



Speciation and mass-balance of mercury from pulverized coal fired power plants burning western Canadian subbituminous coals

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This report summarizes the results of a study carried out on six pulverized coal-fired power plants in western Canada burning subbituminous coal for the mass-balance and speciation of mercury. The main objectives of this study were to: determine the total gaseous mercury (TGM) emitted from stacks of power plants using the Ontario Hydro method; identify the speciation of emitted mercury such as metallic (Hg^0) and gaseous elemental (GEM) mercury; and perform mass-balance calculations of mercury for milled-coal, bottom ash, electrostatic precipitators (ESP) fly ash and stack-emitted mercury based on three tests. Sampling of mercury was carried out using the Ontario Hydro method and mercury was determined using the USEPA method 7473 by cold vapor atomic absorption (CVAAS). The sample collection efficiencies confirmed that both oxidized and the elemental mercury had been successfully sampled at all power plants. The total gaseous mercury emitted (TGM) is $6.95\text{--}15.66\text{ g h}^{-1}$ and is mostly in gaseous elemental mercury (GEM, Hg^0) form. The gaseous elemental mercury is emitted at a rate of $6.59\text{--}12.62\text{ g h}^{-1}$. Reactive gaseous mercury (RGM, Hg^{2+}) is emitted at a rate of $0.34\text{--}3.68\text{ g h}^{-1}$. The rate of emission of particulate mercury (Hg^p) is low and is in the range $0.005\text{--}0.076\text{ g h}^{-1}$. The range of mass-balances for each power plant is more similar to the variability in measured mercury emissions, than to the coal and ash analyses or process data. The mass-balance calculations for the six power plants, performed on results of the three tests at each power plant, are between 86% and 123%, which is acceptable and within the range 70–130%. The variation in mass-balance of mercury for the six power plants is mostly related to the variability of coal feed rate.

1. Introduction

Mercury is a naturally occurring element found in the atmosphere, hydrosphere and biosphere.¹ As a result of an increased awareness of the adverse effects of trace elements in our environment, the scientific community has responded with countless studies and papers documenting anthropogenic contributions of elements to the environment. The total Hg burden in the atmosphere, more specifically in the northern hemisphere, increased up until the late 1980s and has since decreased to a plateau in 1996 to 2001.² The global anthropogenic input of Hg decreased from 3560 t/y in 1979/1980, to 2140 t/y in 1990, and then to 1900 t/y in 1995.² The amount of Hg present in the atmosphere has subsided, owing to a lesser amount of anthropogenic emissions.²

Many elements need to be investigated, but mercury is of considerably high priority due to its inherent toxic effects on humans and wildlife.^{1,3–8} The challenge lies in the quality of research data attained, as well as its interpretations. Controversies over sampling methods and analyses have limited the scope of data that can be drawn from, thus necessitating the need for further study and refinement of analytical techniques and analysis. Elemental speciation is of considerable importance, as it has been shown that the valence state of an element governs its behavior on many levels. Knowledge of mercury speciation is critical in predicting its fate upon release into the environment from a point source.⁹ Understanding its speciation is also crucial in identifying and preventing adverse health and environmental effects.^{1,3,4} It is important to note that the total amount of mercury in the environment is not changed since mercury is an element that is part of the earth system.⁹ Without human intervention, mercury cycles as a result of natural and geogenic activities.^{10,11} However, anthropogenic activities have influenced the redistribution of mercury from

geogenic sources into the air, water and topsoil, where it may more readily enter the food chain.¹⁰ The majority of mercury in water, soil, sediments, plants, and animals is in the form of inorganic mercury salts and organic forms of mercury, primarily methyl mercury.^{3,6–8}

There still remains the question of whether the mercury (oxidized or not) found at the surface is coming from the atmosphere or from emanations from the ground.^{10,12} However, this question is basically unresolved for forested ecosystems.¹²

1.1. Mercury speciation

While exposure levels and quantities of mercury are important factors in assessing its environmental and physiological impact, equally important is its speciation. The understanding of speciation is critical in evaluating the transport, deposition, and environmental impact of mercury emissions.¹¹ Mercury in the atmosphere is found in both the gaseous and particulate form. The dominant form of the total gaseous mercury (TGM) is gaseous elemental (Hg^0) mercury (GEM).¹³ Pacyna and Munch¹⁴ suggested mercury emissions from human activities occur in three main forms:

Hg^0 : elemental (metallic, GEM) mercury, which is relatively non-reactive and an insoluble form of mercury. This is mostly related to mercury associated with minerals

Hg^{2+} : mercuric mercury, an inorganic (ionic) form, which is soluble in water. This is “oxidized mercury”, a term that is commonly used for species of mercury (particularly HgCl_2) emitted from the stack of coal-fired power plants.

