signatory member states must apply the best available technique (preventive, management or off-gas dust control practices) for sources of heavy metals on their territory including all combustion installations with a rated thermal input of 50 MW. In parallel, the European Commission has prepared a BAT reference document in 2006 on large combustion plants discussing and proposing best available techniques to control criteria pollutants and resulting emission levels associated with them.[74] By giving relevant information concerning BAT, this document is intended to provide valuable tools to member states in order to drive their environmental performance.

The directives already implemented in recent years by the European Union have resulted in significant reductions in mercury emissions. It justifies why few countries have enforced mercury emission limit values to their coal-fired electric generation industry. Only Germany and Austria are known to enforce a mercury limit (0.05 mg/m^3) applicable to coal-fired EGUs.[75,76] The German legislation requires the installation of measuring instruments at relevant sources which continuously determine mercury mass concentrations unless it has been reliably proven that the mercury mass flow and concentration do not exceed 2.5 g/h and 0.01 mg/m^3, respectively.

The Protocol on heavy metals also instructs the authorities to continuously monitor mercury emissions or a performance parameter indicating that the control device is being properly operated if the emitted mass flow of particulates is greater than 10 kg/h. According to the Protocol, compliance of the particulate emissions limit contributes significantly to the reduction of heavy metals emissions in general. Besides, particulate emissions monitoring is generally less expensive than for individual heavy metals.

3.2.5 Australia

Australia does not regulate emissions of mercury from coal-fired EGUs. However, when it exceeds a threshold of 2,000 tonnes of fuel burned per year, mercury must be reported to the National Pollutant Inventory. Five types of emission estimation techniques are suggested to estimate emissions including mercury and its compounds: mass balance approach, fuel analysis data, engineering calculations, emission factors, direct measurement by stack sampling or CEMS.[77]

[74] European Commission Joint Research Center, Integrated pollution prevention and control (IPPC) reference document on best available techniques for large combustion plants, July 2006.
[75] Sloss, L.L., Mercury emissions and control from coal-fired power stations in countries outside the USA, Paper presented to the 1998 Science experts workshop on Mercury, Las Vegas, 1998.
[76] German Ministry for Environment, Nature Conservation and Nuclear Safety, Federal Immission Control Act, 2002.
[77] Australian Government – Department of the Environment, Water, Heritage and the Arts, Emission estimation technique manual for fossil fuel electric power generation, V2.4, March 2005.

3.3 Monitoring mercury emissions to air

Mercury monitoring regimes have roots in three broad approaches: predictive, mass balance and direct measurement methods. Predictive methods including mercury emission factors, historical analysis, statistical models and engineering calculations are considered in this study on account that they can provide a result although most are highly inaccurate. They rely greatly on crystal-clear understanding of mercury displacement through a power generation process. Their applicability is therefore limited. Mercury emissions calculated by mass balance are also prone to inaccuracies due to variability and number of measurements (i.e. mercury in coal, coal combustion residues, and wastewater) required for a valid estimate. The accumulation of measurements inaccuracies only decreases the mass balance method overall precision. Direct measurement is a more precise method in determining mercury emissions since it implies only one level of accuracy (measuring point). It depends however on the method of operation (periodic, semi-continuous and continuous). Periodic stack testing using wet chemistry absorption, electronic CEMS, dry sorbent trap adsorption and semi-continuous electronic monitoring are all considered in this report. The monitoring regimes are examined according to the following criteria:

Table 3-3: Criteria used in the assessment of mercury monitoring regimes

Criteria	Definition
Measurement frequency	Number of discrete mercury emission measurements annually.
Accuracy and uncertainties	**Accuracy:** Level of closeness of mercury emission measurements to its true value. **Uncertainties:** Describe the level of confidence in the mercury emission measurement procedure and if it can provide meaningful results to calculate an annualized mercury emission rate.
Detection limit	Minimum mercury concentration in flue gas for which the monitoring regime can still provide meaningful, accurate results.
Reliability	Ability of the monitoring regime to perform its required functions consistently without problems.
Practicality and extent of application	**Practicality:** Level of complexity to implement the monitoring regime. **Extent of application:** Degree of utilization of the monitoring regime in Canada and elsewhere.
Costs	Approximate investment and operating costs for implementing the monitoring regime. More precise and detailed costs will be provided in Section 5.
Advantages	Describes key advantages the monitoring regime would give compared to other regimes.
Limitations	Describes key flaws/difficulties associated with the monitoring regime.

3.3.1 Predictive monitoring

Predictive monitoring includes methods that rely on knowledge of physics and chemistry principles associated to the process or on compilation of mercury emissions from historical data. Ideally, the displacement of mercury could be modeled completely from engineering principles and relationships (ex. mercury volatilization rate, mass transfer coefficients, etc...). Since these calculations rely on process parameters, careful knowledge of operations is vital. Possible transient operation of power plants would alter calculated mercury emissions and make the

concept difficult to apply. Although fundamental research is done in this area, development of widely validated technical models has yet to be achieved.

Historical data are more convenient since they can be compiled into emission factors or regressed into correlations that are specific to coal-fired EGUs. For example, the U.S. EPA has developed during the 1990s a wide array of emission factors known as AP-42 for different industries and pollutants including mercury. Chapter 1 of U.S. EPA's *Compilation of air pollutant emission factors* deals with external combustion sources and provides emission factors for bituminous/sub-bituminous, lignite and anthracite coal combustion.[78] However, the scarcity of historical mercury emission data twenty years ago renders the validity of the few AP-42 emission factors questionable at best (Tab. 3-4). In AP-42, only the coal rank can discriminate between emission factors. Whether the emission factor is specified on coal consumption (mg/t), heat input (kg/TWh_{th}) or electricity output (kg/TWh_e), total mercury emission rate (i.e. kg/h) can be obtained by multiplying it with the process activity (t coal/h, TW_{th} or TW_e). Application of emission factors obtained from published facility measurement campaigns (i.e. NPRI) is another option to estimate mercury emissions from a similar facility.

Table 3-4: Mercury emission factors retrieved from U.S. EPA's *Compilation of air pollutant emission factors* (AP-42) applicable to coal combustion

Fuel	Emission factors	Comments
Anthracite coal [a]	Mass specific: 65 mg Hg/t coal Heat specific: 7.1 kg/TWh_{th} Electric specific: 21.3 kg/TWh_e [b]	o obtained from Stoker fired boilers o emission factor rating: poor
Sub-bituminous and bituminous coal [c]	Mass specific: 138 mg Hg/t coal Heat specific: 24.8 kg/TWh_{th} Electric specific: 74.3 kg/TWh_e [b]	o obtained from uncontrolled combustion for pulverized coal o emission factor rating: poor
Sub-bituminous, bituminous and lignite coal	Mass specific: 0.042 mg Hg/t coal Heat specific: 0.007 kg/TWh_{th} Electric specific: 0.022 kg/TWh_e [b]	o obtained from controlled coal combustion utilizing venturi scrubbers, spray dryer absorbers, wet scrubbers/ESP or wet scrubber/baghouse o emission factor rating: good

[a] Average gross calorific value for anthracite: 33 kJ/t.
[b] Electric efficiency for coal-fired power plants fixed at 33% (kW_e/kW_{th}).
[c] Average gross calorific value for bituminous/sub-bituminous: 20 kJ/t.

Predictive regression modeling based on a pool of data is an improvement compared to single value emission factors. Resulting airborne mercury emissions from the CEA mercury program along with some CEMS and wet chemistry stack tests were used to develop statistical models in the past.[79] The mercury emission rates were regressed in function of mercury and chlorine content in coal for different data subsets (coal rank, particulate emission control method and post-combustion controls). Valid predictions were obtained for data sets related to EGUs operating a cold-side ESP (most Canadian facilities). Although the correlation coefficient was deemed acceptable, the model still presents important uncertainties since the measurements from the CEA mercury program were obtained by mass balance (see next section).

[78] U.S. EPA, Emission factors & AP 42: Compilation of air pollutant emission factors website.
[79] Mazzi, E. et al., Canada wide standards mercury measurement methodologies for coal-fired power plants, EPRI-EPA-DOE-AW&MA Symposium paper #15, August 2006, Baltimore, Maryland, USA.

Table 3-5: Assessment of predictive methods for mercury monitoring

Criteria	Comments	Grade
Measurement frequency	o Not applicable.	N/A
Accuracy and uncertainties	o Emission factors provide only broad approximations. o Performance of statistical models although they provide good predictions on specific data sets is highly dependant on the operating parameters. Uncertainties on models can vary depending if the regressed data are direct measurements or not.	very low
Detection limit	o Not applicable.	N/A
Reliability	o Not applicable. These methods can be applied as soon as the information is available.	N/A
Practicality and extent of application	o Not practical to obtain acceptable results in accordance to a monitoring program.	None
Costs	o The costs are minimal for labour except when specific information (i.e. mercury content in coal) is required to calculate a value.	<$10 k/a
Advantages	o Easy of application if information is available. However, the high number of information often required for this task reduces its applicability. o Provides a quick appraisal of mercury emissions.	
Limitations	o Inaccurate and highly uncertain predictions.	

