EVALUATION OF MERCURY EMISSIONS FROM COAL-FIRED FACILITIES WITH SCR AND FGD SYSTEMS

Project Final Report

for the Period September 9, 2002, through March 7, 2006

U.S. DOE NETL Cooperative Agreement DE-FC26-02NT41589

Issued: April 2006

J. A. Withum

CONSOL Energy Inc.,
Research & Development
4000 Brownsville Rd.
South Park, PA 15129
(412) 854-6600

DISCLAIMER

ABSTRACT

CONSOL Energy Inc., Research & Development (CONSOL), with support from the U.S. Department of Energy, National Energy Technology Laboratory (DOE) and the Electric Power Research Institute (EPRI), evaluated the effects of selective catalytic reduction (SCR) on mercury (Hg) capture in coal-fired plants equipped with an electrostatic precipitator (ESP) - wet flue gas desulfurization (FGD) combination or a spray dyer absorber – fabric filter (SDA-FF) combination. In this program CONSOL determined mercury speciation and removal at 10 bituminous coal-fired facilities; at four of these facilities, additional tests were performed on units without SCR, or with the existing SCR bypassed.

This project final report summarizes the results and discusses the findings of the body of work as a whole. Eleven Topical Reports were issued (prior to this report) that describe in great detail the sampling results at each of the ten power plants individually.

The results showed that the SCR-FGD combination removed a substantial fraction of mercury from flue gas. The coal-to-stack mercury removals ranged from 65% to 97% for the units with SCR and from 53% to 87% for the units without SCR. There was no indication that any type of FGD system was more effective at mercury removal than others. The coal-to-stack mercury removal and the removal in the wet scrubber were both negatively correlated with the elemental mercury content of the flue gas and positively correlated with the scrubber liquid chloride concentration. The coal chlorine content was not a statistically significant factor in either case. Mercury removal in the ESP was positively correlated with the fly ash carbon content and negatively correlated with the flue gas temperature.

At most of the units, a substantial fraction (>35%) of the flue gas mercury was in the elemental form at the boiler economizer outlet. After passing through the SCR-air heater combination very little of the total mercury (<10%) remained in the elemental form in the flue gas; this was true for all SCR catalyst types and sources. Although chlorine has been suggested as a factor affecting the mercury speciation in flue gas, coal chlorine was not a statistically significant factor affecting mercury speciation at the economizer exit or at the air heater exit. The only statistically significant factors were the coal ash CaO content and the fly ash carbon content; the fraction of mercury in the elemental form at the economizer exit was positively correlated with both factors.

In a direct comparison at four SCR-equipped units vs. similar units at the same sites without SCR (or with the SCR bypassed), the elemental mercury fractions (measured at the ESP outlet) were lower, and the coal-to-stack mercury removals were higher, when the SCR was present and operating. The average coal-to-stack mercury removal at the four units without an operating SCR was 72%, whereas the average removal at the same sites with operating SCRs was 88%.

The unit mercury mass balance (a gauge of the overall quality of the tests) at all of the units ranged from 81% to 113%, which were within our QA/QC criterion of 80-120%.

TABLE OF CONTENTS

LIST OF FIGURES

Page

LIST OF TABLES

INTRODUCTION

CONSOL Energy Inc., Research and Development (CONSOL) determined mercury speciation and removal at 10 coal-fired facilities with SCR/FGD combinations, as shown in Table 1. All of the plants burned bituminous coal during the tests. The plants were chosen to provide a variety of SCR types, FGD types, unit sizes, and bituminous coal sources. At two of the facilities (Sites 6 and 7), additional tests were performed when the SCR was bypassed. At two other facilities (Sites 4 and 5), tests were performed at a second unit on site that did not have an SCR but was otherwise similar to the SCR-equipped unit tested at those sites. At one facility (Site 3), tests were performed in which calcium chloride ($CaCl_2$) was added to the coal to examine the effect of coal chlorine content on mercury speciation and removal. The added $CaCl_2$ increased the chlorine content by 200 ppm and 350 ppm.

At each unit, the Ontario Hydro Flue Gas Mercury Speciation Method was used simultaneously at two to five locations. Solid and liquid samples were collected and mercury mass balances were calculated to confirm the observed removals. The mercury measurements were made using the Ontario-Hydro Flue Gas Hg Speciation Method. The tests were performed under U.S. Department of Energy (DOE) Cooperative Agreement No. DE-FC26-02NT41589, and the Electric Power Research Institute (EPRI) Agreement No. EP-P13687/C6820. The test details and results for each site are reported individually in Topical Reports 1 through 11. This report summarizes the individual Topical Reports and analyzes the results as a whole body of work.

Table 1. Coal-fired facilities in program

Site #	MW	SCR Type	Particulate / SO_2 Control Devices	SCR Operation
1	330	Siemens Plate + Hitachi Plate	Spray Dryer / Baghouse	year round
2	245	IHI Corp. Honeycomb	Spray Dryer / Baghouse	year round
3 [(1)]	508	KWH Honeycomb	ESP/ Limestone FGD, inhibited oxidation	ozone season
4 [(2)]	468	Siemens Plate	ESP/ Limestone FGD, natural oxidation	year round
5 [(2)]	1,300	Cormetech Honeycomb	ESP/ Limestone FGD, in-situ oxidation	ozone season
6 [(3)]	544	Hitachi Plate	ESP/ Limestone FGD, ex-situ oxidation	ozone season
7 [(3)]	566	Hitachi Plate	ESP/ Limestone FGD, ex-situ oxidation	ozone season
8	684	Haldor-Topsoe Corrugated Plate	ESP / Mg-Lime FGD, ex-situ oxidation	ozone season
9	640	Haldor-Topsoe Corrugated Plate	ESP/ Mg-Lime FGD, inhibited oxidation	ozone season
10	1,300	Siemens Plate	ESP/ Mg-Lime FGD, inhibited oxidation	ozone season

[(1)] Additional tests were conducted with calcium chloride added to the coal.
[(2)] Additional tests were conducted on a separate, non-SCR equipped unit at the same site.
[(3)] Additional tests were conducted on the same unit during non-ozone season while flue gases bypassed the SCR.

EXECUTIVE SUMMARY

Mercury removal. The results show that the SCR-FGD combination can remove a substantial fraction of mercury from flue gas. The coal-to-stack mercury removals ranged from 65% to 97% for the units with SCR and from 53% to 87% for the units without SCR. There was no indication that any type of FGD system was better at mercury removal than others.

The scrubber mercury removal and the coal-to-stack mercury removal were examined by multiple linear regression. The significant factors were the elemental mercury content of the flue gas at the air heater outlet (negative correlation) and the scrubber liquid chloride concentration (positive correlation). The coal chlorine content was not a statistically significant factor for scrubber mercury removal or coal-to-stack mercury removal.

A statistical analysis showed that mercury removal in the ESP was positively correlated with the fly ash carbon content and negatively correlated with the flue gas temperature.

Mercury speciation. At most of the units, substantial amounts of elemental mercury were measured at the boiler economizer outlet. At all but one unit, more than 35% of the mercury was in the elemental form at this location. After passing through the SCR-air heater combination, a substantial portion of the elemental mercury was oxidized. The elemental mercury concentration on each SCR-equipped unit was less than 10 % of the total mercury in the flue gas at the air heater exit. There was no clear effect of SCR catalyst type or source on mercury oxidation. In a direct comparison of SCR vs. non-SCR operation at four sites, the SCR increased the oxidation of the mercury (measured at the ESP outlet).

Chlorine has been suggested as a factor affecting the mercury speciation in flue gas; others have reported that low chlorine coals tend to produce less oxidized mercury and more elemental mercury at the air heater outlet compared to higher chlorine coals. However, over the range of coal chlorine levels in the coals in this study, an effect of coal chlorine on mercury speciation was not observed.

A statistical analysis was performed on the economizer outlet flue gas mercury speciation data. The only statistically significant factors were the coal ash CaO content and the fly ash carbon content; both were positively correlated with the percent elemental mercury at the economizer outlet. None of the other measured factors were statistically significant, including the coal chlorine content. At the air heater outlet and the ESP outlet locations, no statistically significant correlations with coal chlorine or any other tested variable were found.

Mercury mass balances. The mercury mass balance closure is a gauge of the overall quality of the tests. The mass balances were calculated from the mercury contents of all input streams (coal, lime or limestone, and liquid input to the FGD

system) and all output streams (bottom ash, ESP or baghouse ash, FGD blowdown, and stack gas). The mercury mass balances at all of the units ranged from 81% to 113%, which were within our QA/QC criterion of 80-120%.

EXPERIMENTAL

CONSOL performed flue gas mercury determinations using the Ontario-Hydro sampling method at two to five locations on each unit. As a quality assurance/quality control (QA/QC) measure, samples of the coal, bottom ash, FGD slurry, limestone slurry, and ESP ash were taken to determine a mercury balance for each unit tested. Details of the locations sampled and the process samples collected are included in the Topical Reports for this project[1-11]. Details of QA/QC procedures and results are in the Topical Reports, also.

It is important to recognize that caution should be employed on the use of the Ontario Hydro method to speciate mercury in flue gas. The method was validated for use in stack conditions, i.e., downstream of the plant's air heater and particulate collection device. The method's ability to properly speciate mercury under the conditions of high dust loading (such as upstream of the ESP or fabric filter) or high temperatures (such as upstream of the air heater) has not been demonstrated. The method's ability to measure total mercury at these locations, however, is believed to be accurate.

The purpose of choosing a variety of plants in different geographic areas was to perform tests at plants burning a variety of bituminous coals. No special arrangements were made to burn specific coals during the tests, i.e., all of the plants were burning their normally scheduled fuel during the tests. Table 2 confirms that a wide variety of coals were burned during testing; for example, the coal sulfur content varied over a range of 1.0 to 4.7%, the mercury content varied over a range of 0.09 to 0.14 ppm, and the chlorine content varied over a range of 130 to 1630 ppm. The chlorine content was of interest because of its purported effect on flue gas mercury speciation.

Table 3 shows the variation in flue gas temperatures at various locations, fly ash carbon content, and scrubber filtrate chloride content. Flue gas temperature and fly ash carbon were of interest because they may affect the amount of mercury capture on the ESP ash.

RESULTS AND DISCUSSION

Mercury Speciation

Mercury speciation was a subject of this study because FGD scrubbers are efficient at removing oxidized mercury, but not elemental mercury. On units with an SCR system for NOx control, the SCR catalyst could potentially oxidize some of the elemental mercury. The results of the mercury speciation measurements from this study are summarized in Table 4.