Hg^p : particulate mercury, which is mercury associated with particles of ash and soil. This fraction of mercury is mostly removed by particulate control equipment in coal-fired power plants.

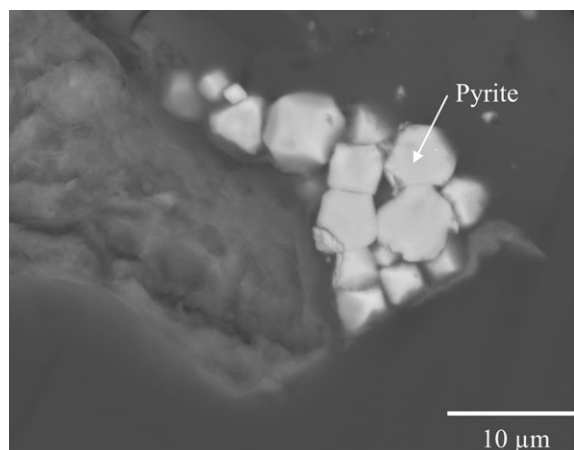


Fig. 1 Pyrite minerals found in coal.

1.2. Mineralogy and mode of occurrences of mercury in coal

Mercury in most coals is associated with sulfide minerals, which include pyrite (FeS_2) (Fig. 1), sphalerite (ZnCdS) and cinnabar (HgS) and selenides such as ferroselite (FeSe_2).^{15–19} Mercury can also occur as metallic mercury or be incorporated into organometallic compounds in coal.^{10,11,20–22} However, comparison of a suite of coals and their pyrite concentrates from eastern Canada indicates that the concentration of chalcophilic elements including Hg is larger in coals than in pyrite concentrates from the same sample.^{18,23}

The studies on the modes of occurrence of mercury in four coals from Australia, Canada, the United Kingdom and the United States indicate that mercury is mostly associated with the organic fraction of coal followed by pyrite (FeS_2) and then carbonate.^{24,25}

1.3. Mercury in western Canadian subbituminous coal

The mercury content of an *in situ* coal seam (a sedimentary rock) includes mercury found in both the partings and coal layers, and represents the geologic aspect of mercury in coal.

The range of mercury content in coals and associated partings, from active subbituminous coal mines in western Canada where the ash content can vary from 5% to 80%, is shown in Table 1. These *in situ* coals (including partings) have mercury contents ranging from 0.010–0.460 mg kg^{-1} (Table 1). The higher values recorded for these coals are attributed to inclusion of high mercury from partings. For example, a coal-bearing stratum such as #3 may contain mercury in the range 0.10–0.460 mg kg^{-1} , but feed coal prepared from the same stratum has a mercury content of 0.058 mg kg^{-1} (Table 1), this being because portions of the coal seam that have a high ash content (generally greater than 25% ash) are not included in feed coal blend. In general, mercury content in western Canadian subbituminous feed coal is between 0.05 and 0.08 mg kg^{-1} (Table 1), which is within the range for World coal (0.02–1.0 mg kg^{-1}).¹¹ The range for US coal is 0.08–0.22 mg kg^{-1} ,^{26,27} the lowest mercury in US coal is in the Utah coal area (0.08 mg kg^{-1}) and the highest is in the Gulf Coast coal area (0.22 mg kg^{-1}).²⁸

1.4. The inconsistency in mass-balance of mercury emitted from coal-fired power plants

The early field tests of mercury could not account for the mercury that entered the coal-fired power plant *via* feed/milled coal, and the mercury that was subsequently emitted to the atmosphere.²⁹ There is still the assumption that all, or at least most, of the mercury in feed coal is emitted upon combustion. This assumption was based on early, inaccurate data. Mercury may be retained in bottom ash and ESP/baghouse fly ash by carbon. In addition, there is evidence that mercury species in flue gases may vary with temperature from the boiler to the stack.³⁰

The sources of inconsistency in the mass-balance calculations of mercury are as follows:

a. Inaccurate feed/milled coal, bottom and fly ash analyses: in the past, the techniques for determination of mercury in coal were not accurate. Therefore, the amount of mercury in coal was usually overestimated.^{29,31,32} The mercury content of power plant ashes (bottom ash and ESP ash) is often very low, therefore high accuracy is required to determine the mercury contents of these samples.