3.3.2 Mercury mass balance

Airborne mercury emissions estimated by mass balance require constant monitoring of mercury content in coal and coal combustion residues like bottom ash and fly ash recovered from dry particulate matter control device (i.e. ESP). Mercury content in other materials added to the boiler (i.e. limestone for circulating fluid beds) must be evaluated for valid estimation of mercury emissions. Other waste streams like waste scrubber liquors should be considered as well.

Accurate mass balance estimation requires ideally that coal and residues samplings are synchronized so the results are representative of that period. Sampling methodologies are also important. Representative samples should be collected preferably using an automatic sampler according to the ASTM standard D2234.[80] In absence of an auto-sampler, manual sampling can still be considered. Synchronized fly ash samples from ESP hoppers or silos should be collected as well since it is known to contain large quantities of mercury (usually > 100 ppb according to the CEA mercury program) if the inherent mercury control by the baghouse or ESP is significant.[81] Bottom ash samples should be considered for accurate results but are known, in contrast to fly ash, to contain little amount of mercury (<10 ppb). Special care should be taken throughout the procedures to ensure that mercury contamination does not occur. The samples are then analysed by an accredited lab station according to ASTM standards (i.e. D6414, D3684, D6722).[82,83,84] There also exists specialty integrated sampler and analyzer that can provide reliable in situ mercury analysis, especially in coal.

[80] ASTM International, ASTM D2234/D2234M Standard practice for collection of a gross sample of coal.
[81] Canadian Electricity Association, CEA mercury program website.
[82] ASTM International, ASTM D6414 – 01(2006) Standard test methods for total mercury in coal and coal combustion residues by acid extraction or wet oxidation/cold vapour atomic absorption.

Mercury transfer rates in coal and residues are obtained from the measured concentrations in samples and the coal consumption (residues generation) rates for a specific period of time. The difference between the mercury input rate in coal and output rates in coal combustion residues results in an airborne mercury emission rate.

Table 3-6: Assessment of mass balance approach for mercury monitoring

Criteria	Comments	Grade
Measurement frequency	o Sampling and analysis can be done as often as the operator wants in accordance with the specifications of the regulation. o Weekly composite sampling (i.e. 1 per day) is more than sufficient. In some cases, monthly composite sampling provides equivalent results. o For coal, there exists specialty integrated analyzers providing real-time elemental mercury analysis.	Indefinite
Accuracy and uncertainties	o Mercury laboratory analysis of samples provides accurate results. o Solid sampling is mostly responsible for inaccuracies since it may not be representative of long term average. High frequency composite sampling or on-line analysis may improve the situation. o Several Canadian EGUs have obtained comparable results (< 10%) with wet chemistry stack tests.[85] o Large number of residues (incl. coal) for analysis amplifies overall inaccuracy.	low
Detection limit	o Not relevant to mercury vapour as the measurements are made on coal and coal combustion residues. o Cold vapour atomic absorption spectrometry used in laboratory can achieve very low detection limits (i.e. 1 ppt) which is rarely required for coal and coal combustion residues (> 1 ppb).	Good
Reliability	o Manual sampling is not a problem. o Laboratory analyses are normally duplicated for validation. o Reliability problems may appear from auto-sampling devices or mercury contamination.	Good
Practicality and extent of application	o Easily applicable method. Not cumbersome. o Method actually in use by NS Power, SaskPower, Ontario Generation Power and Manitoba Hydro for compliance purpose.[86]	Yes
Costs	o Outside laboratory analysis covers most of the costs (300–400 $/sample). o $5k/a for plant technician labour is considered. o (*) for monthly analysis, 3 composite samples.	$15–20 k/a *
Advantages	o Provides accurate measurements of mercury content in coal and coal combustion residues = accurate mercury emission estimation (all sampling uncertainties aside). o Not highly expensive method.	
Limitations	o Do not provide real-time data often necessary for compliance. o Uncertainties from sampling (i.e. short term variations) and contamination/loss. o Large number of solid medium to analyse decreases the method's accuracy.	

[83] ASTM International, ASTM D3684 – 01(2006) Standard test method for total mercury in coal by the oxygen bomb combustion/atomic absorption method.
[84] ASTM International, ASTM D6722 – 01(2006) Standard test method for total mercury in coal and coal combustion residues by direct combustion analysis.
[85] Canadian Electricity Association, Canada-wide standard for mercury emissions from coal-fired electric power generation plants, Progress report 2008, personal communication.
[86] Ibid.

3.3.3 Wet chemistry stack testing

Source stack testing requires the installation of a stack-sampling train to collect continuous samples of flue gas for a short period of time. The train consists generally of an isokinetic nozzle, a heated filter to capture fly ash and a liquid and/or solid sorption system that can capture specific gaseous pollutants. Flue gas velocity, temperature, oxygen, carbon dioxide and moisture content are usually quantified simultaneously. During sampling campaigns, all plant conditions like power generation, coal feed rate, air flow, etc., should be stabilized for a few hours prior to start-up and should be maintained as such until the end of sampling. Likewise, the boilers' operating conditions during the test period should be representative of normal conditions if it is used to estimate long term projections. Several sampling protocols have been developed over the years to capture mercury emissions. For coal-fired boilers, recognized protocols include EPA Method 29,[87] EPA Method 101A,[88] EN-13211[89] and Ontario Hydro Method.[90] Other methods have been and are still considered to improve the mercury selectivity in aqueous solutions but are rarely applied today.

The EPA Method 29 protocol (also known as EPA Method 0060) is a stack emission monitoring method for multiple metals. Gaseous metal emissions are collected in a succession of aqueous acidic solution of hydrogen peroxide (2 impingers) and aqueous acidic solutions of potassium permanganate (2 impingers) separated by an empty impinger. The EPA Method 101A protocol, measuring total mercury exclusively, uses potassium permanganate solutions only. A desiccant-filled impinger completes the train removing moisture before the gas sample volume can be quantified. The European standard EN-13211 is similar to the EPA methods as it applies isokinetics, particulate filtration and two impinger solutions of acidic potassium permanganate or potassium dichromate to capture total mercury vapours. These solutions are however ineffective for mercury speciation according to their oxidation states (Hg^0, Hg^{2+}). Modifications to the EPA Method 29 were researched and proposed to make up for this limitation and classify mercury emissions by oxidation states (Hg-bound, Hg^{2+}, Hg^0).

The Ontario Hydro Method (OHM, ASTM D6784-02) is an off-shoot of the EPA Method 29 protocol. The CCME CWS monitoring protocol recommends it for the measurement of independent mercury emissions by oxidation state. Developed in 1994, this method is applicable for mercury concentrations between 0.5–100 $\mu g/Nm^3$. Gaseous emissions are collected successively in three solutions of potassium chloride (Hg^{2+} capture), one acidic solution of hydrogen peroxide (Hg^0 capture) and three acidic solutions of potassium permanganate (Hg^0 capture). The heated filter prior to the impinger train captures particle-bound mercury. After sampling, aliquots of individual impinger solutions are prepared and shipped to an accredited laboratory for analysis according to an established standard (i.e. EPA 1631, EPA 7471A). Cold-vapour atomic absorption spectroscopy (CVAAS) and atomic fluorescence spectrometry (CVAFS) are standard systems for accurate quantification of mercury in solutions.

[87] U.S. EPA, Emission Measurement Center – Method 29: Metals emissions from stationary sources.
[88] U.S. EPA, Emission Measurement Center – Method 101A: Mercury from sewage sludge incineration.
[89] European Committee for Standardization, EN 13211:2001 – Air quality: Stationary source emissions. Manual method of determination of the concentration of total mercury, August 2001.
[90] ASTM International, ASTM D6784 – 02(2008) Standard test method for elemental, oxidized, particle-bound and total mercury in flue gas generated from coal-fired stationary sources (Ontario Hydro Method).