At most of the units, the Ontario Hydro (OH) method measured substantial amounts of

elemental mercury at the boiler economizer outlet, where the flue gas enters the SCR (or air heater on non-SCR-equipped units). At all but one plant, more than 35% of the mercury was in the elemental form at this location, as indicated by OH sampling.

The flue gas was not sampled between the SCR and air heater at all plants due to the unavailability of usable sampling ports at this location at some plants. Thus, mercury speciation between the SCR and the air heater was determined at five of the ten sites, as shown in Table 4. At Sites 5, 6, and 10, the percentage of elemental mercury was substantially reduced compared to the SCR inlet, as expected. During the test with the SCR at Site 7 the percentage of elemental mercury was about the same at the SCR inlet and outlet, within experimental error, but the mercury was already substantially oxidized (only 14% elemental) during this test at the economizer exit. At all three test conditions at Site 3, the OH method showed a substantial increase in the percentage of elemental mercury, which is the opposite of the expected results. It is not clear if the results are real or due to error.

After passing through the SCR-air heater combination, there was very little elemental mercury remaining in the flue gas. At each SCR-equipped plant, the elemental mercury concentration was less than 10% of the total mercury in the flue gas at the air heater exit. There was no clear indication that any particular SCR type or manufacturer resulted in substantially more oxidized mercury at the air heater exit than another.

Listed in Table 4 along with the mercury speciation results are the coal chlorine contents. Chlorine has been suggested as a factor that affects the mercury speciation in flue gas; low chlorine coals are purported to produce less oxidized mercury and more elemental mercury at the air heater outlet compared to higher chlorine coals[12]. However, over the range of coal chlorine in this study, an effect of coal chlorine on mercury speciation was not observed. Figure 1 shows the flue gas elemental mercury (as a percent of total mercury) versus the coal chlorine content, for three different locations.

The percent elemental mercury at the economizer outlet was examined by multiple linear regression against the coal chlorine, sulfur, ash components, fly ash carbon and flue gas temperature. All of the independent variables were included in the initial model, and the least significant factors (i.e., those having the largest p-values) were removed in a stepwise manner until the remaining factors were all statistically significant at the 95% confidence level ($p<0.05$). The only statistically significant factors were the coal ash CaO content and the fly ash carbon content; the intercept was not significantly different from zero. Figure 2 shows the boiler economizer outlet flue gas elemental mercury percentage as a function of the coal ash CaO content and separately as a function of the fly ash carbon content. The summary statistics are given below:

Regression Statistics	
Multiple R	0.974217
R Square	0.949098
Adjusted R Square	0.853561
Standard Error	14.00235
Observations	13

ANOVA

	df	*SS*	*MS*	*F*	*Significance of F*
Regression	2	40213.27	20106.64	102.5504	2.17E-07
Residual	11	2156.725	196.0659		
Total	13	42370			

	Coefficients	*Standard Error*	*t Stat*	*P-value*
% CaO in Coal Ash	10.76255	1.617089	6.655512	3.58E-05
% Carbon in Fly Ash	4.929528	0.981515	5.022366	3.89E-04

Figure 3 shows a parity plot of the measured elemental mercury fraction against the values predicted by the regression equation. The regression was tested by adding the other factors one-at-a-time to determine if they were statistically significant. The results in the table below show that none of the other factors were statistically significant, including the coal chlorine content.

Factor	*t Statistic*	*P-value*
Regression Intercept	0.1972	0.8476
% S in Coal	0.6597	0.5259
% Cl in Coal	-0.1712	0.8675
% SiO_2 in Coal Ash	-0.0423	0.9671
% Al_2O_3 in Coal Ash	0.1347	0.8955
% Fe_2O_3 in Coal Ash	0.6619	0.5230
% K_2O in Coal Ash	-0.2764	0.7879
Flue Gas Temperature at Boiler Economizer Outlet, °F	-0.1358	0.8947

The percent elemental mercury at the air heater outlet and the ESP outlet locations were also examined by multiple linear regression analysis. The independent variables for the air heater outlet were the coal chlorine, sulfur, ash components, fly ash carbon, elemental mercury at the air heater inlet, and air heater inlet and outlet flue gas temperatures. The independent variables for the ESP outlet were the coal chlorine, sulfur, ash components, fly ash carbon, elemental mercury at the ESP inlet, and ESP inlet and outlet flue gas temperatures. None of the variables showed a statistically significant correlation with the percent elemental mercury at either location.

Coal-to-Stack Mercury Removal

The principal purpose of this work was to develop a better understanding of the potential mercury removal "co-benefits" achieved by NOx and SO_2 control technologies. The results show that these technologies can remove a substantial fraction of mercury from flue gas. The amount removed depends on the fraction of elemental mercury in the gas entering the FGD system. There is also some indication that scrubber chemistry could play a part as well.

The mercury removal results for the units equipped with an SCR operating at the time of testing are listed in Table 5, and for the units without SCR (or with the SCR bypassed) in Table 6. The units tested include two with lime spray dryers, five with wet limestone scrubbers, and three with magnesium-enhanced wet lime scrubbers. The coal-to-stack mercury removals ranged from 65% to 97% for the units with SCR and from 53% to 87% for the units without SCR. There is no indication from these data whether any type of FGD system is better at mercury removal than any other.

The coal-to-stack mercury removal in the SCR-equipped units was examined by multiple linear regression in a manner similar to that described for mercury speciation earlier. The independent variables examined were the coal chlorine, sulfur, ash components, fly ash carbon, flue gas temperatures at the air heater inlet and exit, elemental mercury content of the flue gas at the air heater exit, and the natural logarithm of the scrubber liquid chloride content. For this statistical analysis, the mercury removal at Site 8 was adjusted to 84% to account for 15% of the flue gas bypassing the scrubbers at that unit. The significant factors were the elemental mercury content of the flue gas and the scrubber liquid chloride concentration. The coal chlorine content was not a statistically significant factor. Figure 4 shows the coal-to-stack removal as a function of the two statistically significant variables. Data from units without SCR or with the SCR bypassed, and data from the dry scrubber–equipped units, are included in the figure for reference only; they are not included in the statistical model. The summary statistics are given below:

Regression Statistics	
Multiple R	0.892
R Square	0.796
Adjusted R Square	0.737
Standard Error	5.323
Observations	10

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	772.5	386.2623	13.63126	0.003855
Residual	7	198.4	28.3365		
Total	9	970.9			

	Coefficients	*Standard Error*	*t Stat*	*P-value*
Intercept	42.59	16.18	2.632013	0.033814
% elemental mercury at the air heater exit	-2.429	0.811	-2.99459	0.020095
ln(chloride in scrubber filtrate, mg/L)	6.026	1.864	3.23319	0.014388

Figure 5 shows a parity plot of the measured coal-to-stack mercury removal at SCR-equipped plants against the values predicted by the regression equation. The regression was tested by adding the other factors one-at-a-time to determine if they were statistically significant. The results in the table below show that none of the other factors were statistically significant, including the coal chlorine content.

Factor	*t Statistic*	*P-value*
% C in Fly Ash	-1.27522	0.249381
% S in Coal	1.310322	0.23801
% Cl in Coal	-0.63473	0.549026
% SiO_2 in Coal Ash	-0.78873	0.46029
% Al_2O_3 in Coal Ash	-0.26676	0.798586
% Fe_2O_3 in Coal Ash	1.009218	0.351823
% CaO in Coal Ash	0.01025	0.992154
% K_2O in Coal Ash	-0.07288	0.94427
Flue Gas Temperature at Air Heater Outlet, °F	-1.25186	0.257212

Mercury Removal in the ESP

Also included in Tables 5 and 6 are the mercury removal in the ESP, calculated based on the mercury content in the collected ESP samples and the fly ash production rate.

The mercury removal in the ESP was examined by multiple linear regression in a manner similar to that described for coal-to-stack mercury removal. The independent variables examined were the coal chlorine, sulfur, ash components, fly ash carbon content, flue gas temperature at the ESP inlet, and the elemental mercury fraction (as a % of total mercury) of the flue gas at the ESP inlet. The significant factors were the fly ash carbon content and the flue gas temperature. The coal chlorine content was not a significant factor, nor was the elemental mercury fraction of the flue gas at the ESP inlet. The statistics are summarized below.

Regression Statistics	
Multiple R	0.9040
R Square	0.8171
Adjusted R Square	0.7765
Standard Error	2.5514
Observations	12

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	261.81	130.9	20.11	0.000478
Residual	9	58.59	6.510		
Total	11	320.4			

	Coefficients	*Standard Error*	*t Stat*	*P-value*
Intercept	26.70	7.31	3.652	0.00530
% Carbon in Fly Ash	1.58	0.369	4.298	0.00200
Flue Gas Temperature at ESP Inlet, °F	-0.0785	0.0216	-3.642	0.00538

Figure 7 shows a parity plot of the measured ESP mercury removal against the ESP removal predicted by the regression equation.

Mercury Removal in the Wet Scrubber

An objective of this work was to develop a better understanding of the factors affecting mercury removal in wet scrubbers. The results show that most of the oxidized mercury is removed in wet scrubbers. Elemental mercury, however, was not removed but actually increased in concentration after passing through most of the wet scrubbers.

The scrubber mercury removal is based on the difference between the ESP outlet (FGD inlet) gas and the stack gas concentrations. However, the ESP outlet gas mercury concentrations were not measured at all sites. The air heater outlet (ESP inlet) gas concentrations can be used as an estimate of the ESP outlet concentrations because the mercury removal in the ESP was less than 10% of the total mercury in all but two plants. The results for the units equipped with an SCR operating at the time of

testing are listed in Table 7, and for the units without SCR (or with the SCR bypassed) in Table 8. The units tested include five with wet limestone scrubbers, and three with magnesium-enhanced wet lime scrubbers. The scrubber mercury removals ranged from 72% to 95% for the units with SCR and from 67% to 83% for the units without SCR. There is no indication from these data that any type of FGD system is better at mercury removal than any other.