b. Chlorine content of milled/feed coal: the chlorine content of coal has an effect on the amount of mercury emitted from the stack.³³ Mercury is partially captured by chlorine as mercuric chloride (HgCl_2) and may remain within the power plant. This is important in coal with high Cl content. Mercuric chloride is soluble in water and is effectively removed by wet scrubbing.³⁰

c. Mercury accumulation within the power plant: mercury accumulated within the power plant is often emitted during “sooting”. The accumulation of mercury is related to the temperature of the ESP.³³ More mercury is emitted from power plants in the hot side ESP.^{33,34}

d. Inaccurate flue gas measurements: an important factor in the determination of mercury mass-balance calculations is accurate flue gas measurements.²⁹

1.5. Emission of mercury from coal-fired power plants

It is perceived that most mercury from coal-fired power plants is emitted into the atmosphere. The inaccurate determination of the mercury content of coal and power plant ashes facilitated such an assumption.^{31,32}

Chow *et al.*³⁵ have expressed concern regarding the amount of mercury supposedly emitted due to the combustion of coal. They stated that, “The literature is quite confusing regarding mercury emission from coal-fired power plants. First it is not clear whether the measured mercury was total, phase, or that condensed on particulates. Secondly, the sampling and analytical methods used may have been unreliable. Finally, most data available on mercury removal are from the municipal waste incinerator industry where mercury concentration is much higher by several orders of magnitude than utility flue gas”.

A review of the literature indicates that mercury removal from coal-fired power plants ranges from 10 to 90% by fabric filters and ESP's, and ranges from 20 to 95% by FGD systems.^{35,36} The results of EPRI³⁰ and Chow *et al.*³⁵ indicate that between 20 and 90% of the mercury was removed by cold

Table 1 Range of mercury concentrations (mg kg^{-1}) in Alberta Plains region *in situ* coals^a (5–80% ash) and feed coals^b (<25% ash)

	1	2	3	4 and 5	6	World ⁵
<i>In situ</i>	N/A	0.010–0.150 ^a	0.010–0.460 ^a	0.015–0.150 ^a	0.010–0.170 ^a	0.020–1.000
Feed coal ^b	0.065	0.053	0.058	0.074–0.075	0.051	

1, 2, etc. indicate the station number in this study.

N/A = not available.^a These high values represent parting(s) and interbedded rocks in coal seam. ^b Feed coals may be a blend of several seams, some of them may have been cleaned.

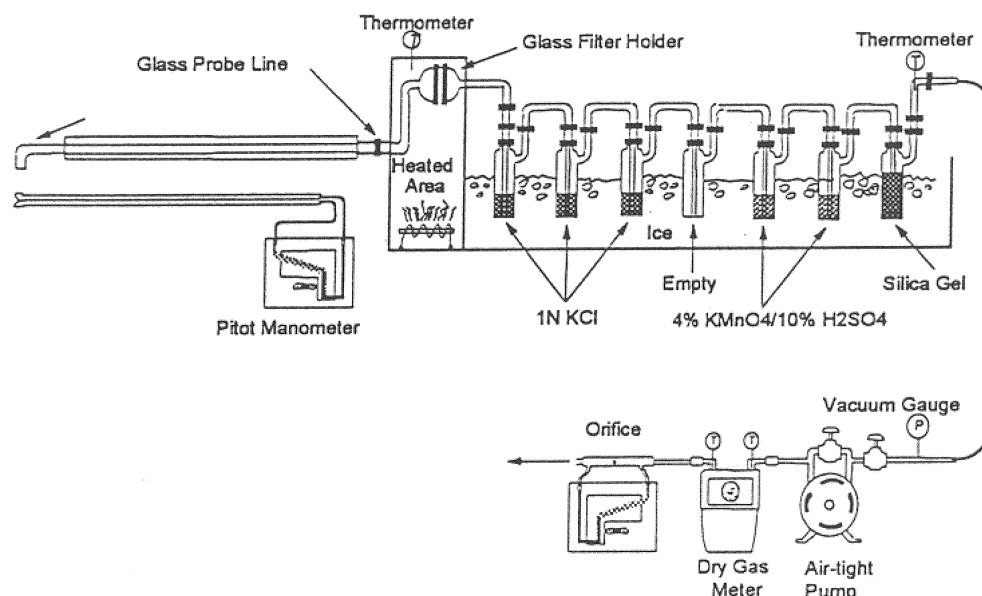


Fig. 2 Ontario Hydro mercury speciation train.

side ESP's in 5 stations, and between 85 and 90% of the mercury was removed by fabric filters in 3 stations. Jones *et al.*³⁷ estimated that up to 50% of the mercury is removed by ESP's and between 59 and 90% is removed by wet scrubbers. They estimated an emission factor of 0.1 g t^{-1} of mercury for subbituminous coal (the same rank as western Canadian subbituminous coals).