Table 3-7: Assessment of wet chemistry stack testing for mercury monitoring

Criteria	Comments	Grade
Measurement frequency	o Sample is collected continuously over a few hours. o Sampling could be performed every week but this is not practical and is expensive. A campaign is usually performed once or twice per year unless the regulation indicates otherwise. Many U.S. states regulations require quarterly monitoring campaigns.	1-4 times/a
Accuracy and uncertainties	o Mercury analysis procedures are standardized so it provides accurate results. Duplication further reduces uncertainties on that respect. o Uncertainties are more prominent during sampling which requires extensive analytic recovery and preparation steps that may introduce contamination or result in a loss of mercury. o Strict adherence to the protocol, leak free system, proper calibration of system components and proper sampling location all improves the precision of results. o The periodicity of stack testing, although performed during normal operation, is also responsible for uncertainties on long term projections.	Med
Detection limit	o CVAAS used in labs can achieve very low detection limits (<1 ppt) in liquid samples. CVAFS has better detection limit than CVAAS (<0.1 ppt). o According to the OHM method, accurate detection is achievable for concentrations higher than 0.5 μg Hg/Nm^3 gas. It may not be reliable for low mercury emitters (< 20 kg/a) with substantive power production. At minimal detection and a typical flow rate of 4 Nm^3/kWh_e, the annual mercury output would be 6 kg/a for a 400 MW_e power plant operating at 80% capacity.	Good
Reliability	o Laboratory analyses are normally duplicated for validation. o Complex sampling trains with glassware, filters, tubing and electronic devices are not full proof against a failure. However, if detected, the sampling campaign can be resumed later.	Good
Practicality and extent of application	o Easiest and cheapest method for reliable results. o Widely considered in various industries for mercury emissions including the coal-fired electric power sector. o Method applied for flue gas characterisation during the CEA mercury program o OHM method and EPA Method 29 are approved by Alberta Environment for mercury monitoring.[91] o Some U.S. states impose stack testing to monitor mercury emissions for compliance (mainly for regulations developed prior to the U.S. EPA CAMR)	Yes
Costs	o Sampling and analysis campaign ($3–5k) from an independent consultant + overhead for assistance and management. o (*) quarterly analysis	$20–25 k/a *
Advantages	o Minimal infrastructure investment required. o Accurate measurement for a short period of operation.	
Limitations	o Do not provide real-time data often necessary for compliance. o Wet chemistry stack testing engages extensive procedures (sampling, sample management, laboratory analysis, post-analysis). o Uncertainties from sampling (i.e. short term variations), contamination and mercury loss. o Could produce bias if the measurements are used for annual projections.	

[91] Canadian Electricity Association, Canada-wide standard for mercury emissions from coal-fired electric power generation plants, Progress report 2008, personal communication.

3.3.4 Continuous emission monitoring (CEMS)

Continuous emission monitoring systems (CEMS) detects vapour-phase mercury emissions on site from samples extracted continuously from the stack. Some systems dilute the extracted sample prior to analysis. Most advanced mercury CEMS integrate the following components: heated sampling probe, heated sample line, oxidized mercury converter, sample conditioning, remote mercury analyser, elemental and oxidized mercury calibrators and data recorder.[92,93]

After extraction through a heated probe, the sample is routed through a heated tube to the remote analyser where mercury is detected by either cold-vapour atomic absorption or atomic fluorescence (most sensitive technique). However, the analysers respond only to elemental mercury. Oxidized mercury (Hg^{2+} species) must therefore be transformed into its elemental state prior to analysis which is a burdensome process. Hg^{2+} conversion in commercial CEMS is generally done by wet chemistry or thermal catalysis which can also remove other interfering gases (i.e. SO_2, NO_X) detrimental to accurate mercury detection. For many systems, the conversion process takes place at the probe to avoid potential problem with Hg^{2+} during transport. Sample conditioning including PM and moisture removal is also necessary prior to analysis.

Regardless of the measurement technique or conversion system, all instruments must have an auto-calibration system. All CEMS are zeroed by passing a mercury-free sample gas through the analyzer. Several methods are available to set up the span value or upper-limit concentration (i.e. manual injection, use of calibration gas, sealed cell containing a drop of elemental mercury). Capable CEMS have remote diagnostic capabilities allowing for problem diagnosis. In such case, internal system variables (i.e. pressure regulators, temperatures, sample flow) are displayed and are range checked against error limits. Error alarming provides an indication of system problems and QC failures for the CEMS.

Table 3-8 Assessment of continuous mercury monitoring system

Criteria	Comments	Grade
Measurement frequency	o Provides real-time data (every few minutes) often necessary for compliance.	Continuous
Accuracy and uncertainties	o Accurate and repeatable detection of total mercury emissions within 10% provided the QA/QC requirements for CEMS are respected. [94] o Confidence in results is conditional to a 'clean' sample mostly exempted of PM and interfering gases during detection. Installation of air pollution control prior to the CEMS improves the quality of mercury detection. o Confidence in long term average (i.e. 12-month rolling average) from CEMS measurements is good.	High
Detection limit	o The minimum detection limit for most commercial CEMS today is lower than 0.1 $\mu g/Nm^3$.	Good

[92] Electric Power Research Institute, Continuous mercury monitoring guidelines, March 2007.
[93] Canadian Electricity Association, Mercury Information Clearinghouse – Quarter 2: Mercury measurement, April 2004.
[94] Lehigh University Energy Research Center, Armstrong Project: Evaluation and comparison of U.S. and EU reference methods for measurement of mercury, heavy metals, $PM_{2.5}$ and PM_{10} emissions from fossil-fired power plants, February 2007.

Criteria	Comments	Grade
Reliability	o Mercury sampling and detection is reliable unless the sample is dirty. Most reliability problems are related to the Hg^{2+} converter setup (i.e. maintenance required). It varies with the quality of the CEMS. o Internal diagnostics of CEMS allow detection of problems from the instrument itself or the EGU operation. o Reliable for low mercury emitters (< 20 kg/a) with substantive power production. At minimal detection (0.1 μg/Nm^3) and a typical flow rate of 4 Nm^3/kWh_e, the annual mercury output would be 1.1 kg/a for a 400 MW_e power plant operated at 80% capacity.	Good
Practicality and extent of application	o CEMS is one of the recommended approaches by the CCME CWS monitoring protocol to measure total mercury. o U.S. EPA CAMR (prior to vacancy) was imposing the use of continuous monitoring as part of the mercury reduction program. It included CEMS and dry sorbent trap monitoring (see next). o Europe considers certified mercury CEMS in the field of municipal and hazardous waste combustion.	Yes
Costs	o Mercury CEMS unit cost approaches $125k. o Supplemental 30–50% for auxiliary systems, facilities and installation should be considered. o Labour and system performance testing during installation adds another 40–60%. o Day-to-day operation, consumables and annual RATA = $50–90k	Inst: $200–300k Op.: $50–90 k/a
Advantages	o Real-time data. Provide most accurate way to calculate annualized mercury emissions. o Automatic operation with a data logger. o Can provide an evaluation of mercury control strategies. o Provides greater understanding of process variability and operation.	
Limitations	o Particulate-bound mercury is not quantified since it is previously filtered from the gas sample. Similarly, vapour-phase mercury detection can be biased if the captured particulates are reactive towards mercury. o Challenges are expected for long-term, low-maintenance continuous operation and in collecting a representative sample for mercury analysis due to flue gas chemistry, particulate loading and high temperatures. o Monitoring of dirty flue gas is problematic. An efficient particulate control system should be ideally installed prior to the CEMS. Interfering gases such as carbon monoxide, sulphur oxides, nitrous oxides and others may also hamper clear mercury detection. o Wet chemistry Hg^{2+} conversion producing a large amount of waste (> 1 litre/day) is the limiting factor for reliable CEMS. Spent reagents are hazardous and must be treated as such. Thermal catalytic Hg^{2+} conversion produces less waste (< 1 litre/week) but may be sensible to high acid gas conditions. o Wet flue gas (i.e. following a wet scrubber) makes representative sampling difficult. o Operation and maintenance requires trained technicians. o Inexistence (as of late 2009) of NIST traceable protocols for mercury field calibrators and mercury gas cylinders.	

3.3.5 Dry sorbent trap monitoring

Dry sorbent trap monitoring relies on the capture of vapour-phase mercury on a solid medium through adsorption, diffusion and ion exchange phenomena. In contrast to wet chemistry absorption, solid sorbents offer greater stability and easier handling as well as the possibility to selectively capture Hg^{2+} and Hg^{0} species. Typical dry sorbent trap monitoring systems include the following components: isokinetic nozzle, PM filter, heated probe, paired sorbent traps, moisture removal system (i.e. chiller, desiccant), certified dry gas volumetric flow meter and data logger system.[95,96]

Normal operation consists of extracting a known volume of flue gas through paired parallel sorbent traps supported by a probe directly inserted into the stack. This configuration minimizes potential mercury loss during transport through a sample line. Paired train sampling is required to determine the method precision and verify the adequacy of the results. Individual sample collection period can range from several minutes to several days depending on flue gas flow rate, mercury concentration and sorbent mercury capacity. After sampling, the dry sorbent traps are retrieved, sent to a laboratory (external or in-house), conditioned and analysed for mercury with a suitable method. Mercury recovery techniques from the sorbent matrix includes but is not limited to acid leaching, strong acid digestion and thermal desorption. Meanwhile, particulate-bound mercury captured on the micro-filter is usually desorbed by heat prior to analysis. Mercury detection is carried out using a CVAAS or CVAFS.