As removals approach 100%, variable effects tend to approach asymptotic limits and, thus, examination of the variable effects using a linear model is not appropriate. Therefore, the scrubber mercury removal data were transformed into the number of transfer units (NTU) by the following equation:

NTU = - ln(1-%removal/100)

The number of transfer units is a dimensionless number that is used by engineers in the FGD scrubber design industry as a measure of scrubber mass transfer performance. (SO_2 removal in a wet scrubber, expressed as NTU, generally is a linear function of the liquid-to-gas ratio in the scrubber.) The transformed scrubber mercury removal was examined by multiple linear regression in a manner similar to that described earlier for mercury speciation and coal-to-stack mercury removal. The independent variables examined were the coal chlorine, sulfur, ash components, flue gas temperatures at the scrubber inlet, elemental mercury content of the flue gas at the scrubber inlet, and the natural logarithm of the scrubber liquid chloride content. Although the presence/absence of an SCR is not listed as a variable, the effect of an SCR is included indirectly by including the elemental mercury content at the scrubber inlet as a variable. For this statistical analysis, the mercury removal at Site 8 was adjusted to 84% to account for 15% of the flue gas bypassing the scrubbers at that unit. The significant factors were the elemental mercury content of the flue gas and the scrubber liquid chloride concentration. The intercept was not significantly different from zero. Figure 8 shows the scrubber mercury removal as a function of these two variables. The coal chlorine content was not a statistically significant factor.

The summary statistics are given below:

Regression Statistics	
Multiple R	0.9841
R Square	0.9684
Adjusted R Square	0.8825
Standard Error	0.3512
Observations	14

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	45.43003	22.71502	184.1569	3.49E-09
Residual	12	1.480152	0.123346		
Total	14	46.91018			

	Coefficients	*Standard Error*	*t Stat*	*P-value*
% elemental mercury at the scrubber inlet	-0.0277	0.01125	-2.462	0.0299
ln(chloride in scrubber filtrate, mg/L)	0.245	0.01565	15.65	2.39E-09

Figure 9 shows a parity plot of the measured scrubber mercury removal against the values predicted by the regression equation. The regression was tested by adding the other factors one-at-a-time to determine if they were statistically significant. The results in the table below show that none of the other factors were statistically significant, including the coal chlorine content.

Factor	*t Statistic*	*P-value*
Regression Intercept	0.0562	0.9561
% C in Fly Ash	-0.5652	0.5857
% S in Coal	-0.2723	0.7905
% Cl in Coal	0.9987	0.33942
% SiO_2 in Coal Ash	0.3552	0.7292
% Al_2O_3 in Coal Ash	-0.6995	0.4988
% Fe_2O_3 in Coal Ash	-0.0892	0.9305
% CaO in Coal Ash	0.8922	0.3914
% K_2O in Coal Ash	-0.6584	0.5238
Flue Gas Temperature at ESP Outlet, °F	-0.2243	0.8267

Removal of mercury in wet scrubbers is limited because elemental mercury is not easily captured in wet scrubbers; in fact, an increase in elemental mercury has often

been observed in wet scrubbers, which further limits the total mercury removal. Table 9 shows the increase in the elemental mercury from the air heater outlet (ESP inlet) to the stack and from the ESP outlet (wet scrubber inlet) to the stack for the units with wet scrubbers in this study. In many cases, the elemental mercury exiting the scrubber was more than double the amount entering the scrubber. However, when considered as a percentage of the oxidized mercury entering the scrubber, the increase represented a relatively small amount, less than 8% for all but one plant.

In two units the elemental mercury decreased between the air heater outlet and the stack, and in two other units the elemental mercury decreased between the scrubber inlet and the stack. There was no apparent reason for these plants to be different from the others. The elemental mercury increases were examined by multiple linear regression analysis. The independent variables were the coal chlorine, sulfur, ash components, fly ash carbon, scrubber liquid chloride concentration, elemental and oxidized mercury concentrations at the air heater outlet and the ESP outlet, and air heater inlet and outlet flue gas temperatures. None of the variables showed a statistically significant correlation with the increase in the percent elemental mercury, whether measured from the air heater outlet to the stack or from the ESP outlet to the stack.

Mercury Mass Balances

Tables 5 and 6 show the mercury mass balances measured at each unit tested. The mercury mass balance closure is the total mercury output from the plant divided by the total mercury input (expressed as %). This is an important criterion to gauge the overall quality of the tests by accounting for the all of mercury entering and leaving the plant during the tests. The mercury mass balances at all of the units ranged from 81% to 113%, which are within our QA/QC criterion of 80-120%. The measurements, calculations, and assumptions for calculating the material balances are described in the Topical Reports.

SCR/Non-SCR Comparison

There was a direct comparison of SCR vs. non-SCR operation at four sites. Sites 4 and 5 each had a non-SCR-equipped unit at the same site that was sampled separately from the SCR-equipped unit. Sites 6 and 7 were sampled with the SCR operating during ozone season, and again during non-ozone season when the SCR was bypassed. The results show that the SCR increased the oxidation of the mercury and the coal-to-stack mercury removal was higher when the SCR was present. Table 10 shows the average mercury speciation of the flue gas at three locations and the coal-to-stack mercury removal at the four sites with and without the SCR. The four units without an operating SCR had coal-to-stack mercury removals of 53.0% to 87.1% (average = 71.9%) whereas the units at the same sites with operating SCRs had mercury removals of 83.5% to 97.1% (average = 88.1%).

LIST OF PUBLICATIONS AND PRESENTATIONS

1. J.A. Withum, S.C. Tseng. "Field Test Program to Evaluate Mercury Emissions from Coal-Fired Facilities with SCR-FGD Systems," Conference on Air Quality IV, Arlington, VA, September 22-24, 2003.

2. J.A. Withum, S.C. Tseng, J.E. Locke. "Field Test Program to Evaluate Mercury Emissions from Coal-Fired Facilities with SCR-FGD Systems," Forum '03: Multi-Pollutant Emission Controls and Strategies, Nashville, TN, October 14-15, 2003.

3. J.A. Withum, S.C. Tseng, J.E. Locke. "Evaluation of Mercury Emissions from Coal-Fired Facilities with SCR-FGD Systems," 2003 Conference on Selective Catalytic Reduction (SCR) and Selective Non-Catalytic Reduction (SNCR) for NOx Control, Pittsburgh, PA, October 30, 2003.

4. S.C. Tseng, J.A. Withum, J.E. Locke. "Evaluation of Mercury Emissions from Coal-Fired Facilities with SCR-FGD Systems," Mercury Control Technology R&D Program Review Meeting, Pittsburgh, PA, August 12-13, 2003.

5. S.C. Tseng, J.A. Withum, J.E. Locke. "Evaluation of Mercury Emissions from Coal-Fired Facilities with SCR-FGD Systems," Pollution Control Users Group Roundtable, NOx Week 2004, Akron, OH, January 26-27, 2004.

6. J. A. Withum. "Mercury Sampling at Power Plants with SCR/FGD Combinations," Stationary Source Sampling & Analysis for Air Pollutants XXIX Conference, Rohnert Park, CA, March 13-18, 2005.

7. J. A. Withum. "Mercury behavior in 10 Coal-Fired Plants with SCR-FGD," MEC2 - Mercury Emissions from Coal - 2nd International Experts' Workshop, Ottawa, Canada, May 24-25, 2005.

8. J. A. Withum, S. C. Tseng, J. E. Locke. "Mercury Emissions from Coal-Fired Facilities with SCR-FGD Systems," DOE/NETL Mercury Control Technology R&D Program Review, Pittsburgh, PA, July 12-14, 2005.

9. J. A. Withum, S. C. Tseng, J. E. Locke. "Mercury Emissions from Coal-Fired Facilities with SCR-FGD Systems," 22th Annual International Pittsburgh Coal Conference, Pittsburgh, PA, September 18-22, 2005.

10. J. A. Withum, S. C. Tseng, J. E. Locke. "Mercury Emissions from Coal-Fired Facilities with SCR-FGD Systems," Air Quality V Conference, Arlington, VA, September 19-21, 2005.

11. J.A. Withum. "Mercury Speciation and Emissions from Bituminous Coal-Fired Facilities: A Compilation of CONSOL's test Results Since 1994," accepted for the Twenty-Third Annual International Pittsburgh Coal Conference, Pittsburgh, PA, September 25-28, 2006

CONCLUSION

The results of this study likely to have the most impact in the scientific, engineering, and regulatory communities are:

- 65% to 97% coal-to-stack mercury removals for the FGD units with SCR and 53% to 87% removals for the FGD units without SCR.
- The scrubber mercury removal and the coal-to-stack mercury removal were positively correlated with the scrubber liquid chloride concentration. The coal chlorine content was not a statistically significant factor.
- Coal chlorine was not a statistically significant factor affecting mercury speciation at the economizer outlet. The only statistically significant factors were the coal ash CaO content and the fly ash carbon content. The elemental mercury (as a percentage of the total mercury) at the economizer outlet was positively correlated with both factors.
- Mercury removal in the ESP was positively correlated with the fly ash carbon content and negatively correlated with the flue gas temperature.
- In a direct comparison of SCR vs. non-SCR operation at four sites, the SCR increased the oxidation of the mercury (measured at the ESP outlet), and the coal-to-stack mercury removal was higher when the SCR was present.

It appears from these results that the initial assumptions by regulatory agencies about the “co-benefits effect” of FGD and SCR-FGD may have been too optimistic. In early cost-modeling studies, EPA assumed that FGD processes remove an average of 80% of the mercury in the flue gas exiting the boiler, and SCR-FGD combinations remove 95% of the mercury. The assumption concerning Hg removal in the SCR-FGD combination was based on measurements at two bituminous coal-fired plants, and the assumption concerning Hg removal in an FGD was based on measurements at four bituminous coal-fired plants. Clearly, these few plants were not an adequate sample of the boiler fleet. The results reported here demonstrate that both removal assumptions (80% and 95%) were too high. If regulatory agencies issue state implementation plans (SIPs) using these assumptions, they could be setting a standard that is not achievable without using a mercury-specific control process.

The data reported here suggest that the coal ash CaO content and the fly ash carbon content, not the coal chlorine content, were the major factors affecting flue gas mercury speciation as the flue gas exits the boiler economizer, at least for bituminous coals. It would be interesting to examine the same factors in comparing speciation at facilities burning subbituminous coal. The flue gas at such units tends to have a greater fraction of the mercury in the elemental form compared to bituminous coal units. The chlorine effect assumption had been based on earlier work on mercury in waste incinerator flue gas, which typically has a high flue gas HCl content and a very low fraction of elemental mercury. Coupled with the fact that subbituminous coal is typically very low in chlorine content, it was logical to assume that chlorine was the “major player.” The results reported here raise the possibility that fly ash CaO content somehow prevents or slows the oxidation of the elemental mercury in the flue gas,

perhaps by neutralizing acid gases (HCl or SO_3) that might otherwise react with the elemental mercury . Subbituminous coals have substantially higher ash CaO contents compared to bituminous coal and, thus, the higher elemental mercury fraction at units burning subbituminous coal could be due, in part, to the higher fly ash CaO content.