The boiling point of mercury is 360°C , so at combustion temperatures of 1500°C it is present in elemental (Hg^0) form. Because of this, it was previously assumed that mercury would be emitted during combustion. However, the temperature of the flue gases decreases by the time flue gas passes through the ESP's ($350\text{--}400^\circ\text{C}$ for hot side and 150°C for cold side) and mercury behaves differently in the cooler areas of the power plant.³³

2. Analytical methods

The ultimate, proximate and sulfur forms in feed coal were determined using standard ASTM methods.³⁸ Mercury content of feed coal, bottom and fly ashes was determined using USEPA method 7473.³⁹ Each sample fraction in speciation study of stack emission was individually analyzed, with duplicates, for mercury by cold vapor atomic absorption.³⁹

2.1. Sampling

Sampling of the feed coals, bottom and ESP ashes was carried out using manual and auto samplers for a period of three days following the recommendation of Electric Power Research Institute.³⁰

Stack sampling was carried out using the Ontario Hydro (OH) methodology.⁴⁰ This method is more complex than the usual stack sampling procedures (Fig. 2). This is especially true for the sample recovery procedures that are a very important aspect of this method. This method developed by Ontario Power Technology (OPT) is a modification of EPA method 29.

2.2. Sample collection efficiency

OPT recovers and analyzes each of the seven impingers in the sampling train separately, thereby obtaining information that allows the success of the sample collection to be evaluated. For example, if a collection pattern of 90%, 8% and 2% was obtained for a three impingers system, one could have a reasonable degree of confidence that the mercury had been

successfully collected. In contrast, a pattern such as 50%, 30% and 20% would suggest that a considerable breakthrough of the target species had occurred and that the sample collection was not as successful.

2.3. Recovery of mercury from on-site spiked QA/QC samples

The use of QA/QC samples spiked with known amounts of mercury and recovered on-site has now been included in the method. Two KCl impinger samples, one acidic peroxide impinger sample and two permanganate impinger samples were spiked with known amounts of mercury for sampling in the stacks. The quantity of mercury added to each sample was based on what might reasonably be expected to be collected in the corresponding test samples.

3. Results and discussion

As of January 4, 1999, the US Environmental Protection Agency (USEPA) requires all coal-fired electric utility steam generating units in the US to provide data to calculate annual mercury emissions. The data will assist in regulating emissions of hazardous air pollutants (HAPs) from electric utility steam generating units, and to potentially gain insight into the industry's contribution to the global mercury burden.

A similar program was carried out in Alberta and six pulverized coal-fired power plants burning western Canadian subbituminous coals participated in a similar program on a voluntary basis between 1999–2001. These coal-fired power plants use local subbituminous coal from their adjacent coal mines and mostly a blend of various coal seams from the mines.

3.1. Characteristic of the stations

All stations in this study are equipped with cold side ESP's except #6, which operates with hot side ESP. The samples from these stations were taken from stacks of 121–161 m height. These stations have generating capacities of 300–2158 MW. The average annual production of electricity for these stations ranges between 3.87 and 13.83 million megawatt hours (MW h).

Table 2 Proximate and ultimate analysis (weight %) of milled coal from stations #1–#6 (based on the average of three samples)

		Station #1		Station #2		Station #3		Station #4		Station #5		Station #6	
		Average	σ	Average	σ	Average	σ	Average	σ	Average	σ	Average	σ
As-received basis	Calorific value/MJ kg ⁻¹	21.28	1.06	21.92	0.36	18.49	0.38	19.46	0.44	19.34	0.21	n/a	n/a
	Ash content (%)	13.06	3.49	14.18	3.61	26.32	1.24	20.38	1.56	21.15	0.72	15.90	0.74
Dry basis	Total sulfur (%)	0.363	0.021	0.647	0.021	0.250	0.031	0.210	0.050	0.210	0.040	0.320	0.010
	Sulfate sulfur (%)	0.007	0.006	0.053	0.005	0.007	0.000	0.010	0.000	0.010	0.010	0.040	0.000
	Pyritic sulfur (%)	0.042	0.016	0.014	0.005	0.043	0.010	0.020	0.010	0.010	—	0.060	0.040
	Organic sulfur (%)	0.314	0.029	0.580	0.028	0.200	0.021	0.180	0.030	0.190	0.030	0.220	0.060

3.2. Characteristics of feed-coal

The subbituminous feed coals are burned in the all stations. These feed coals have an average sulfur content from 0.21% to 0.65% (air dry basis) and a calorific value of 18.49 to 21.92 MJ kg⁻¹ (as-received) (Table 2).

