Alt Sorbent 1 with algorithm b and FGD1 with algorithm a, the deviation is reduced sharply.

Figure 6. Brayton Point Testing

Data from reference 8

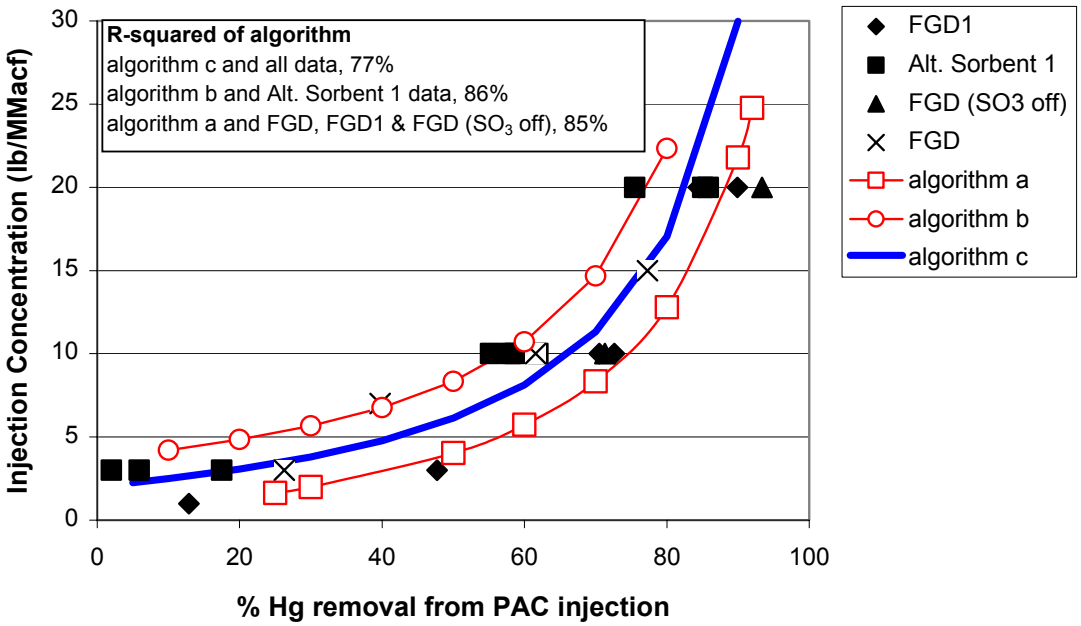
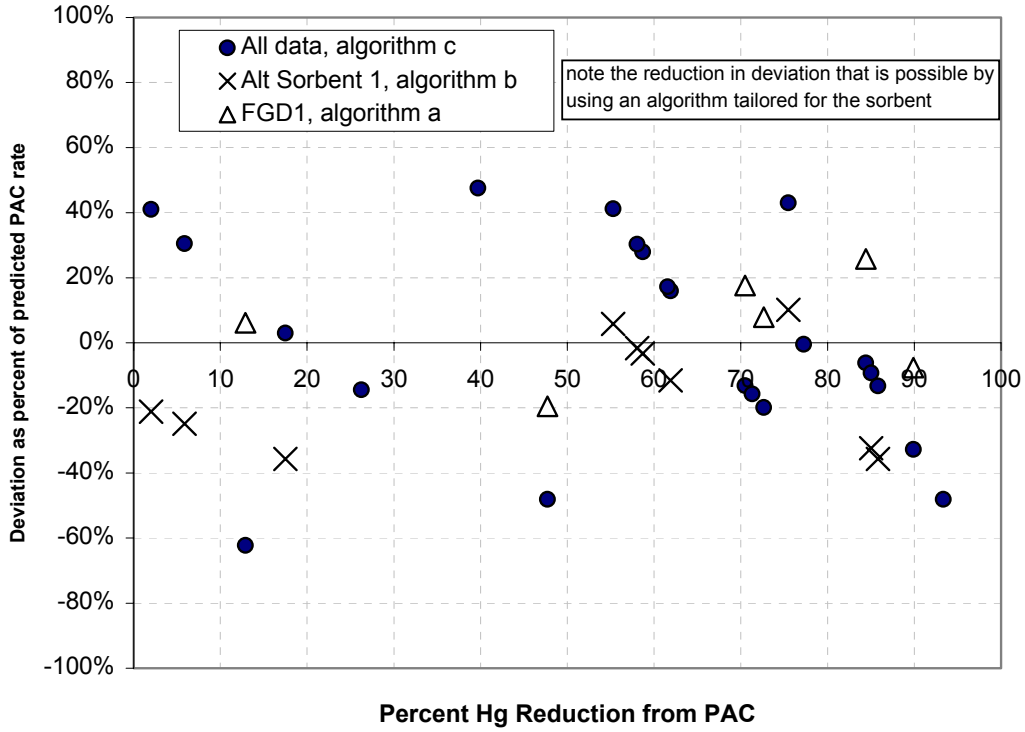


Figure 7. Deviation from the Brayton Point PAC Algorithms

deviation = (actual PAC rate minus predicted PAC rate) divided by predicted PAC rate



Salem Harbor

According to Reference 6, long-term testing of PAC injection with baseline coal indicated about 90% reduction of mercury without any PAC injection as well as with 10 lb/MMacf of PAC injection. Because of the high level of intrinsic mercury reduction at Salem Harbor and the sensitivity of the measuring methods, the increased mercury reduction from PAC is difficult to assess. Therefore, it was not analyzed in this effort. However, Salem Harbor information provided useful insights to the effects of unburned carbon and gas temperature on intrinsic levels of mercury reduction as previously discussed in this paper.

CONCLUSIONS

In this program, correlations for mercury removal from coal-fired power plants have been developed. The model incorporates information on mercury removal from existing equipment that was developed from the ICR data in Reference 2. It also incorporates mercury removal from injection of PAC, as developed from full-scale demonstrations of PAC injection where data is available. These algorithms should be updated and modified as more information becomes available on experience with mercury removal.

The following summarize some important findings that affect modeling mercury removal:

- Models that permit isolation of the effects of different air pollution control equipment on the fate of mercury will facilitate modeling combined effects with PAC injection over a wide range of boiler configurations and scenarios without the need for new regressions of PAC injection test data. Impact of a specific piece of equipment can be estimated with models best suited for that equipment. The models here are a step in that direction in that they isolate the effects of PAC injection from the effects of other air pollution control equipment.

- PAC injection followed by a PJFF results in much lower injection concentrations being necessary for a given level of mercury reduction than for PAC injection followed by a cold-side ESP. Thus, economic modeling may show that in some cases the additional capital cost of a FF may be justified by reduced operating costs associated with PAC consumption.

- Sorbent selection appears to have little effect on performance when PAC injection is followed by a FF, but it appears to have a significant effect when PAC injection is followed by an ESP.

- As demonstrated by the Salem Harbor test results, LOI and temperature can have a significant effect on the mercury removal by existing equipment. For this reason, the correlations of Reference 2, which do not include these effects, do not always provide an accurate indication of mercury removal by existing equipment.

- In some cases PAC injection without a downstream FF may not be able to achieve mercury removal rates of 90% or more regardless of PAC injection concentration.

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