According to the U.S. EPA CAMR, the sorbent medium (i.e. iodine-impregnated activated carbon, KCl-coated quartz filter) must be configured in a cylindrical trap with three serial segments that can be analysed separately. The first section aims to capture vapour-phase mercury while the second section verifies the potential breakthrough which should be kept to a minimum (<5% of section 1 mercury content). The final section which is previously spiked with a known elemental mercury quantity is intended for QA/QC of the analytical method. However, accurate spiking (i.e. mercury purging into the sorbent) is a difficult task inducing possible uncertainties. The sorbent media must be obtained from a source that can demonstrate QA/QC to ensure consistent reliability.

Table 3-9 : Assessment of dry sorbent trap mercury monitoring

Criteria	Comments	Grade
Measurement frequency	o Provides continuous sampling for a short-to-medium period of time depending on the sorbent mercury capacity and flue gas mercury concentration. Time-averaged concentrations are obtained. o Sampling train can be fixed permanently. Only sorbent traps are replaced regularly in order to comply with regulations.	Continuous

[95] Canadian Electricity Association, Mercury Information Clearinghouse – Quarter 2: Mercury measurement, April 2004.
[96] Electric Power Research Institute), Continuous mercury monitoring guidelines, March 2007.

Criteria	Comments	Grade
Accuracy and uncertainties	o Comparable results (±15%) with the wet chemistry OHM method were obtained in a previous study.[97] o Accurate detection of total mercury emissions by labs. o Uncertainties caused by mercury loss or contamination are possible. Attention should be paid to cleanliness during transport, handling and laboratory analysis. o Confidence in results is conditional to a particle-free flue gas which could disturb proper operation (i.e. filter plugging). Installation of an efficient PM control system is recommended. o Confidence in long term average (i.e. 12-month rolling average) from dry sorbent trap monitoring is good as long as the EGU operation is relatively stable.	High
Detection limit	o Low detection limit: 0.03 $\mu g/Nm^3$ for typical sampling duration. o Expanding the sampling duration will enable the user to reach lower detection limits, if required. It increases though the uncertainty for long-term projections.	Very good
Reliability	o Laboratory analyses are normally duplicated for validation. Multi segment sorbent traps improve the reliability of results (spiked mercury third section acts as calibrator). o Simultaneous operation of two sorbent traps in parallel allows for the detection of corrupted samples. o Auxiliary systems are not full proof against a failure. Unless noticed on place, unreliable results may not be detected rapidly. Laboratory results may be obtained several weeks after sampling. o Method is not reliable if the flue gas contains large amounts of fine particulate matter. o Reliable for low mercury emitters (< 20 kg/a) with substantive power production. At minimal detection (0.03 $\mu g/Nm^3$) and a typical flow rate of 4 Nm^3/kWh_e, the annual mercury output would be 0.3 kg/a for a 400 MW_e power plant operated at 80% capacity.	Good
Practicality and extent of application	o Dry sorbent trap monitoring is a recommended alternative to CEMS for long-term mercury measurement under the vacated U.S. EPA CAMR. o Method has been tested conclusively on coal combustion units.	Yes
Costs	o Dry sorbent trap hardware installation cost including performance testing is on the order of 1/4 to 1/3 of that of a typical CEMS. o Day-to-day operation, maintenance and annual RATA = $30–70k. o Laboratory costs: $60–80 k (200 samples/a; $400/sample). o (*) these costs are based on external lab analysis. An alternative to decrease O&M costs is to purchase a sorbent trap mercury analyser and perform the analyses on-site (see Section 5.3 for details).	Inst: $40–60 k * Op.: 90–150 k/a *
Advantages	o Relatively simple concept with high flexibility of operation (flexible sampling period and frequency). o Becomes a viable option for low emitting sources since the sample volume can be adjusted accordingly. With possible implementation of effective mercury control technologies, it could become an important tool in monitoring ultra low concentrations. o High frequency sampling provides pseudo real-time data. Averaging will provide acceptable annualized mercury emission rates. o Strict QA/QC procedures improve the confidence on measured emission rates. o No interference from other gases.	

[97] Lehigh University Energy Research Center, Armstrong Project: Evaluation and comparison of U.S. and EU reference methods for measurement of mercury, heavy metals, $PM_{2.5}$ and PM_{10} emissions from fossil-fired power plants, February 2007.

Criteria	Comments	Grade
Limitations	o System designed for low-dust conditions. o System failure may not be detected immediately which can corrupt several days/weeks of measurement.	

3.3.6 Semi-continuous CEMS monitoring

CEMS and dry sorbent trap monitoring systems are mounted permanently but there exists field-transportable instruments that can be installed temporarily for the measurement of total mercury emissions. Although such system is specially designed for testing and certification of permanent CEMS, it can still be considered for periodic sampling and analysis campaigns providing the stack sampling platform makes it possible. Set-up and take-down are usually done within a day or so. Portable CEMS components and operation procedure are similar to permanent CEMS as it uses CVAAS for mercury detection and thermal catalysis to convert Hg^{2+} species into elemental mercury (see Section 3.3.4).

Table 3-10 : Assessment of CEMS mercury monitoring for semi-continuous operation

Criteria	Comments	Grade
Measurement frequency	o Provides real-time data (every few minutes) for a specific period of time. This procedure can be repeated several times per year.	Semi-continuous
Accuracy and uncertainties	o Accuracy and uncertainties during sampling and analysis are equivalent to permanent CEMS (see Table 3-8). o Set-up and take-down of CEMS increase possible uncertainties. It requires a thorough quality check prior to each sampling campaign. o Annual average quality is dependant on sampling duration and annual frequency.	Good
Detection limit	o Equivalent to permanent CEMS (<0.1 $\mu g/Nm^3$).	Good
Reliability	o Equivalent to permanent CEMS (see Table 3-8).	Good
Practicality and extent of application	o Practicality is similar to permanent CEMS but not commonly applied in the industry. o Mostly applicable for permanent CEMS system check and certification.	No
Costs	o Purchase cost is similar to permanent CEMS. However, if bought, the portable CEMS would be installed permanently. o Equipment lease fee is unknown. o Day-to-day operation, maintenance and annual RATA = $20–50 k.	
Advantages	o Technical advantages are equivalent to permanent CEMS (see Table 3-8). o Annual cost is reduced compared to permanent CEMS.	
Limitations	o Technical limitations are equivalent to permanent CEMS (see Table 3-8). o Quality of annual averages is reduced compared to permanent CEMS.	

3.3.7 Summary

A summary regrouping key elements from mercury monitoring methods described above is given in Table 3-11.

Table 3-11 : Overview of mercury monitoring regimes according to specific performance criteria

Criteria	Predictive	Mass balance	Stack testing	CEMS [a]	Dry sorbent trap
Measurement frequency	Not applicable	Discontinuous Several sampling & analysis are required annually (typically once per week)	Continuous sampling for a few hours Sampling campaign 1–4 times per year	Real-time data	Continuous sampling for a short-to-medium period (typically 1–7 days)
Accuracy and uncertainties	Very low	Lab analysis accurate Solid (and liquid) sampling responsible for uncertainties	Sampling and analysis procedures are accurate Strict application of QA/QC reduces uncertainties significantly	± 15% vs. stack testing Strict application of QA/QC and referenced procedures reduce uncertainties significantly	Comparable accuracy with stack testing method Uncertainties associated to mercury loss and sample quality
Detection limit	Not applicable	Very low detection limit for coal and coal combustion residues analysis (< 1 ppt)	Sampling procedure: 0.5 $\mu g/Nm^3$ CVAAS analysis: 0.1–1 ppt	Typically < 0.1 $\mu g/Nm^3$	Typically < 0.03 $\mu g/Nm^3$
Reliability	Not applicable	Reliable sampling procedure involving multiple sampling	Sampling campaign is reliable if QA/QC procedures are respected Multiple laboratory analyses are performed	Reliability problems may appear if sample is dirty Frequent maintenance by trained personnel is required	Sampling campaign is reliable if QA/QC procedures are respected Two sorbent traps are operated simultaneously
Practicality and extent of application	Not practical for a compliance program	Easily applicable method Method applied during the CEA mercury program	Widely used for gas characterisation campaigns Considered during the CEA mercury program	Recommended by the vacated U.S. EPA CAMR and several U.S. states regulations	Recommended as an alternative by the vacated U.S. EPA CAMR
Costs [b]	< $10k	$15–20k annually for monthly analysis	$3–5k/campaign $20–25k annually for quarterly campaigns	$200–300k investment $50–90k annually	$40–60k investment $90–150k annually
Key advantages	Easy of application	Not highly expensive method	Minimal investment required Accurate snapshot monitoring	Real-time data Can provide an evaluation of mercury control strategies	Good option for low mass emitters (low detection limit) No interference from other gases
Key limitations	Inaccurate and uncertain predictions	Do not provide real-time data & uncertainties associated to sampling	Do not provide real-time data, contamination & mercury loss	Particulate-bound mercury not measured Interfering gases may affect Hg detection	Not reliable for dirty gas Sorbent trap analysis in lab can be time consuming

[a] Includes semi-continuous monitoring.