The positive correlation of scrubber liquid chloride concentration on mercury removal in the scrubber bears further investigation. It suggests that units using scrubber additives, such as adipic acid, that allow operation of the scrubber at higher chloride levels might tend to remove a higher percentage of the total mercury. In a cap-and–trade mercury regulation scenario, this might affect the choice of scrubber technology or the use of such additives.

The correlation of fly ash carbon content (positive) and flue gas temperature (negative) on mercury capture in the ESP re-affirms other information; CONSOL recently completed a successful pilot plant demonstration of a process that relies on this to achieve low-cost mercury control by lowering the flue gas temperature at facilities with somewhat high (>6%) fly ash carbon content[13]. The data reported here confirm the effect over a broader range of coals and units.

REFERENCES

1. J.A. Withum, S.C. Tseng, J.E. Locke. “Evaluation of Mercury Emissions from Coal-Fired Facilities with SCR and FGD Systems – Topical Report No. 1,” U.S. DOE NETL Cooperative Agreement DE-FC26-02NT41589, May 2004.

2. J.A. Withum, S.C. Tseng, J.E. Locke. “Evaluation of Mercury Emissions from Coal-Fired Facilities with SCR and FGD Systems – Topical Report No. 2,” U.S. DOE NETL Cooperative Agreement DE-FC26-02NT41589, October 2004.

3. J.A. Withum, S.C. Tseng, J.E. Locke. “Evaluation of Mercury Emissions from Coal-Fired Facilities with SCR and FGD Systems – Topical Report No. 3,” U.S. DOE NETL Cooperative Agreement DE-FC26-02NT41589, October 2004.

4. J.A. Withum, S.C. Tseng, J.E. Locke. “Evaluation of Mercury Emissions from Coal-Fired Facilities with SCR and FGD Systems – Topical Report No. 4,” U.S. DOE NETL Cooperative Agreement DE-FC26-02NT41589, April 2005.

5. J.A. Withum, S.C. Tseng, J.E. Locke. “Evaluation of Mercury Emissions from Coal-Fired Facilities with SCR and FGD Systems – Topical Report No. 5,” U.S. DOE NETL Cooperative Agreement DE-FC26-02NT41589, August 2005.

6. J.A. Withum, S.C. Tseng, J.E. Locke. “Evaluation of Mercury Emissions from Coal-Fired Facilities with SCR and FGD Systems – Topical Report No. 6,” U.S. DOE NETL Cooperative Agreement DE-FC26-02NT41589, October 2005.

7. J.A. Withum, S.C. Tseng, J.E. Locke. “Evaluation of Mercury Emissions from Coal-

Fired Facilities with SCR and FGD Systems – Topical Report No. 7," U.S. DOE NETL Cooperative Agreement DE-FC26-02NT41589, December 2005.

8. J.A. Withum, S.C. Tseng, J.E. Locke. "Evaluation of Mercury Emissions from Coal-Fired Facilities with SCR and FGD Systems – Topical Report No. 8 (Plant 6)," U.S. DOE NETL Cooperative Agreement DE-FC26-02NT41589, December 2005.

9. J.A. Withum, S.C. Tseng, J.E. Locke. "Evaluation of Mercury Emissions from Coal-Fired Facilities with SCR and FGD Systems – Topical Report No. 9 (Plant 7)," U.S. DOE NETL Cooperative Agreement DE-FC26-02NT41589, January 2006.

10. J.A. Withum, S.C. Tseng, J.E. Locke. "Evaluation of Mercury Emissions from Coal-Fired Facilities with SCR and FGD Systems – Topical Report No. 10 (Plant 4)," U.S. DOE NETL Cooperative Agreement DE-FC26-02NT41589, January 2006.

11. J.A. Withum, S.C. Tseng, J.E. Locke. "Evaluation of Mercury Emissions from Coal-Fired Facilities with SCR and FGD Systems – Topical Report No. 11 (Plant 3)," U.S. DOE NETL Cooperative Agreement DE-FC26-02NT41589, February 2006.

12. P. Chu. "Effect of SCRs on Mercury," EUEC Conference, Tuscon, AZ, January 23, 2006.

13. M. L. Fenger, R. A. Winschel. "Multi-Pollutant Emissions Control: Pilot Plant Study of Technologies for Reducing Hg, SO3, NOx and CO2 Emissions - Final Technical Report for the Period September 5, 2001, through May 30, 2005," U.S. DOE NETL Cooperative Agreement DE-FC26-01NT41181, January 2006.

LIST OF ABBREVIATIONS

CONSOL	-	CONSOL Energy Inc., Research and Development
DOE	-	U.S. Department of Energy
EPA	-	U.S. Environmental Protection Agency
EPRI	-	Electric Power Research Institute
ESP	-	electrostatic precipitator
FGD	-	flue gas desulphurization
Hg	-	mercury
Hg^{part}	-	mercury in particulate form
Hg^{total}	-	total mercury in particulate, oxidized, and elemental forms
Hg^{++}	-	mercury in oxidized form
Hg^{o}	-	mercury in elemental form
L	-	liter
lb	-	pound
m	-	meter
mg	-	milligram, 10^{-3} gram
min	-	minute
mL	-	milliliter
ppm	-	parts per million
QA	-	quality assurance
QC	-	quality control
temp	-	temperature
TBtu	-	trillion (10^{12}) British thermal unit
wt	-	weight
vs	-	versus
° F	-	temperature in degrees Fahrenheit
<	-	less than
>	-	more than
µg	-	microgram, 10^{-6} gram

Table 2. Average analyses of coal samples taken during tests at each unit. Data shown as averages of 3 or 4 test runs ± 1 standard deviation

Site No.	Average Coal Content ± 1 Standard Deviation								
	% S, dry	%Cl, dry	%Hg, dry	% Ash, dry	% SiO_2 in Coal Ash	% Al_2O_3 in Coal Ash	% Fe_2O_3 in Coal Ash	% CaO in Coal Ash	% K_2O in Coal Ash
1	1.0 ± 0.2	0.104 ± 0.023	0.09 ± 0.02	10.1 ± 0.8	54.3 ± 2.1	26.4 ± 1.4	8.6 ± 2.3	1.52 ± 0.39	2.98 ± 0.15
2	1.9 ± 0.0	0.100 ± 0.005	0.11 ± 0.01	7.2 ± 0.2	48.1 ± 0.4	23.8 ± 0.2	18.2 ± 0.7	2.09 ± 0.13	1.89 ± 0.08
3 baseline	3.6 ± 0.1	0.039 ± 0.014	0.11 ± 0.01	10.3 ± 0.1	43.8 ± 0.8	20.1 ± 0.7	24.9 ± 0.9	2.89 ± 0.64	2.07 ± 0.07
3 low $CaCl_2$ addition	3.6 ± 0.1	0.043 ± 0.007	0.11 ± 0.01	10.8 ± 0.1	43.5 ± 0.5	20.0 ± 0.2	24.7 ± 1.6	2.77 ± 0.21	2.09 ± 0.13
3 high $CaCl_2$ addition	3.6 ± 0.0	0.070 ± 0.015	0.11 ± 0.01	11.1 ± 0.2	44.7 ± 0.4	19.9 ± 0.1	22.8 ± 1.0	3.52 ± 0.11	1.94 ± 0.03
4 Unit 1	1.4 ± 0.1	0.147 ± 0.007	0.09 ± 0.02	9.0 ± 1.9	51.4 ± 2.1	26.9 ± 0.6	11.8 ± 1.8	1.65 ± 0.10	2.44 ± 0.31
4 Unit 2	1.6 ± 0.1	0.141 ± 0.008	0.09 ± 0.01	8.5 ± 0.2	50.6 ± 0.7	25.1 ± 2.1	14.7 ± 2.1	2.22 ± 0.68	2.16 ± 0.36
5 Unit 1	3.0 ± 0.2	0.136 ± 0.009	0.09 ± 0.01	9.8 ± 0.3	47.2 ± 1.0	19.0 ± 1.4	18.7 ± 0.7	5.70 ± 1.11	2.25 ± 0.08
5 Unit 2	3.3 ± 0.0	0.163 ± 0.018	0.09 ± 0.01	9.8 ± 0.2	47.0 ± 0.5	17.4 ± 0.2	20.0 ± 0.5	5.67 ± 0.11	2.12 ± 0.02
6 (w/SCR)	3.7 ± 0.1	0.110 ± 0.034	0.13 ± 0.01	13.6 ± 1.3	46.3 ± 2.0	19.0 ± 0.6	20.4 ± 2.4	4.45 ± 0.43	2.56 ± 0.17
6 (SCR bypassed)	3.7 ± 0.1	0.065 ± 0.034	0.11 ± 0.01	12.7 ± 0.3	45.3 ± 1.1	19.3 ± 1.2	18.7 ± 0.9	6.42 ± 1.06	2.61 ± 0.30
7 (w/SCR)	3.6 ± 0.2	0.013 ± 0.005	0.11 ± 0.01	11.0 ± 0.2	47.4 ± 1.8	22.1 ± 1.0	22.9 ± 2.2	1.59 ± 0.26	2.86 ± 0.19
7 (SCR bypassed)	3.7 ± 0.1	0.057 ± 0.005	0.14 ± 0.01	12.1 ± 0.2	44.9 ± 0.2	20.8 ± 0.5	22.9 ± 0.2	2.84 ± 0.12	2.51 ± 0.15
8	4.7 ± 0.2	0.046 ± 0.006	0.10 ± 0.01	9.4 ± 0.2	38.6 ± 1.9	19.1 ± 1.1	31.9 ± 1.5	2.63 ± 0.20	1.52 ± 0.09
9	3.7 ± 0.1	0.050 ± 0.001	0.11 ± 0.01	12.6 ± 0.9	45.0 ± 0.8	19.6 ± 0.4	21.5 ± 1.4	4.56 ± 0.19	2.25 ± 0.07
10	3.7 ± 0.1	0.063 ± 0.005	0.12 ± 0.01	9.6 ± 0.2	43.2 ± 0.4	21.0 ± 0.3	26.4 ± 0.6	3.09 ± 0.11	1.60 ± 0.02

Table 3. Flue gas temperatures, fly ash carbon content, and scrubber chloride content during testing. Data shown as averages of 3 or 4 test runs ± 1 standard deviation. Blanks indicate no data collected.