Sulfur form. The feed coals have low pyritic sulfur content (Table 2). Their pyritic sulfur is between 0.014 and 0.060%, the sulfate sulfur is between 0.007 and 0.053% (Table 2). The organic sulfur accounts for most of the sulfur in these feed coals and ranges from 0.18 to 0.58% (Table 2).

Mercury content of feed coal. The average mercury content of the feed coals from the six power plants, based on three tests, ranges from 0.051 mg kg⁻¹ to 0.075 mg kg⁻¹ (Table 3). There is some variation in the mercury content of feed coal during the test periods and in general, the variation in mercury content of feed coal is low. For example, the mercury content of feed coal from station #6 is 0.046, 0.049 and 0.059 mg kg⁻¹ for three tests, giving an average of 0.051 mg kg⁻¹ (Table 3).

3.3. Mercury and carbon content of bottom ash

The mercury content of bottom ash shows very little variation during the three tests. The average Hg content of bottom ash ranges between 0.003 and 0.020 mg kg⁻¹ (Table 3). The carbon content of bottom ash ranges between 0.11 and 16.46% (Table 3). There is some variation in the carbon content of bottom ash for different stations.

3.4. Mercury and carbon content of ESP fly ash

The mercury content of ESP fly ash shows very little variation during the three tests. The average Hg content of fly ash ranges from 0.005 to 0.240 mg kg⁻¹ (Table 3). The mercury content of fly ash is similar to that of feed coal for station #2, is less than feed coal for stations #1 and #6 and greater than the Hg in feed coals for stations #3–#5 (Table 2). The carbon content of fly

ash ranges between 0.13 and 2.72% (Table 2). There is little variation in carbon content of fly ash for any station.

In general, the mercury content of fly ash is greater than that of bottom ash for all stations that are equipped with cold side ESP's (station #1–#5, Table 2). The bottom ash has higher Hg content than fly ash in station #6, which is probably due to the hot side ESP used in this station which is operating at a temperature of >350 °C. Mercury at this temperature is in gaseous form and therefore does not precipitate.

3.5. Sample collection efficiency

The collection efficiency pattern for all the test runs and for all stations was good, and indicates successful sample capture. For example the collection efficiency patterns for the test runs at station #6 indicate that the average collection patterns for the three days of testing for the KCl impingers (oxidized mercury) were 86.0, 6.0 and 6.0% (Table 4a). The average collection patterns for three permanganate impingers on the other hand (elemental mercury) were 81.7, 15.3 and 1.0% (Table 4a).

3.6. Recovery of mercury from on-site spiked QA/QC samples

The results of the analysis of the QA/QC samples for all stations were acceptable, with a high level of recoveries of the KCl impinger spikes obtained. The overall weighted average recovery of the spiked mercury samples for all stations was calculated at 95%, which gives the desired confidence in the overall mercury emission results.

An example of recovery of mercury from on-site spiked QA/QC samples is presented in Table 4b. Both sets of results for the KCl and the permanganate impingers are near identical, with excellent spike recoveries between 101 and 106%. The weighted average recoveries for the entire QA/QC sampling train for station #6 are 101% and 102% (Table 4b).

4. Mass-balance study

Mass-balance calculations for volatile elements such as mercury, where the elemental release rates in the various effluent

Table 3 Concentration of mercury (mg kg⁻¹) in coal, bottom ash and fly ash and carbon content (%) in bottom ash and fly ash from stations #1–#6

	Station #1		Station #2		Station #3		Station #4		Station #5		Station #6	
	Average	σ	Average	σ	Average	σ	Average	σ	Average	σ	Average	σ
<i>Feed coal</i>												
Hg ^a /mg kg ⁻¹	0.065	0.011	0.053	0.031	0.058	0.005	0.075	0.006	0.074	0.009	0.051	0.007
<i>Bottom ash</i>												
Hg/mg kg ⁻¹	0.018	0.007	0.005	0.003	0.004	0	0.003	0	0.011	0.006	0.02	0.014
C (%)	2.30	3.10	6.25	5.02	0.11	0.07	2.32	0.70	16.46	10.00	1.22	0.58
<i>Fly ash</i>												
Hg/mg kg ⁻¹	0.037	0.003	0.054	0.011	0.133	0.005	0.157	0.047	0.240	0.089	0.005	0.003
C (%)	0.13	0.01	0.19	0.04	0.29	0.13	2.72	0.32	1.32	0.48	1.27	0.17