[b] Cost values presented here (and previous sections) correspond to initial approximation taken from literature and personal knowledge. More detailed/precise cost estimates are provided in Section 5.

3.3.8 Mercury monitoring regimes applied in Canada

Since the inauguration of the Canada-Wide Standards in 2006, the Canadian coal-fired EGUs are required to monitor and report their mercury emissions to the CCME every year until 2010 and every two years thereafter. They must apply one of the monitoring approaches recommended in the CCME monitoring protocol including CEMS, mass balance or any other equivalent method shown to be as accurate (within ±20% of what is normally obtained by stack testing and mass balance approaches).[98] The monitoring protocol also requires facilities to perform annual wet chemistry stack testing (Ontario Hydro method) from 2008 to 2011 for the speciation of mercury emissions. Mercury content in coal and coal combustion residues during that same period must be reported as well. Table 3-12 exposes, by province, the mercury monitoring regime applied by EGUs until recently and what is expected in the near future (2010+).

As of 2008, all provincial jurisdictions have approved the use of a mercury mass balance approach to assess the annual airborne mercury emissions. Specific procedures are based on the guidance document developed in 2003 for the Canadian Uniform Data Collection Program (UDCP)/CEA mercury program. Amendments were proposed to adapt to the units' situations (i.e. sampling frequencies). No change in mercury monitoring programs is expected in the near future except for Alberta which by law requires their EGUs to install a continuous emission monitoring system (CEMS) or an equivalent program for compliance purposes. Although the significance of 'equivalent program' has not been specified in the regulation, it is understood that any of the monitoring regimes recommended in the CCME CWS monitoring protocol would be eligible as long as it is established that they are as accurate as mercury CEMS.

[98] Canadian Council of Ministers of the Environment, Monitoring protocol in support of the Canada-wide standards for mercury emissions from coal-fired electric power generation plants, July 2007.

Table 3-12 : Mercury monitoring regimes for CCME CWS compliance

Province	Recent monitoring (2008 report)[99]	Near future monitoring
Alberta	o **Mass balance approach** including weekly coal composite samples (if manual: 3–7/week, if automatic: 3/day), weekly fly ash composite samples (3/week), weekly bottom ash composite samples (1-3/boiler) & periodic quench water analysis. o Annual wet chemistry stack testing for mercury speciation & validation of the mass balance approach.	o Alberta Environment regulation request installation of a continuous emission monitoring system (CEMS or an equivalent program) by 2011. o Equivalent program relates to any method able to obtain equivalent results than CEMS (refer to CCME CWS monitoring protocol)
Manitoba	o **Mass balance approach** according to the UDCP guide including weekly composite samples (3/day) & periodic bottom ash samples. o Annual wet chemistry stack testing for mercury speciation (inlet and outlet of ESP) & validation of the mass balance approach.	o No change in sight. o May not be required anymore since coal was phased out from the Brandon EGU since January 2010.
New Brunswick[100]	o **Mass balance approach** including weekly composite sample of coal, ash and gypsum (once per month). o Source stack testing is also required once every two years.	o No change in sight.
Nova Scotia[101]	o **Mass balance approach** following the UDCP guideline.	o No change in sight.
Ontario	o **Mass balance approach** including weekly (or monthly) coal composite samples, weekly (or monthly) fly ash composite samples, weekly (or annual) bottom ash samples & monthly gypsum (incl. FGD sludge) samples, when applicable.	o No change in sight since the coal-fired EGUs will be phased out by 2014.
Saskatchewan	o **Mass balance approach** in accordance with the agreement between SaskPower and Saskatchewan Ministry of Environment. It includes biweekly coal composite samples (3/day), biweekly fly ash samples & periodic bottom ash samples (usually on a quarterly basis). Mercury analysis is performed at SaskPower's in-house laboratory.	o No change is sight.

3.4 Monitoring mercury emissions in solid and liquid media

As discussed earlier, the mercury initially present in the burned coal can be found after combustion in the residual fly ash, bottom ash, boiler slag, quenching water and flue gas desulfurization (FGD) material of the combustion process. The FGD material refers to the scrubber sludge and/or liquor. Mercury monitoring in solid and liquid effluents from coal combustion is normally performed with direct measurement methods.

[99] Canadian Electricity Association, Canada-wide standards for mercury emissions from coal-fired electric power generation plants, Progress report 2008, personal communication.
[100] Government of New Brunswick, Approval to operate D-6923 New Brunswick Power Generation Corporation for the operation of the Belledune thermal generating station, 2010.
[101] Nova Scotia Environment, personal communication, 2010.

Although theoretical estimation of mercury content in coal combustion residues can be derived based on raw coal mercury composition, predictive methods are not used because direct measurement are far more accurate and reliable and relatively easy to perform. Mass balance methods are also not used to estimate the emissions of mercury in solid and liquid waste since this would require that air emission of mercury be determined. In practice, it is easier to determine the solid and liquid emissions of mercury and therefore the mass balance is used to determine those specific mercury air emissions which are more complex to obtain.

Direct measurement is a more precise method in determining mercury emissions since it implies only one level of accuracy (measuring point). It depends however on the method of operation (automatic composite sampling or manual sampling). Fly ash can be sampled either during conveying to temporary onsite storage or directly from the hopper of electrostatic precipitators or fabric filters although the latter involves some safety risks. Bottom ash is typically sampled during conveying to temporary onsite storage but again it may be achievable only after quenching for safety reasons.

3.4.1 Automatic composite liquid/solid sampling and analysis

Representative samples should be collected preferably using an automatic sampler according to the ASTM standard D2234[102] or D7430.[103] Standard practices for the automatic sampling of coal combustion residues like fly ash have not been established. A composite sample taken automatically and periodically is considered to be more representative than a manual sample. Special care should be taken throughout the procedures to ensure that mercury contamination does not occur.

The samples are then analysed by an accredited lab station according to a recognized standard (coal: ASTM D6414[104], D3684[105], D6722[106], EPA 7473[107]; solid residues: ASTM D6414, D6722, EPA 7473, 7471[108]; liquid residues: EPA 7473, 1631[109]).

[102] ASTM International, ASTM D2234/D2334M Standard practice for collection of a gross sample of coal.
[103] ASTM International, ASTM D7430–10a Standard practice for mechanical sampling of coal.
[104] ASTM International, ASTM D6414 – 01(2006) Standard test methods for total mercury in coal and coal combustion residues by acid extraction or wet oxidation/cold vapour atomic absorption.
[105] ASTM International, ASTM D3684 – 01(2006) Standard test method for total mercury in coal by the oxygen bomb combustion/atomic absorption method.
[106] ASTM International, ASTM D6722 – 01(2006) Standard test method for total mercury in coal and coal combustion residues by direct combustion analysis.
[107] U.S. EPA, Test methods for evaluating solid waste, physical/chemical methods (SW-846) – Method 7473: Mercury in solids and solutions by thermal decomposition, amalgamation and atomic absorption spectrophotometry.
[108] U.S. EPA, Test methods for evaluating solid waste, physical/chemical methods (SW-846) – Method 7471B: Mercury in solid or semisolid waste (manual cold-vapour technique).
[109] U.S. EPA, Clean Water Act Analytical methods – Method 1631: Mercury in water by oxidation, purge and trap, and cold-vapour atomic fluorescence spectrometry.