No.	Flue Gas Temperature, °F					Carbon in Fly Ash, wt %	Avg. Scrubber Filtrate Chloride Content, mg/L
	Boiler Economizer Exit	SCR Exit	AH Exit	ESP Exit	Stack		
1	628 ± 13		256 ± 13		191 ± 2	5.19 ± 2.81	
2	758 ± 4		349 ± 7		182 ± 1	12.71 ± 0.97	
3 baseline	731 ± 2	715 ± 1	358 ± 0	355 ± 0	136 ± 0	5.30 ± 1.14	885 ± 191
3 low $CaCl_2$ addition	731 ± 0	716 ± 3	356 ± 2	356 ± 1	136 ± 0	3.82 ± 0.06	1595 ± 49
3 high $CaCl_2$ addition	725 ± 13	709 ± 11	357 ± 2	354 ± 0	137 ± 0	5.13 ± 0.05	1940 ± 537
4 Unit 1	710 ± 5		277 ± 3	272 ± 2	127 ± 0	3.75 ± 0.81	27813 ± 554
4 Unit 2	679 ± 7		284 ± 3	255 ± 46	125 ± 1	6.25 ± 0.23	30000 ± 2031
5 Unit 1	642 ± 1	665 ± 1	315 ± 0	305 ± 1	124 ± 1	0.67 ± 0.28	2185 ± 21
5 Unit 2				321 ± 4	130 ± 0	1.01 ± 0.32	2287 ± 23
6 (w/SCR)	696 ± 3	665 ± 12	329 ± 1	340 ± 3	132 ± 0	1.25 ± 0.11	1913 ± 160
6 (SCR bypassed)				332 ± 3	129 ± 1		1320 ± 76
7 (w/SCR)	660 ± 4	681 ± 1	327 ± 6	330 ± 3	137 ± 1	0.80 ± 0.02	2731 ± 55
7 (SCR bypassed)				315 ± 2	126 ± 0		3258 ± 19
8	678 ± 3		333 ± 6		151 ± 1	5.62 ± 1.94	6913 ± 2027
9	654 ± 7		267 ± 6		125 ± 3	4.46 ± 1.05	5348 ± 483
10	639 ± 2	674 ± 1	357 ± 1		130 ± 0	1.22 ± 0.08	1975 ± 671

Table 4. Mercury speciation in the flue gas. Data shown as averages of 3 or 4 test runs ± 1 standard deviation. Blanks indicate no data collected.

Site #	SCR Type	Coal Chlorine Content, wt %	Elemental Mercury as % of Total Mercury			
			Boiler Economizer Exit	SCR Exit	AH Exit	ESP Exit
1	Siemens Plate + Hitachi Plate	0.104 ± 0.023	54 ± 8		5 ± 1	
2	IHI Corp. Honeycomb	0.100 ± 0.005	82 ± 8		3 ± 1	
3 baseline	KWH Honeycomb	0.039 ± 0.014	37 ± 2	82 ± 10	9 ± 0	6 ± 1
3 low $CaCl_2$ addition		0.043 ± 0.007	39 ± 7	74 ± 1	5 ± 2	10 ± 1
3 high $CaCl_2$ addition		0.070 ± 0.015	58 ± 7	77 ± 10	3 ± 0	11 ± 4
4 Unit 1	(none)	0.147 ± 0.007	39 ± 7		9 ± 4	7 ± 4
4 Unit 2	Siemens Plate	0.141 ± 0.008	42 ± 5		3 ± 1	2 ± 0
5 Unit 1	Cormetech Honeycomb	0.136 ± 0.00	61 ± 14	10 ± 6	2 ± 0	5 ± 3
5 Unit 2	(none)	0.163 ± 0.018				34 ± 4
6	Hitachi Plate	0.110 ± 0.034	49 ± 4	8 ± 3	2 ± 3	2 ± 0
6	(bypassed)	0.065 ± 0.03				12 ± 11
7	Hitachi Plate	0.013 ± 0.005	14 ± 5	19 ± 9	2 ± 1	3 ± 0
7	(bypassed)	0.057 ± 0.00				7 ± 2
8	Haldor-Topsoe Corrugated Plate	0.046 ± 0.006	86 ± 10		6 ± 2	
9	Haldor-Topsoe Corrugated Plate	0.050 ± 0.001	81 ± 8		4 ± 1	
10	Siemens Plate	0.063 ± 0.005	54 ± 11	5 ± 2	2 ± 0	

Table 5. Mercury removal and mass balances at units with SCR installed and operating. Data shown as averages of 3 or 4 test runs ± 1 standard deviation.

Site No.	Particulate Control Device	FGD	% Hg Removal across ESP (NOTE 1)	% Hg Removal, Coal-to-Stack	Mercury Mass Balance, Out/In, %
1	FF	Lime Spray Dryer	N.A.	87.3 ± 3.8	100 ±13
2	FF	Lime Spray Dryer	N.A.	94.7 ± 0.3	99 ± 5
Average % Hg Removal for SCR/FF/FGD				**91.0 ± 5.2**	
3 baseline	ESP	Limestone, inhibited Oxidation	5.8± 0.3	64.5 ± 6.2	96 ± 6
3 low $CaCl_2$ addition	ESP	Limestone, inhibited Oxidation	4.8± 0.1	69.5 ± 1.8	99 ± 3
3 high $CaCl_2$ addition	ESP	Limestone, inhibited Oxidation	7.9± 0.4	69.8 ± 8.9	109 ± 8
4, Unit 2	ESP	Limestone, Natural Oxidation	19.7 ± 1.3	97.1 ± 0.8	84 ± 13
5, Unit 1	ESP	Limestone, in-situ Oxidation	2.0 ± 1.5	85.8 ± 2.8	105 ± 8
6 (Ozone Season)	ESP	Limestone, ex-situ Oxidation	3.5 ± 0.6	83.5 ± 2.7	107 ± 17
7 (Ozone Season)	ESP	Limestone, ex-situ Oxidation	0.8 ± 0.1	85.8 ± 4.9	81 ± 3
8	ESP	Mg-Lime, ex-situ Oxidation	7.8 ± 3.6	71.6 ± 5.3 **(NOTE 2)**	113 ± 7
9	ESP	Mg-Lime, Inhibited Oxidation	7.7 ± 2.0	86.8 ± 2.8	99 ± 7
10	ESP	Mg-Lime, Inhibited Oxidation	2.7 ± 0.4	89.6 ± 3.3	88 ± 12
Average % Hg Removal for SCR/CS-ESP/FGD			**6.3 ± 6.0**	**83.1 ± 10.3 (NOTE 3)**	

NOTE 1: Calculated based on ESP fly ash mercury mass flow divided by the coal mercury mass flow. N.A. = Not Applicable
NOTE 2: 15% of flue gas is bypassed around FGD. Coal-to-stack Hg removal would be 84% if the scrubber treated all of the flue gas.
NOTE 3: Calculated using Site 3 baseline (not $CaCl_2$ addition) data and 71.6% removal at Site 8. If the removal at Site 8 is adjusted to 84% to account for bypass around the scrubber, the average coal-to-stack Hg Removal is **84.6% ± 9.2**

Table 6. Mercury removal and mass balances at units with SCR bypassed or with no SCR installed. Data shown as averages of 3 or 4 test runs ± 1 standard deviation

Site No.	Particulate Control Device	FGD	% Hg Removal across ESP (NOTE 1)	% Hg Removal Coal-to-Stack	Mercury Mass Balance, Out/In, %
4, Unit 1	ESP	Limestone, Natural Oxidation	13.8 ± 5.6	87.1 ± 2.3	103 ± 7
5, Unit 2	ESP	Limestone, in-situ Oxidation	3.6 ± 2.8	53.0 ± 3.9	97 ± 9
6 (Non-Ozone Season)	ESP	Limestone, ex-situ Oxidation	4.0 ± 0.4	74.2 ± 5.0	87 ± 11
7 (Non-Ozone Season)	ESP	Limestone, ex-situ Oxidation	(not determined)	73.4 ± 4.6	87 ± 11
Average % Hg Removal for CS-ESP/FGD			**7.1 ± 5.8**	**71.9 ± 14.1**	

NOTE 1: Calculated based on ESP fly ash mercury mass flow divided by the coal mercury mass flow.

Table 7. Wet scrubber mercury removals at units with SCR installed and operating. Data shown as averages of 3 or 4 test runs ± 1 standard deviation.

Site No.	Particulate Control Device	FGD	% Hg Removal, AH Outlet-to-Stack	% Hg Removal, FGD Inlet-to-Stack
3 baseline	ESP	Limestone, inhibited Oxidation	72.5 ± 3.6	74.9 ± 6.9
3 low $CaCl_2$ addition	ESP	Limestone, inhibited Oxidation	81.0 ± 1.6	78.1 ± 0.9
3 high $CaCl_2$ addition	ESP	Limestone, inhibited Oxidation	81.2 ± 5.8	78.6 ± 7.2
4, Unit 2	ESP	Limestone, Natural Oxidation	95.0 ± 1.5	95.2 ± 1.4
5, Unit 1	ESP	Limestone, in-situ Oxidation	87.6 ± 2.0	88.6 ± 0.9
6 (Ozone Season)	ESP	Limestone, ex-situ Oxidation	83.6 ± 1.9	82.4 ± 3.3
7 (Ozone Season)	ESP	Limestone, ex-situ Oxidation	88.5 ± 4.2	85.8 ± 3.7
8	ESP	Mg-Lime, ex-situ Oxidation	72.4 ± 5.0 **(NOTE 1)**	
9	ESP	Mg-Lime, Inhibited Oxidation	88.1 ± 2.2	
10	ESP	Mg-Lime, Inhibited Oxidation	87.4 ± 3.1	
Average % Hg Removal for SCR/CS-ESP/FGD			**84.4 ± 8.0 (NOTE 2)**	**85.4 ± 7.9**

NOTE 1: 15% of flue gas is bypassed around FGD. AH Outlet-to-stack Hg removal would be 84% if the scrubber treated all of the flue gas.

NOTE 2: Calculated using Site 3 baseline (not $CaCl_2$ addition) data and 72.4% removal at Site 8. If the removal at Site 8 is adjusted to 84% to account for bypass around the scrubber, the average coal-to-stack Hg Removal is **85.9% ± 6.4**

Table 8. Wet scrubber mercury removals at units with SCR bypassed or with no SCR installed. Data shown as averages of 3 or 4 test runs ± 1 standard deviation

Site No.	Particulate Control Device	FGD	% Hg Removal, AH Outlet-to-Stack	% Hg Removal, FGD Inlet-to-Stack
4, Unit 1	ESP	Limestone, Natural Oxidation	84.0 ± 2.5	83.0 ± 3.8
5, Unit 2	ESP	Limestone, in-situ Oxidation		68.6 ± 7.9
6 (Non-Ozone Season)	ESP	Limestone, ex-situ Oxidation		71.7 ± 15.3
7 (Non-Ozone Season)	ESP	Limestone, ex-situ Oxidation		66.6 ± 8.2
Average % Hg Removal for CS-ESP/FGD				**72.5 ± 7.3**

Table 9. Elemental mercury increase in the wet scrubbers. Data shown as averages of 3 or 4 test runs ± 1 standard deviation.