^a Concentration of mercury on a dry basis

Table 4 a. Sample collection efficiency for mercury at the stack of station #6; b. results from the analysis of a spiked QA/QC mercury train, prepared and recovered on-site at the stack from station #6

a.				
Test no.	Impinger	Total mercury/ μg	Recovery pattern (%)	Percent of total phase mercury
Test 1	Filter/front half	0.014	2	7%
	1KCl	0.730	86	
	2KCl	<0.050	6	
	3KCl	<0.050	6	
	4H ₂ O ₂	<0.25	2	93%
	5KMnO ₄	9.30	78	
	6KMnO ₄	2.20	18	
Test 2	7KMnO ₄	0.17	1	
	Filter/front half	0.010	1	5%
	1KCl	0.660	86	
	2KCl	<0.050	6	
	3KCl	<0.050	6	
	4H ₂ O ₂	<0.25	2	95%
	5KMnO ₄	13.00	86	
Test 3	6KMnO ₄	1.70	11	
	7KMnO ₄	0.11	1	
	Filter/front half	0.012	1	5%
	1KCl	0.860	86	
	2KCl	0.079	8	
	3KCl	<0.050	5	
	4H ₂ O ₂	<0.25	1	95%
	5KMnO ₄	15.00	81	
	6KMnO ₄	3.10	17	
	7KMnO ₄	0.24	1	
b.				
QA/QC mercury train (fraction)	Spiked quantity of mercury/ μg	Quantity of mercury found/ μg	Recovery of spiked mercury	
			Individual fraction	Weighted average
Nitric acid probe wash	0.179	0.13	0.73	73%
KCl	1.790	1.80	1.01	101%
KCl	0.358	0.36	1.01	
KCl	0.179	0.19	1.06	
H ₂ O ₂ /HNO ₃	0.358	0.36	1.01	101%
KMnO ₄	0.895	0.91	1.02	102%
KMnO ₄	0.269	0.28	1.04	
Weighted average recovery for entire QA/QC mercury train			100%	

streams are compared to the input from the fuel, are an extremely useful QA/QC tool.

The details of the average mass-balances of mercury for the three days of sampling for all six stations are presented in Table 5.

The averages of three days of mass-balance calculations for all six stations range from 86.2% to 123% (Table 5). The results of the mass-balances performed for these stations are within the acceptable error range ± 20 –30%.^{34,41}

In general, the results of average mass-balance for three tests and for stations #2, #3, #5 and #6 are excellent at 110%, 104%, 107% and 101% respectively (Table 5), only stations #1 at 123% and #4 at 86.21% are slightly above and below the range of 101–110% mass-balance.

The present results indicate approximately 3.33–57.58% of mercury is retained by bottom and fly ash and 42.42–96.67% is emitted from the stack (Table 5).

5. Speciation of mercury

Most of emitted mercury is the gaseous elemental mercury (GEM, Hg⁰) and emitted at a rate of 6.6–12.6 g h⁻¹, which accounts for 70.5–95.0% of the total emissions for all 6 stations (Table 6). GEM is not soluble in water. This species of mercury is generally carried away from the point source and has a more regional input to the mercury budget.

Only 5.00–28.93% of the total emission is in the reactive gaseous mercury (RGM, Hg²⁺) or “oxides mercury” form, emitted at a rate of 0.34–3.68 g h⁻¹. RGM is soluble in water and is mostly emitted as HgCl₂ from coal-fired power plants.⁴² There is very little RGM emitted from power plants equipped with hot side ESP. The rate of emission of particulate mercury (Hg^p) is low and is in the range of 0.005 to 0.076 g h⁻¹ (Tables). Therefore only 0.07–2.50% of total emitted mercury is in particulate form indicating that ESP’s capture most particulate mercury. Along with particulate mercury, RGM is, for the most part, deposited locally.

6. Summary and conclusions

The present data indicate that the variation in mass-balance of mercury for the six power plants is mostly related to the variability of coal feed rate and is within the acceptable error range.