Table 3-13: Assessment of automatic composite sampling and analysis method for mercury monitoring in liquids and solids

Criteria	Comments	Grade
Measurement frequency	o Automatic sampling can be programmed to be done as often as the operator wants.	Indefinite
Accuracy and uncertainties	o Mercury laboratory analysis provides accurate results as long as QA/QC procedures are respected. o High frequency automatic sampling provides results that are representative of long term average. o Each residue and process effluent is sampled and analysed separately, limiting the compounding of inaccuracy.	Good
Detection limit	o CVAAS used in laboratory can achieve very low detection limits (i.e. 1 ppt) which is rarely required for solid and liquid effluents from coal-fired EGUs (> 1 ppb).	Good
Reliability	o Laboratory analyses are normally duplicated for validation. o Reliability problems may appear from auto-sampling devices or mercury contamination.	Good
Practicality and extent of application	o Easily applicable method. Not cumbersome.	Yes
Costs	o Outside laboratory analysis covers most of the costs (300–400 $/sample). o $5k/a for plant technician labour is considered. o (*) for monthly analysis, 3 composite samples.	$15–20 k/a *
Advantages	o Provides accurate measurements of mercury content in coal, coal combustion residues and process effluents. o Not highly expensive method.	
Limitations	o Do not provide real-time data. o Uncertainties from sampling (i.e. short term variations) and contamination.	

3.4.2 Manual liquid/solid sampling and analysis

In absence of an auto-sampler, manual sampling can still be considered as long as it is safe for the operator. The sampling frequency is determined in order to provide adequate representativeness of the results (i.e. weekly monitoring, after changes in operating conditions, etc.). Standard practices for manual sampling of coal exist for different situations (i.e. ASTM D683[110], D2234[111]) but not for coal combustion residues. Many standards exist for the collection of soil depending on the method (i.e. surface, sub-surface, etc.). As a rule, homogeneous composite samples that are representative of the material and location should be collected. The samples are then analysed by an accredited lab station according to ASTM standards as described in the previous section. The sampling of the various solids and liquid effluents should be synchronized. This allows the use of mass balance as a means of data verification.

[110] ASTM International, ASTM D6883 – 04 Standard practice for manual sampling of stationary coal from railroad cars, barges, trucks or stockpiles.
[111] ASTM International, ASTM D2234/D2334M Standard practice for collection of a gross sample of coal.

Table 3-14: Assessment of manual sampling method and analysis for mercury monitoring in liquids and solids

Criteria	Comments	Grade
Measurement frequency	o Sampling and analysis can be done as often as the operator wants.	Indefinite
Accuracy and uncertainties	o Mercury laboratory analysis provides accurate results. o Manual sampling provides results that are subject to process variations and therefore not necessarily representative of long term average. o Each residue and process effluents is sampled and analysed separately, limiting the compounding of inaccuracy.	Low
Detection limit	o CVAAS used in laboratory can achieve very low detection limits (i.e. 1 ppt) which is rarely required for solid and liquid effluents from coal-fired EGUs (> 1 ppb).	Good
Reliability	o Laboratory analyses are normally duplicated for validation.	Good
Practicality and extent of application	o Easily applicable method. o Part of the mass balance method used during the CEA mercury program.	Yes
Costs	o Outside laboratory analysis covers most of the costs (300–400 $/sample). o $5k/a for plant technician labour is considered. o (*) for monthly analysis, 3 composite samples.	$15–20 k/a *
Advantages	o Provides accurate measurements of mercury content in coal combustion residues and process effluents. o Not highly expensive method.	
Limitations	o Obtaining representative samples can be time-consuming o Uncertainties from sampling (i.e. short term variations) and potentially low representativeness.	

3.5 Recommended best option for airborne mercury monitoring

A monitoring regime that can verify with confidence the compliance of airborne mercury emissions from coal-fired EGU stacks must provide reliable, accurate and traceable measurements. In achieving so, the method would consistently quantify total mercury emission rates with a maximum deviation of ±10%. Due to the possible inherent fluctuation in power plants' operation (i.e. coal mercury content variation, coal input, etc.), total assurance that compliance is respected at all time can only be obtained with high frequency direct measurements. To achieve this level of certainty, it is recommended to install and operate an electronic continuous emission monitoring system (CEMS) integrated to the stack following a dust removal technology.

Despite the high accuracy potential, a number of key issues have plagued its reliability over time (i.e. accurate detection of low Hg concentrations, presence of potentially interfering substances like PM, HCl, SO_X and NO_X, adsorption of mercury on filtered fly ash at the probe, physical plugging of the probe, etc.). Improvement of CEMS design and performance has been on going. A U.S. EPA field evaluation of commercial CEMS in 2006 has found that most systems had difficulties at times meeting the certification criteria (i.e. linearity test, system integrity test, drift

test, relative accuracy test).[112] The problems of the mercury CEMS were more mechanical than chemical and analytical. They also noted that the flue gas characteristics can have a significant effect on CEMS performance and that the commercial system should be adapted in consequence. In view of that, they recommended operating the CEMS initially under a performance warranty agreement with the vendor to demonstrate its capability to perform on a long run (i.e. several months) under the site-specific conditions.

Although recurring technical problems have weakened the confidence in this technology, this rapidly developing field has demonstrated more recently that it could achieve accurate measurements and that reliability is improving. Field-testing of several commercial devices has demonstrated the good performance of CEMS within ± 15% of measurements realized simultaneously with the Ontario Hydro stack testing method.[113] Although good performances are achievable, the need for trained personnel to operate them, and the significant burden on time for set-up, space, power and temperature control are required. Research has shown that commercially available mercury CEMS are currently not capable of operating unattended to produce reliable and accurate emission data.[114]

This being said, other monitoring regimes do not provide the level of accuracy and assurance that CEMS provides. Dry sorbent trap is close but provides only time average measurements potentially on several days at a time. High mercury content in flue gas would reduce sampling duration per sorbent trap but it would come to a cost. Other methods like wet chemistry stack testing and mass balance calculation can also deliver acceptable mercury emission rates. However, the periodicity of the sampling campaigns increase the uncertainty associated with airborne mercury fluctuations. Such regimes would require the planning of multiple sampling campaigns making it onerous as well. Mercury CEMS is also an excellent tool for assessing the efficiency of mercury control strategies. With real-time data, it provides means to optimize mercury capture (i.e. sorbent injection capacity and distribution) at lowest possible cost. Other monitoring systems do not offer the same level of flexibility for optimization.

Installation of mercury CEMS has been promoted for coal-fired EGU stack testing in other jurisdictions. In response to the U.S. EPA CAMR in 2005, it has been estimated by the EPRI that orders for over 600 CEMS has been placed, as of April 2008, before the rule was vacated. By that time, fewer than 50% of the CEMS were installed.[115] Still, the orders were shipped even if a number of key issues remained to be resolved including the inexistence of NIST traceable field calibrators. In Europe, mercury CEMS has been implemented for a longer time specially for the monitoring of mercury in flue gas from mixed waste incinerators.

[112] U.S. EPA, Long-term field evaluation of mercury continuous emission monitoring systems: Coal-fired power plant burning eastern bituminous coal and equipped with selective catalytic reduction, electrostatic precipitator, and wet scrubber: Field activities from Nov. 2004–Sept. 2005, November 2006.
[113] Lehigh University Energy Research Center, Armstrong Project: Evaluation and comparison of US and EU reference methods for measurement of mercury, heavy metals, PM2.5 and PM10 emissions from fossil-fired power plants, February 2007.
[114] Laudal, D. L. et al., Use of continuous mercury monitors at coal-fired facilities, Fuel Processing Technology, 85 (7-7), 2004, p. 501.
[115] Continuous Emissions Monitoring Users Group (CEMUG), Lessons learned from CEMUG conference, 7th annual conference, Nashville, TN, May 2008.

3.5.1 Description

Several CEMS are commercially available which all have their own specifications. The basic components of any mercury CEMS provided in the same package are:

- Heated sampling probe
- Probe controller
- Heated sample line
- Oxidized mercury converter ($Hg^{2+} \rightarrow Hg^{0}$)
- Sample conditioning package (moisture, particulate removal)
- Mercury detector (CVAAS, CVAFS analyser)
- Pumps, valves and mass flow controllers
- Elemental mercury calibrator
- Calibration gas transport assembly
- Control computer and software

General description of operating principles is discussed in Section 3.3.4. The CEMS should be operated in accordance with the certification requirements developed by the regulatory body for mercury continuous emission monitoring system (i.e. US EPA 40 CFR Part 75 regulation) and the manufacturer's recommended operating and QA/QC procedures (see Section 4).

At the present time, the elemental mercury generator which produces a known concentration of mercury in a known gas stream flow rate represents the best approach for the calibration of CEMS.[116] These devices need to be certified such that their output at given set points is accurate. A NIST certification protocol for vendor prime generators is already in place but, as of November 2009, the development and application of a formal NIST traceability protocol for field mercury generators (also know as user prime generators) is still in progress. In parallel, a NIST traceability protocol for the shipment and use of elemental mercury gas cylinders for CEMS calibration is also under development. These protocols are expected to be available soon. Meanwhile, the U.S. EPA has released interim NIST traceability protocols for the qualification and certification of elemental and oxidized mercury gas generators that reflect the state of development of the procedures (as of July 2009).[117] These can be applied until the final protocols are released.