	Site No.	FGD	% Increase in Hg^0, AH Exit to Stack	Increase in Hg^0, AH Exit to Stack, as % of Hg^{2+} at the AH Exit	% Increase in Hg^0, FGD Inlet to Stack	Increase in Hg^0, FGD Inlet to Stack, as % of Hg^{2+} at the FGD Inlet
SCR Installed and Operating	3 baseline	Limestone, inhibited Oxidation	37 ± 4	3.7 ± 0.4	89 ± 48	5.5 ± 2.2
	3 low $CaCl_2$ addition	Limestone, inhibited Oxidation	119 ± 27	5.9 ± 1.2	17 ± 33	1.9 ± 3.8
	3 high $CaCl_2$ addition	Limestone, inhibited Oxidation	143 ± 52	4.9 ± 1.7	-12 ± 47	-2.7 ± 6.8
	4, Unit 2	Limestone, Natural Oxidation	-21 ± 14	-0.7 ± 0.6	9 ± 25	0.1 ± 0.5
	5, Unit 1	Limestone, in-situ Oxidation	323 ± 84	5.9 ± 1.5	79 ± 117	1.8 ± 4.3
	6 (Ozone Season)	Limestone, ex-situ Oxidation	397 ± 495	4.3 ± 6.7	268 ± 313	5.7 ± 6.2
	7 (Ozone Season)	Limestone, ex-situ Oxidation	209 ± 143	4.8 ± 4.2	202 ± 183	5.3 ± 5.0
	8	Mg-Lime, ex-situ Oxidation	125 ± 31	7.8 ± 2.6		
	9	Mg-Lime, Inhibited Oxidation	-15 ± 41	-1.0 ± 1.4		
	10	Mg-Lime, Inhibited Oxidation	234 ± 196	3.9 ± 3.1		
No SCR or SCR By-Passed	4, Unit 1	Limestone, Natural Oxidation	24 ± 27	1.6 ± 1.8	101 ± 117	4.8 ± 5.0
	5, Unit 2	Limestone, in-situ Oxidation			-19 ± 20	-10.5 ± 12.1
	6 (Non-Ozone Season)	Limestone, ex-situ Oxidation			60 ± 43	6.5 ± 3.2
	7 (Non-Ozone Season)	Limestone, ex-situ Oxidation			249 ± 93	18.7 ± 6.3

Table 10. Comparison of mercury speciation and removal at SCR and Non-SCR units. Data shown as averages of 3 or 4 test runs ± 1 standard deviation. Blanks indicate no data collected.

Site #	SCR Type	Elemental Mercury as % of Total Mercury			% Hg Removal Coal-to-Stack
		Boiler Economizer Exit	AH Exit	ESP Exit	
4 Unit 1	(none)	39 ± 7	9 ± 4	7 ± 4	87.1 ± 2.3
4 Unit 2	Siemens Plate	42 ± 5	3 ± 1	2 ± 0	97.1 ± 0.8
5 Unit 2	(none)			34 ± 4	53.0 ± 3.9
5 Unit 1	Cormetech Honeycomb	61 ± 14	2 ± 0	5 ± 3	85.8 ± 2.8
6	(bypassed)			12 ± 11	74.2 ± 5.0
6	Hitachi Plate	49 ± 4	2 ± 3	2 ± 0	83.5 ± 2.7
7	(bypassed)			7 ± 2	73.4 ± 4.6
7	Hitachi Plate	14 ± 5	2 ± 1	3 ± 2	85.8 ± 4.9
Average Coal-to-Stack Removal, Tests without SCR					71.9 ± 14.1
Average Coal-to-Stack Removal, Tests with SCR					88.1 ± 6.1

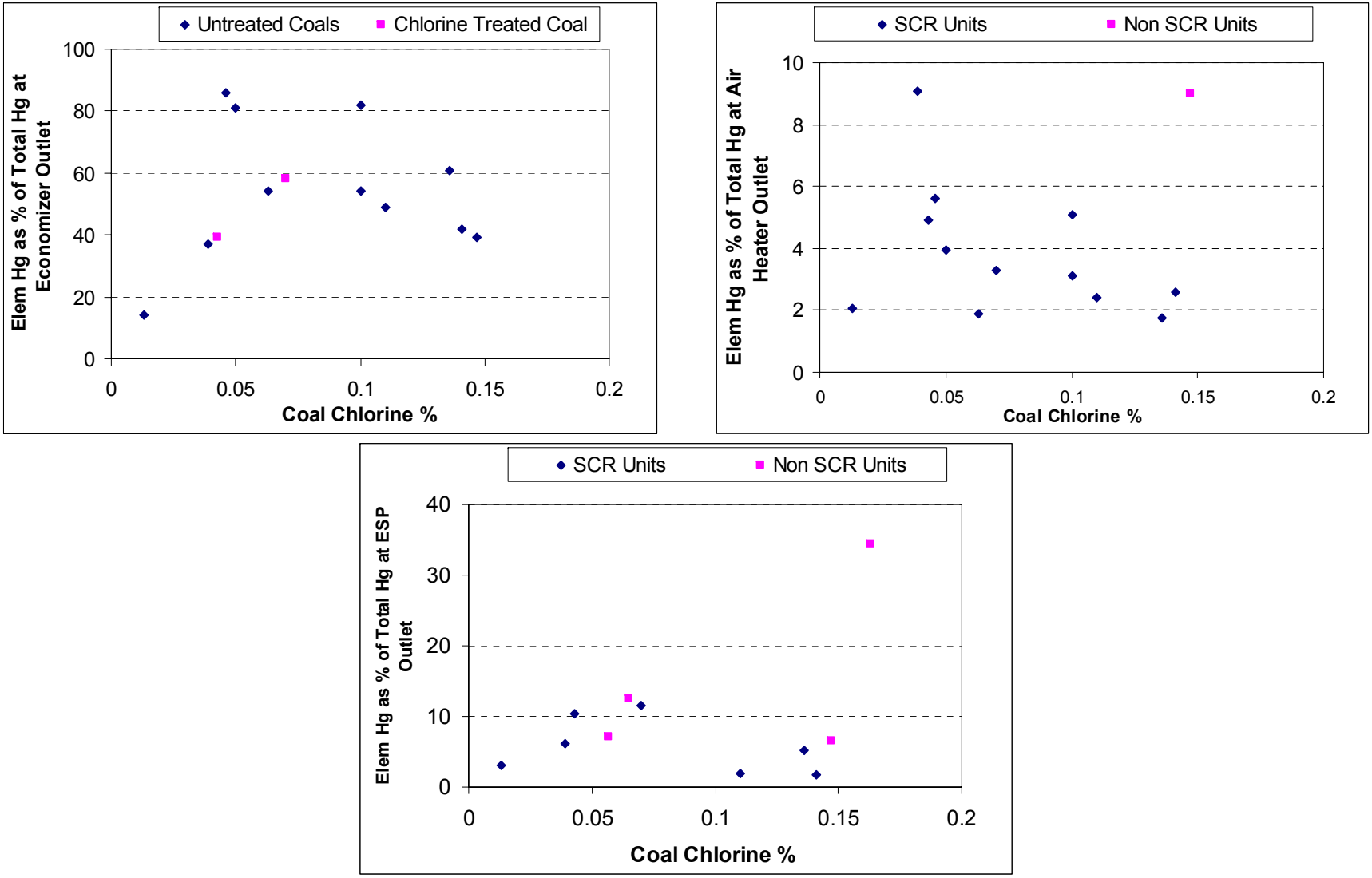

Figure 1. Elemental mercury fraction of the total mercury in the flue gas at three locations: a) economizer outlet, b) air heater outlet, c) ESP outlet

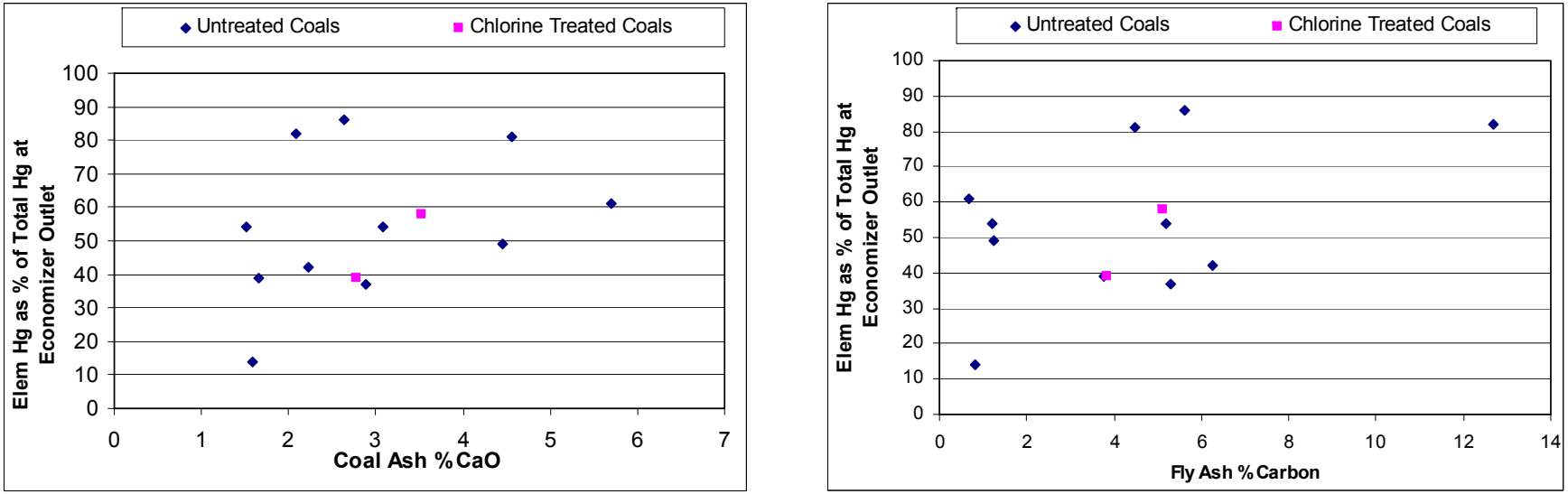

Figure 2. Elemental mercury fraction as a percent of total mercury: a) as a function of coal ash CaO content, and b) as a function of fly ash carbon content.