Most of the emitted mercury is in the form of gaseous elemental mercury (GEM, Hg⁰) and emitted at a rate of 6.6–12.6 g h⁻¹. The reactive gaseous mercury form (RGM, Hg²⁺) is emitted at a rate of 0.34–3.68 g h⁻¹. There is very little RGM emitted from the power plant equipped with hot side ESP. The rate of emission of particulate mercury (Hg^p) is low, in the range of 0.005 to 0.076 g h⁻¹, indicating that ESP’s capture most particulate mercury.

Table 5 Mercury mass-balance calculation for stations #1–#6

	Station #1		Station #2		Station #3 ^a		Station #4		Station #5		Station #6	
	Average	σ	Average	σ	Average	σ	Average	σ	Average	σ	Average	σ
As-fired coal feed rate/Mg h ⁻¹	197	2.55	451	11.32	434	3.8	432	14.72	495	20.61	175	0
As-fired moisture content of the coal (%)	27.83	0.71	26.47	0.67	19.23	0.12	19.7	0.36	19.07	0.5	21	0.46
Dry-basis (DB) coal feed rate/Mg h ⁻¹	143	0.49	335	6.17	351	3.54	347	10.58	400	17.51	138	0.81
Average mercury content of the coal (DB)/mg kg ⁻¹	0.065	0.01	0.053	0.03	0.058	0.005	0.075	0.01	0.074	0.009	0.051	0.01
Inlet mercury mass flow rate/g h ⁻¹	9.47	1.52	19.52	10.34	20.48	1.94	26.15	2.69	29.44	3.129	7.1	0.95
Ash content of the coal (DB, carbon-free) (%)	16.37	4.4	17	4.01	29.53	1.42	23	1.76	23.67	0.760	19.33	1.13
DB carbon-free ash mass flow rate/Mg h ⁻¹	23.31	6.19	36.45	29.84	103.7	5.96	79.85	8.41	94.7	2.61	26.71	1.41
Average DB carbon content of bottom ash (%)	2.89	2.61	6.25	5.02	2.93	0	2.32	0.7	16.5	10	1.22	0.58
Average DB carbon content of ESP fly ash (%)	0.13	0.01	0.19	0.04	0.22	0.07	2.72	0.32	1.32	0.48	1.27	0.17
Assuming a split of 25% bottom ash and 75% ESP ash, the average carbon content of the ash	0.82	0.65	1.71	1.26	1.32	0.3	2.62	0.34	5.11	2.14	1.26	0.03
Total estimated ash flow, including carbon/mg h ⁻¹	23.43	6.1	50.3	2.35	105	6.0	81.99	8.62	99.53	3.04	28.46	1.37
At 25% of total ash, bottom ash mass flow rate/Mg h ⁻¹	5.86	1.53	14.39	3.5	41.97	2.43	20.49	2.15	24.88	0.76	6.76	0.36
Average bottom ash mercury content (DB)/Mg kg ⁻¹	0.018	0.01	0.005	0.003	0.004	0.00	0.003	0.00	0.011	0.006	0.018	0.01
Mercury released in the bottom ash/g h ⁻¹	0.110	0.07	0.2	0.22	0.168	0.01	0.061	0.01	0.267	0.15	0.12	0.07
At 75% of total ash, ESP fly ash mass flow rate/Mg h ⁻¹	17.57	4.57	43.15	10.49	62.96 ^a	3.64 ^a	61.46	6.46	74.65	2.28	20.29	1.07
Average mercury content of the ESP fly ash (DB)/mg kg ⁻¹	0.037	0.00	0.054	0.01	0.133	0.01	0.157	0.05	0.24	0.09	0.006	0.00
Mercury released in ESP ash/g h ⁻¹	0.64	0.15	2.46	0.85	8.38	0.63	9.805	3.80	17.824	6.19	0.126	0.05
Total outlet mercury mass flow rate in ash/g h ⁻¹	0.76	0.22	2.52	0.90	8.54	0.63	9.87	3.81	18.09	6.06	0.247	0.10
Average mercury emission rate in flue gas/g h ⁻¹	10.89	1.74	15.66	2.26	12.74	1.84	12.84	1.07	12.74	1.32	6.95	1.49
Total outlet mercury mass flow rate/g h ⁻¹	11.65	1.96	18.18	3.15	21.29	2.13	22.70	4.87	30.83	4.74	7.195	1.59
Mercury mass balance, outlet versus inlet (%)	123	13.65	110	47.25	104	8.99	86.21	9.94	107	26.85	101	14.53
Of this, fraction found in the ash (%)	7.67	2.08	14.00	3.46	41.77	0.87	37.05	10.54	63.31	26.88	3.42	1.07
Fraction found in the flue gas (%)	115.7	12.01	95.67	44.66	62.37	8.97	49.17	1.67	43.28	0.87	97.62	13.54
Normalized to 100%, fraction found in the ash (%)	6.17	1.15	13.55	3.19	40.3	3.39	42.45	7.04	57.58	10.88	3.33	0.66
Fraction found in the flue gas (%)	93.83	1.15	86.45	3.19	59.7	3.39	57.55	7.04	42.42	10.88	96.67	0.66

^a Station #3 assumes a split of 40% bottom ash and 60% ESP ash.