3.5.2 Applicability to Canadian EGUs

All Canadian coal-fired units are operating a dust control system which is a requirement for optimal operation of a mercury CEMS downstream. Accessibility to a platform and shelter near the stack sampling port is also required. A flue gas flow monitor is also required. If not, these infrastructures will need to be mounted before the mercury CEMS could be installed. As shown in Appendix C, all Canadian coal-fired EGUs can theoretically install and operate a mercury CEMS when comparing the reported 2008 mercury emissions with the mercury CEMS' normal detection range (0.1–15 $\mu g/Nm^3$ – conservative range, can be larger depending of the system). Even with an 80% reduction of mercury emissions, the CEMS low detection limit would be

[116] National Institute of Standards and Technology, Establishing measurement traceability for gaseous mercury emissions monitoring website.
[117] U.S. EPA, Interim EPA traceability protocols for the qualification and certification of elemental and oxidized mercury gas generators, 2009.

sufficient except maybe for the Point Aconi unit in Nova Scotia, which anyway is not expected to reduce its already low mercury emissions.

Although mercury CEMS can theoretically be applied to all Canadian coal-fired EGUs, it should be noted that diverse flue gas conditions per unit (i.e. temperature, moisture, dust, SO_2 content, etc.) will yield different level of performance depending on the quality of individual CEMS. True applicability of a specific system can only be determined jointly with the vendor.

3.6 Recommended second best option for airborne mercury monitoring

Commercial CEMS have already sufficient detection limits which could well cover the LME range. Case in point, minimum detection of mercury (<0.1 $\mu g/Nm^3$) by the CEMS on a 320 MW unit (Canadian average) would result approximately to 1 kg/a at maximum operation. Dry sorbent trap monitoring although it is not as accurate for long term projections as the CEMS can monitor lower mercury emissions. The minimum detection limit for this method is reckoned to approach 0.03 $\mu g/Nm^3$ but can conceptually be lower by extending sampling duration. For the same example above, the minimum detectable annual emission by sorbent traps would approach 0.3 kg/a. It becomes therefore an acceptable alternative to CEMS for LME facilities. Peaking units can also consider this approach which is convenient since sorbent trap operation is discontinuous. Field-testing of several commercial devices has demonstrated the good performance of sorbent traps within ± 12% of measurements realized simultaneously with the Ontario Hydro stack testing method.[118]

Typical sorbent trap sampling durations can generate between 5–30 independent mercury mass emissions per month which are acceptable to calculate a monthly average as long as the power plant's operation remained undisturbed during that time span. Disturbance in coal input, boiler's heat stream or pollution control device operation for example would downgrade the quality of the data set from sorbent traps monitoring since the potential mercury emission peaks/dips would be averaged. Monitoring with a CEMS would be preferred in that case. Ultimately, confirmation that the measured monthly average is satisfactory can be done with the analysis of statistical standard deviations on monthly measurements and with the proof that the unit's did not sustain major disturbances during that time span. Otherwise, if the operation is stable, compliance of a mercury emission limit on the monthly average, annual average or 12-month rolling average from dry sorbent trap monitoring would be acceptable.

Dry sorbent trap monitoring has been promoted by the U.S. EPA CAMR as an alternative method to CEMS for coal-fired EGU stack testing. It has been estimated by the EPRI that orders for over 110 sorbent trap systems has been placed, as of April 2008, before the rule was vacated. By that time, fewer than 25% of the systems were installed.[119] This monitoring approach can also be considered for the annual relative accuracy test audits (RATA) on CEMS and can act too as a backup system for malfunctioning CEMS.

[118] Lehigh University Energy Research Center, Armstrong Project: Evaluation and comparison of U.S. and EU reference methods for measurement of mercury, heavy metals, $PM_{2.5}$ and PM_{10} emissions from fossil-fired power plants, February 2007.
[119] Continuous Emissions Monitoring Users Group (CEMUG), Lessons learned from CEMUG conference, 7th annual conference, Nashville, TN, May 2008.

3.6.1 Description

Typical dry sorbent trap systems include the following components: isokinetic nozzle, miniparticulate filter, heated probe, paired tri-section sorbent traps, moisture removal system, vacuum pump, dry gas volumetric flow meter/controller and data logger system. Major difference between commercial systems involves essentially the composition of sorbent traps and the moisture removal method. Otherwise, the operation principle remains the same between trademarks. After sampling, the sorbent traps are retrieved and sent to an accredited laboratory where mercury is extracted from the solid matrix and analysed by CVAAS, CVAFS or other acceptable analytical method. The system should also be operated in accordance with the manufacturer's recommended operating and QA/QC procedures (see Section 4).

3.6.2 Applicability to Canadian EGUs

Like CEMS, a dust control system is required before sorbent trap monitoring for optimal operation. Dry sorbent trap monitoring provides a wider detection range (0.03–100 $\mu g/Nm^3$) than CEMS which confirms its applicability to all Canadian units including low mass emitters (H.R Milner, Brandon, Belledune, Point Aconi, Atikokan according to 2008 NPRI reported emissions, see Tab. 2-6).

3.7 Recommended third best option for airborne mercury monitoring

Wet stack testing using the Ontario Hydro Method (OHM, ASTM D6784-02) showed good agreement with CEMS within ± 15% according to the Armstrong Project (Lehigh University, 2007) comparing reference methods for mercury measurement. This method does not provide however real-time data that can monitor inherent fluctuations in mercury emissions. Applicability of the OHM for compliance would therefore require several sampling campaigns annually. To limit soaring expenses, quarterly sampling campaigns should be considered as a minimum. Monthly sampling campaigns would be more appropriate but would still generate uncertain results unless the coal-fired power plant overall operation is very stable.

Peaking units are generally defined as electric generating units which operated only during the peak energy demand. They operate generally for less than 500 hours per year. In this case, it is pointless to install and operate a CEMS. The best option would be to perform timely wet chemistry stack testing recommended here covering the units' hours of operation. Wet stack testing can also be applied for LME facilities but considering the relatively higher detection limit of 0.5 $\mu g/Nm^3$, it would be less appropriate for ultra low mass emitters.

Standardized stack testing by Canadian coal-fired EGUs using the OHM or EPA Method 29 was applied to characterize the mercury emission rates in 2002–2003 as part of the CEA mercury program. The OHM or any equivalent wet chemistry sampling method accepted by the regulatory body is being considered in some U.S. states (Connecticut, New Jersey) to monitor mercury emissions and verify their compliances with the imposed limits. For these instances, quarterly sampling campaigns are required but compliance is verified differently (i.e. four consecutive monitoring campaigns average weighted on electricity production rate, two consecutive monitoring campaign average). Whichever mercury emission compliance method is considered, confidence in the measurements for long-term mercury emission representation can be improved by demonstrating that the power plant's operation was not disturbed in any way during the represented calendar quarter year.

Chances that these conditions were prevailing for three consecutive months are however atypical of industrial processes. Still, even in these conditions, it can not guarantee without a doubt the validity of the measurement for long-term projection. Another limitation is the single sampling point for routine mercury analysis which increases sampling uncertainties compared, for example, to dry sorbent traps with the dual-sampling points.

3.7.1 Description

The sampling train is composed of an isokinetic nozzle connected to a heated probe which conveys the sample to the impinger box after being filtered. Gaseous emissions are collected successively in solutions of potassium chloride (KCl for Hg^{2+} capture), acidic solution of hydrogen peroxide (HNO_3/H_2O_2 for Hg^0 capture) and acidic solutions of potassium permanganate ($H_2SO_4/KMnO_4$ for Hg^0 capture). Silica gel is used after mercury absorption to remove moisture from the gas before it could be sent to dry gas flow meter. Pump, valves, manometers and thermocouples are also required.

Although stack sampling could be performed by power plant technicians, it is recommended that an accredited organisation that have experience in stack sampling do the work. The owner would only need to provide a suitable sampling platform and assistance. In addition to the sampling campaign, the owner must operate a continuous flow monitor which measures the hourly stack gas volumetric flow rate. This is required for the calculation of the hourly mercury mass emissions from the measured mercury concentration (cf. Section 4.2.1.3).

3.7.2 Applicability to Canadian EGUs

All Canadian facilities that contributed to the CEA mercury program back in 2002 applied this method for the assessment of mercury emissions and speciation. Although the detection limit for this method is relatively high (0.5 $\mu g/Nm^3$ for normal sampling), it can still be applied confidently for mercury monitoring for every Canadian coal-fired EGUs (Appendix C).