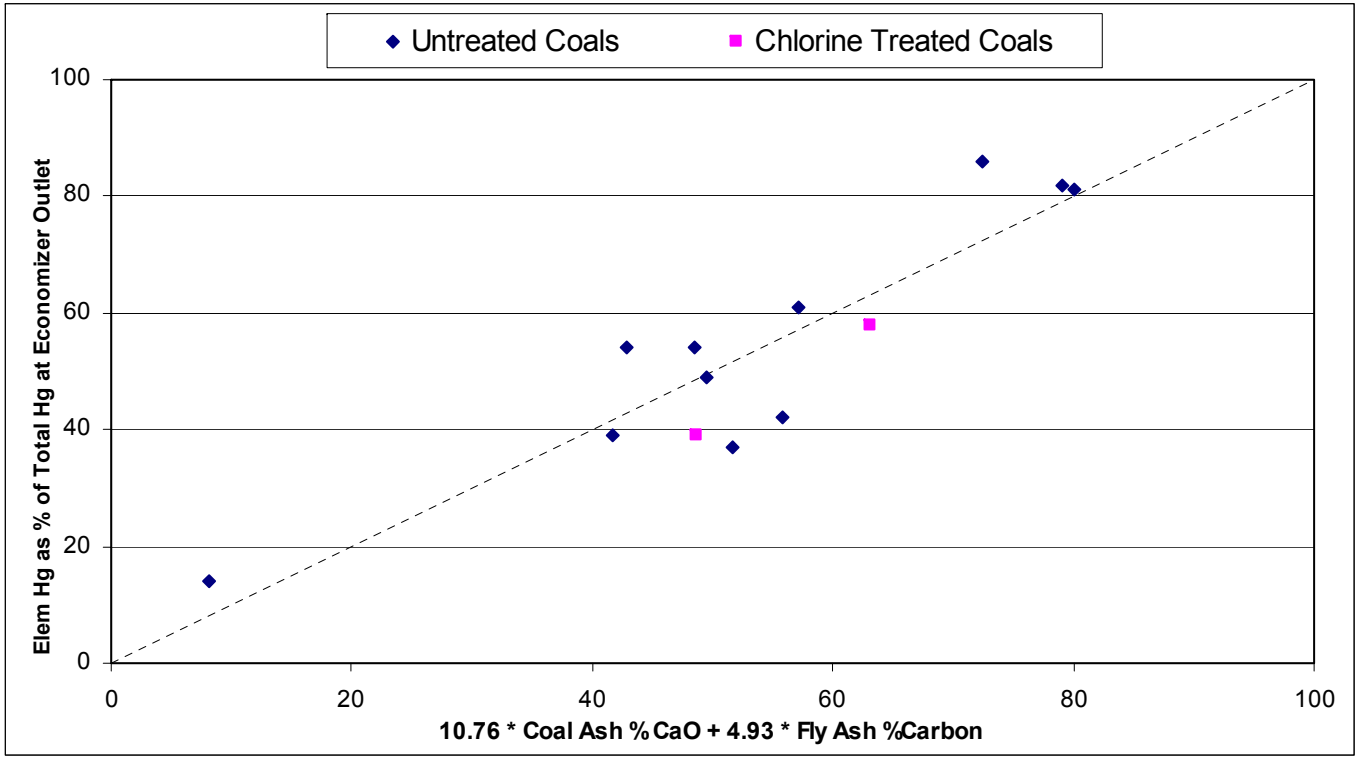

Figure 3. Parity plot of measured elemental mercury fraction as a % of total mercury versus the least squares regression equation.

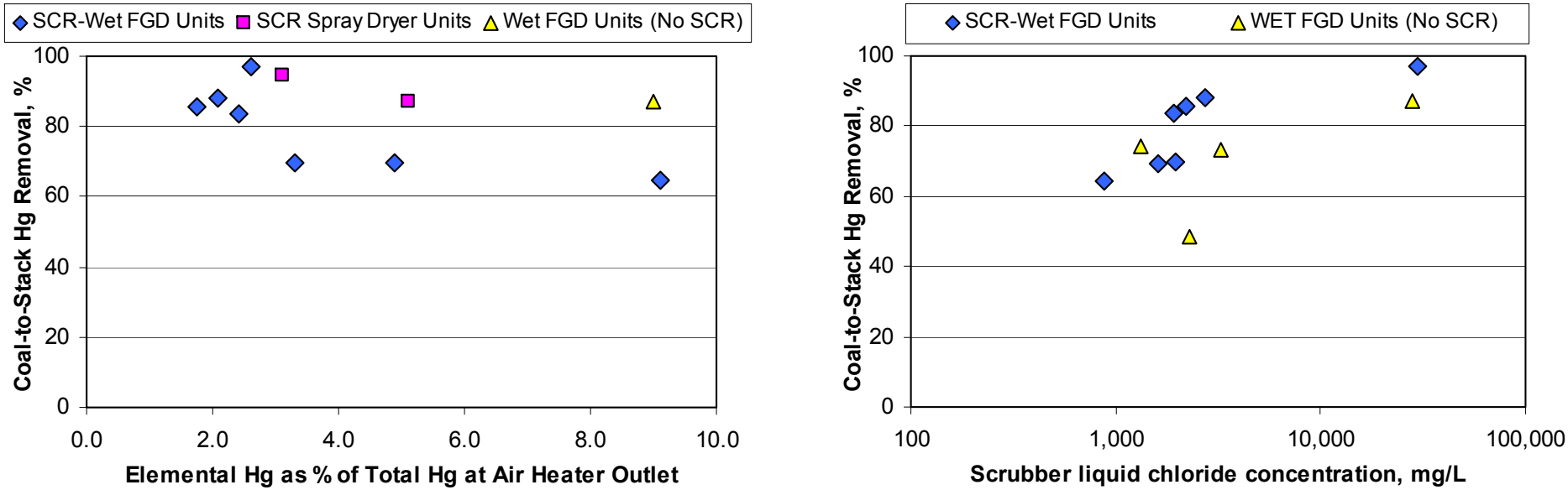

Figure 4. Coal-to-stack mercury removal: a) as a function of the elemental mercury fraction at the air heater outlet, and b) as a function of the scrubber liquid chloride concentration

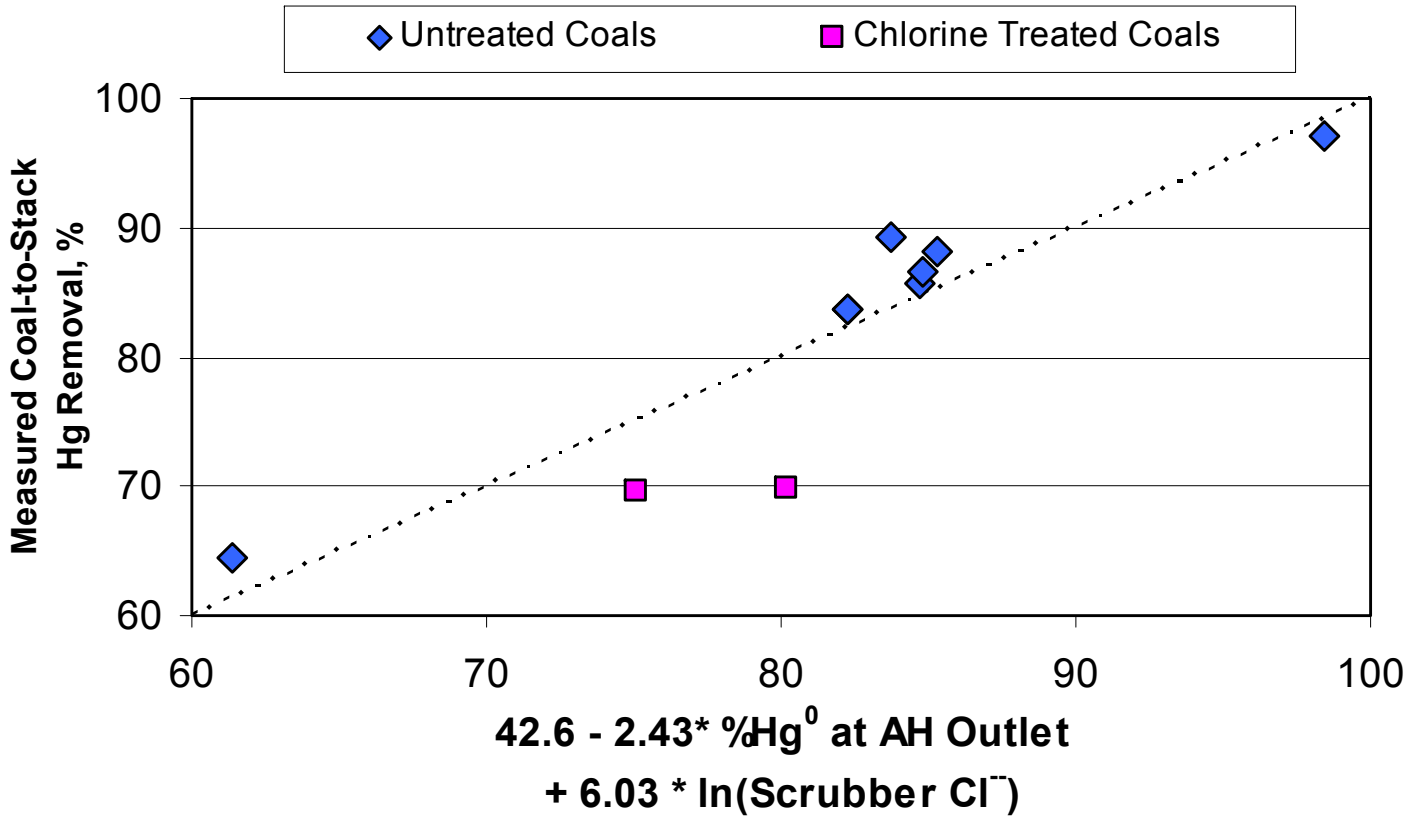

Figure 5. Parity plot of predicted vs. measured coal-to-stack mercury removal for SCR-equipped power plants