In general, the present suite of data based on captured/emitted mercury can be grouped as:

- Low mercury capture/high emission, which includes station #6 with hot side ESP.
- Medium mercury capture, which includes stations #1 and #2 with cold side ESP.
- High mercury capture/low emission, which includes stations #3–#5 with cold side ESP.

The variability in the rate of captures of mercury in stations #1 and #2 compared to that of #3–#5 is due to their petrological differences.⁴³

These data are a further indication of the difficulty in developing a baseline for reduction of mercury even if the feed coal is of the same rank (subbituminous). It is shown that even within the same coal rank and within a narrow range of mercury content in feed coals (0.051–0.075 mg kg⁻¹), there

Table 6 Summary of mercury speciation results using the Ontario Hydro method averaged over three days of sampling from stations #1–#6

	Station #1		Station #2		Station #3		Station #4		Station #5		Station #6	
Parameter	Average	σ	Average	σ	Average	σ	Average	σ	Average	σ	Average	σ
Sample volume collected/m ³ (dry)	3.558	0.568	3.3697	0.011	5.217	0.057	4.48	0.100	4.87	0.695	3.01	0.140
Total mercury												
µg m ⁻³	6.60	1.101	4.92	0.685	4.047	0.593	4.233	0.417	4.125	0.451	6.278	1.309
g h ⁻¹	10.89	1.739	15.66	2.262	12.742	1.835	12.835	1.070	12.738	1.320	6.947	1.487
Oxidized mercury, reactive gaseous mercury (RGM)												
µg m ⁻³	0.77	0.090	0.95	0.212	0.849	0.503	1.214	0.169	0.481	0.184	0.313	0.057
g h ⁻¹	1.27	0.135	3.03	0.680	2.676	1.594	3.683	0.515	1.491	3.470	0.345	0.062
% of the total mercury	11.77	0.007	19.30	0.034	20.41	0.001	28.93	0.054	12.0	0.040	5.00	0.862
Particulate mercury												
µg m ⁻³	0.000	0.006	0.000	0.000	0.012	0.001	0.025	0.029	0.104	0.031	0.005	0.001
g h ⁻¹	0.01	0.000	0.010	0.000	0.037	0.005	0.076	0.086	0.320	0.096	0.005	0.001
% of the total mercury	0.07	0.000	0.09	0.000	0.29	0.000	0.60	0.007	2.48	0.010	0.100	0.000
Total particulate and oxidized mercury												
µg m ⁻³	0.78	0.090	0.96	0.206	0.86	0.504	1.239	0.197	0.585	0.211	0.317	0.057
g h ⁻¹	1.28	0.135	3.04	0.680	0.625	1.083	3.759	0.600	1.803	0.665	0.351	0.062
% of the total mercury	11.80	0.008	19.40	0.034	20.70	0.001	29.50	0.060	14.01	0.045	5.00	0.917
Gaseous elemental mercury (GEM)												
µg m ⁻³	5.83	1.013	3.97	0.602	3.186	0.429	2.995	0.517	3.54	0.336	5.961	1.270
g h ⁻¹	9.61	1.605	12.62	1.965	10.029	1.265	9.075	1.449	10.928	0.875	6.596	1.444
% of the total mercury	88.2	0.008	80.6	0.034	79.3	0.001	70.5	0.060	86.0	0.045	95.0	0.917

are parameters that may influence the rate of emission of mercury. The most important finding of this study is that mercury like any other element can be captured by particulate control equipment. Furthermore, depending on the configuration of particulate control and the nature of feed coal, up to 57.6% of mercury may be retained, in agreement with Chow *et al.*²⁰ The variation in emitted mercury would be even more diverse than the present study if a greater number of power plants burning different ranks of coal from geologically diverse backgrounds and using various controlling devices were considered. One of the approaches that can be suggested for the baseline of mercury reduction is perhaps to provide a range of baselines depending on the mercury content, rank and geologic history of feed coal, and configuration of the system or mechanism that captures the different species of mercury.

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