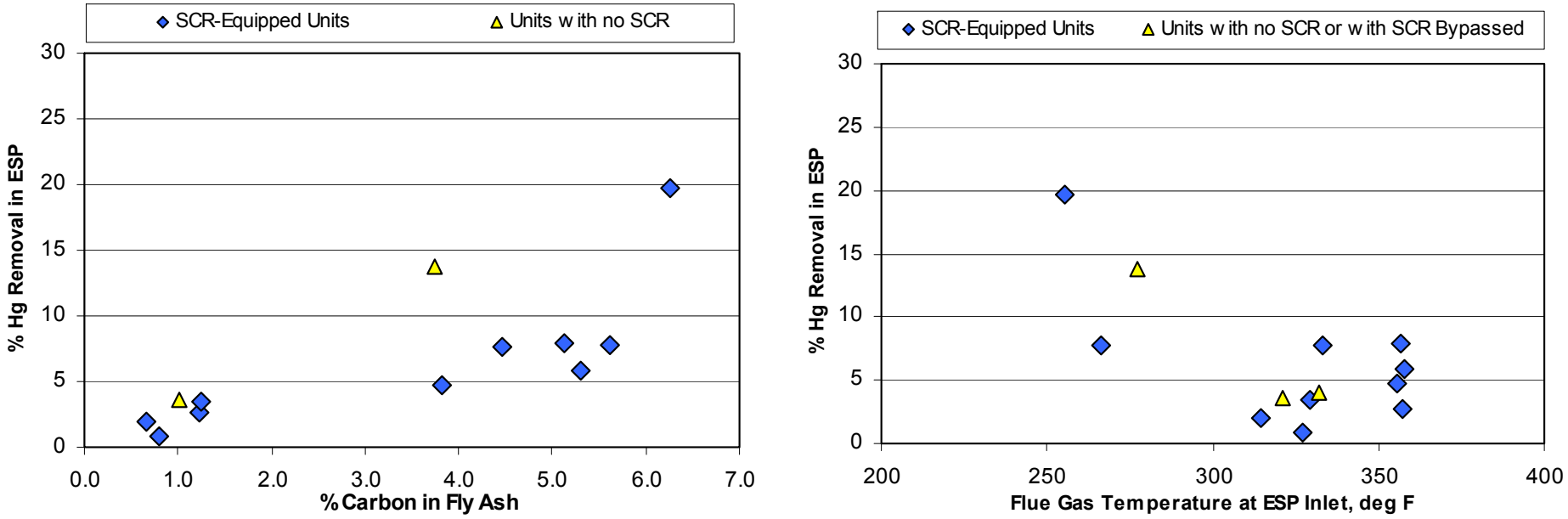

Figure 6. Mercury removal in the ESP: a) as a function of the fly ash carbon content, and b) as a function of the flue gas temperature at the ESP inlet

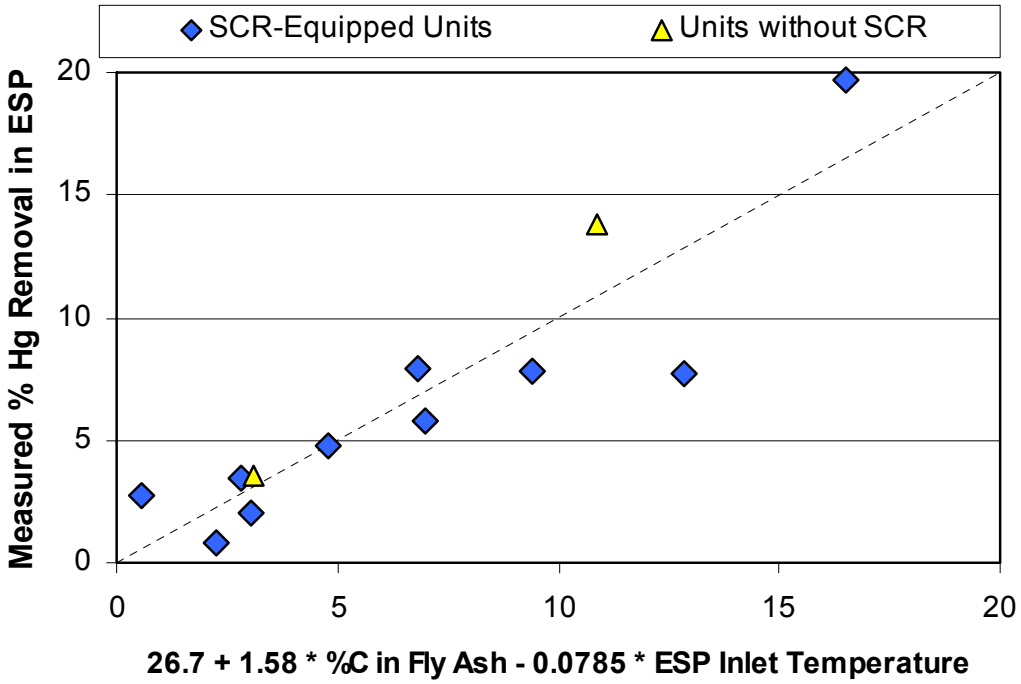

Figure 7. Measured vs. predicted mercury removal in the ESP

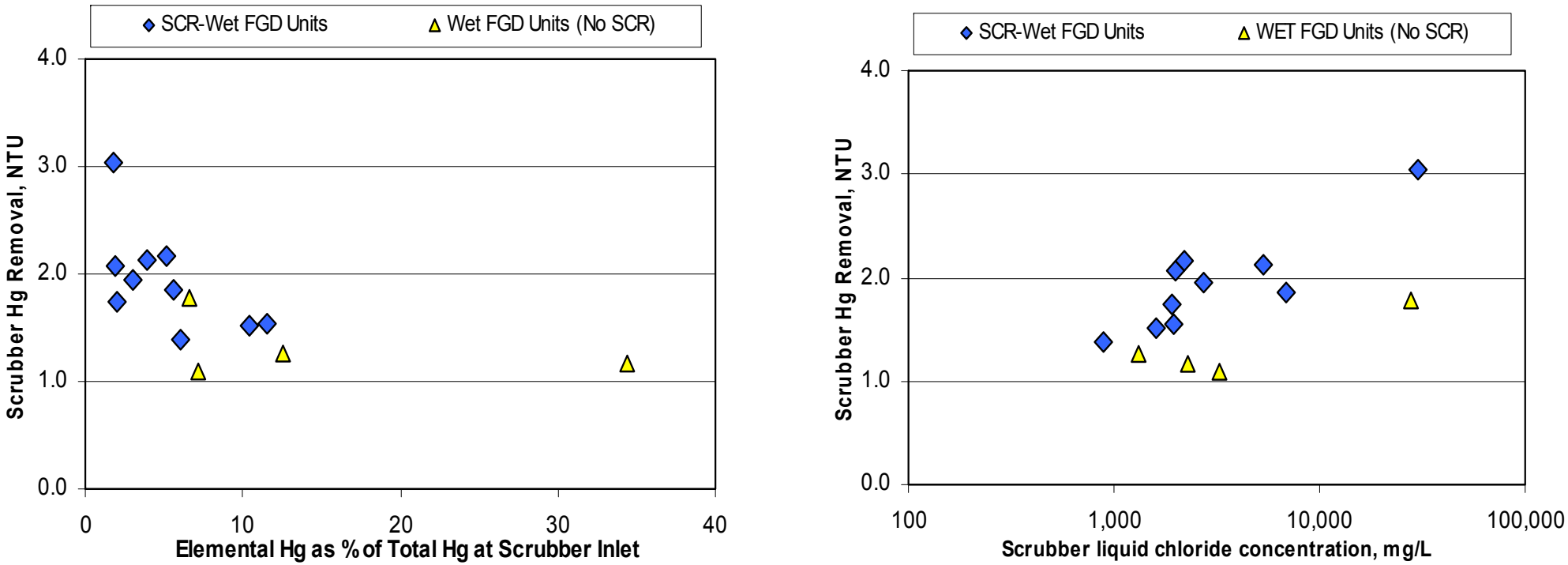

Figure 8. Scrubber mercury removal: a) as a function of the elemental mercury fraction at the scrubber inlet, and b) as a function of the scrubber liquid chloride concentration.

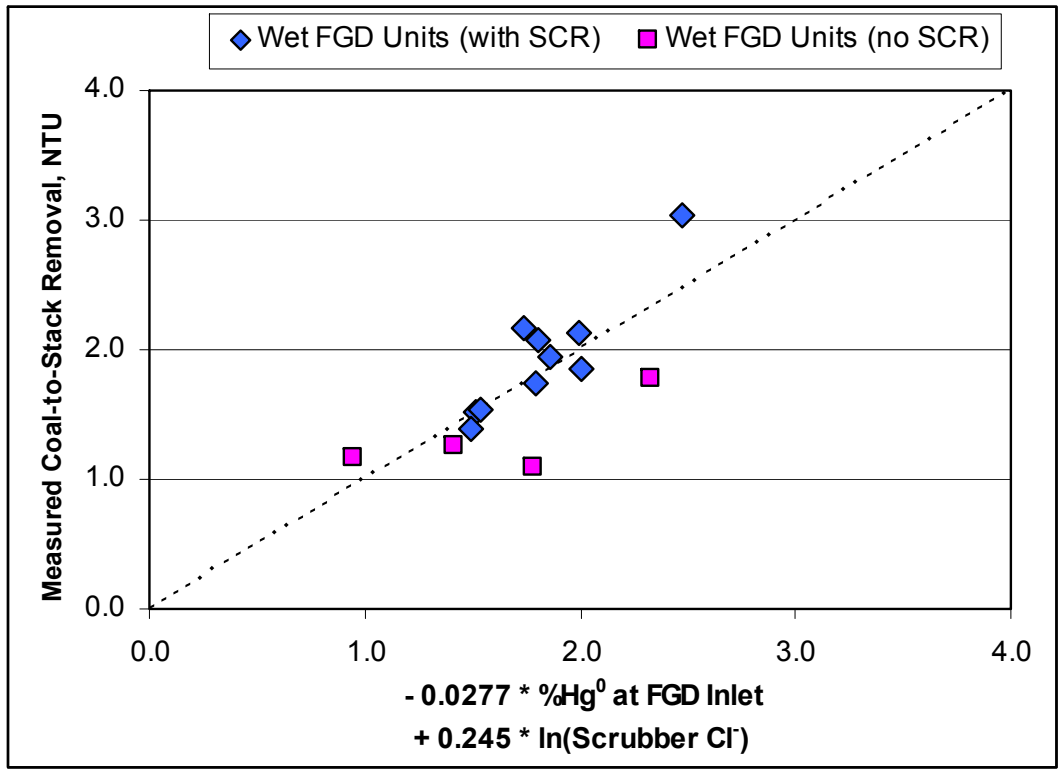

Figure 9. Parity plot of predicted vs. measured scrubber mercury removal.