4. DELIENATION OF REPORTING AND QA/QC REQUIREMENTS

The following section addresses technical requirements deemed important for the reporting of total mercury emissions from the recommended monitoring regimes (1 – CEMS, 2 – dry sorbent trap method and 3 – OHM stack testing). Quality assurance and quality control (QA/QC) requirements regarding the operation of the monitoring regimes will be addressed next. Application of these procedures would consolidate, to our opinion, the quality of reported values to the regulatory body.

4.1 Approach

The following sources were surveyed regarding the mercury airborne emission reporting and QA/QC strategies for each recommended monitoring regime. The provisions considered in this section were developed elsewhere, mostly from the vacated U.S. EPA CAMR. Considering the CAMR suspension was not related to the imposed QA/QC and reporting requirements, their applicability for Canadian mercury monitoring systems are believed appropriate.

- Canadian Council of Ministers of the Environment, Monitoring protocol in support of the Canada-wide standards for mercury emissions from coal-fired electric power generation plants, July 2007.
- Source Technology Associates, Monitoring emissions under a regulatory framework for the electricity sector, prepared for Environment Canada, April 2008.
- U.S. EPA, Standards of performance for new and existing stationary sources: electric utility steam generating units; final rule (40 CFR Part 60, 72 and 75), May 2005.
- U.S. EPA, Performance specification 12A – Specifications and test procedures for total vapor phase mercury continuous emission monitoring systems in stationary sources.
- U.S. EPA, Method 30B – Determination of total vapor phase mercury emissions from coal-fired combustion sources using carbon sorbent traps.
- Clean Air Association of the Northeast States, Suggested states (draft) version of mercury monitoring and reporting protocols: using a continuous emission monitoring system, a sorbent trap monitoring system, from low-emitting stationary sources, September 2008.
- Electric Power Research Institute, Quality assurance/quality control guidelines for mercury measurements, March 2005.
- Electric Power Research Institute, Continuous mercury monitoring guidelines, March 2007.
- European Committee for Standardization, EN 14181:2004. Stationary source emissions. Quality assurance of automated measuring systems.
- Environment Canada, Protocols and performance specifications for continuous monitoring of gaseous emissions from thermal power generation, December 2005.
- Canadian Electricity Association, Quarter 9 – Mercury information clearinghouse final report, December 2005.

4.2 Reporting guidelines

Reporting provisions of airborne mercury emissions under a regulatory framework should cover the following aspects: compliance data reduction, report content, frequency of reporting and method of reporting. For credible regulatory compliance, the report should contain facts and figures that cover, among others, the facility's description and operation, the data reduction procedures and results, the operational parameters during monitoring and any documents that confirm the validity of compliance data. The method and frequency of reporting describe how and when the report should be transmitted to the authority in charge.

4.2.1 Mercury data reduction

4.2.1.1 CEMS

Continuous emission monitoring systems generating real-time mercury emission data must be capable of measuring the total concentration in $\mu g/Nm^3$ regardless of mercury speciation, preferably recording that concentration on a dry basis, corrected at 20°C and 7% CO_2 dilution.[120] Accordingly, most commercial CEMS monitors the temperature, gas flow rate and pressure at the probe. Dry basis is assumed since moisture must be removed from the gas sample prior to mercury detection. If in any case the wet mercury concentration is measured, a correction should be carried out (Eq. 4-1) in accordance with the CEMS moisture monitoring data (B_W: volumetric fraction of moisture in flue gas). The CEMS must also include a continuous CO_2 monitor (β_{CO2}; percent CO_2 in flue gas) for the adjustment of mercury concentrations to the 7% CO_2 dilution level, if required.

$$C_{Hg}\left[\mu g/Nm^3\ dry\right] = \frac{C_{Hg}\left[\mu g/Nm^3\right]}{1 - B_W} \qquad (4\text{-}1)$$

Average mercury mass emissions (M_{Hg}) during a specific time period (i.e. hour) is obtained according to Equation 4-2. The cumulative mercury mass emission over a longer time period (i.e. day, month, year) is obtained by adding individual hourly mass emissions.

$$M_{Hg}\left[kg/hr\right] = \overline{C}_{Hg}\left[kg/Nm^3\right] \times Q_h\left[Nm^3/h\right] \times t_h \qquad (4\text{-}2)$$

where

$\overline{C}_{Hg}$ is the arithmetic average of measured mercury concentrations for the specific time period

Q_h is the flue gas volumetric flow rate for the specific time period

t_h is the fraction of time for which the stack and unit is in operation (1 by default)

Most regulations (vacated and current) establish mercury emission limits on either heat input (kg/TWh_{th}), electrical output (kg/TWh_e) or percent reduction. Conversion of measured mercury concentrations from kg/Nm^3 to kg/TWh_{th} can be achieved using the following relationship (F_{Fuel}) between the CO_2 formation rate and gross fuel calorific value.[121]

[120] U.S. EPA, Performance specification 12A – Specifications and test procedures for total vapor phase mercury continuous emission monitoring systems in stationary sources.

[121] Electric Power Research Institute, Quality assurance/quality control for mercury measurements, March 2005.

$$E_{Hg}\left[kg/TWh_{th}\right] = \overline{C}_{Hg}\left[kg/Nm^3\right] \times F_{Fuel}\left[Nm^3\ CO_2/TWh_{th}\right] \times \frac{100}{\overline{\beta}_{CO_2}}\left[Nm^3/Nm^3\ CO_2\right] \quad (4\text{-}3)$$

$$F_{Fuel}\left[Nm^3 CO_2/TWh_{th}\right] = 72{,}000 \times \frac{\%C_{fuel}}{GCV\left[kJ/kg\ dry\right]} \times 10^6 \quad (4\text{-}4)$$

where

$\overline{C}_{Hg}$ is the arithmetic average of measured mercury concentrations for the specific time period

$\overline{\beta}_{CO_2}$ is the average CO_2 volumetric fraction of the stack gas for the specific time period

$\%C_{fuel}$ is the percent of carbon in coal, dry basis

GCV is the gross calorific value of coal

These calculations were approved by U.S. EPA for reporting purposes, and thus should be used when evaluating mercury emissions for comparison with proposed mercury standards in kg/TWh_{th}. The CCME CWS and other legislations impose a limit based on electric generation output. The following correction could be applied if the plant's thermal efficiency (ε_{boiler}) is known. Typical efficiency values range between 0.25–0.45. Equation 4-6 is however more recommended, if the information is available, for the calculation of kg/TWh_e mercury emissions.

$$E_{Hg}\left[kg/TWh_e\right] = \frac{E_{Hg}\left[kg/TWh_{th}\right]}{\varepsilon_{boiler}\left[kW_e/kW_{th}\right]} \quad (4\text{-}5)$$

$$E_{Hg}\left[kg/TWh_e\right] = \frac{M_{Hg}\left[kg/h\right]}{P_{out}\left[TW_e\right]} \quad (4\text{-}6)$$

where

M_{Hg} is the mercury mass emission for the specific time period, Eq. 4-2

P_{out} is the average electrical power output for the specific time period

If compliance is required on the percent capture of mercury (R_{Hg}), a mercury emission baseline before treatment is required which is normally defined by the regulation (i.e. use of historical data, sampling and analysis campaign of mercury emissions exiting the boiler prior to any APC device, operation of a CEMS, etc.).

$$R_{Hg}\left[\%\right] = \frac{M_{Hg,base}\left[kg/h\right] - \overline{C}_{Hg}\left[kg/Nm^3\right] \times Q_h\left[Nm^3/h\right]}{M_{Hg,base}\left[kg/h\right]} \times 100 \quad (4\text{-}7)$$

where

$M_{Hg,base}$ is the hourly mercury emission baseline

$\overline{C}_{Hg}$ is the average mercury concentration in flue gas for the specific time period

Q_h is the flue gas volumetric flow rate for the specific time period

4.2.1.2 Dry sorbent trap monitoring

Laboratory analysis of dry sorbent measures the total mercury mass (m_{Hg} in μg) captured during sampling. For tri-section sorbent traps (1–Hg capture, 2–Hg breakthrough, 3–Hg spiking for QA/QC), measurements in sections 1 and 2 must be added. Time-average mercury emission concentration is obtained as follow while the hourly mercury mass emission is calculated according to Equation 4-2.

$$C_{Hg}\left[kg/Nm^3\right] \equiv \overline{C}_{Hg} = \frac{m_{Hg}\left[\mu g\right]}{V_h\left[Nm^3\right]} \times \left(1 - B_W\right) \times 10^{-9} \qquad (4\text{-}8)$$

where
m_{Hg} is the total mercury mass captured during sampling
V_h is the total dry gas volume sample
B_w is the average moisture fraction in gas sample

For quality assurance, the relative deviation (RD) between the mercury concentrations measured in both sorbent traps (A and B) should be calculated and reported along with the average mercury concentration.

$$RD = \frac{\left|C_A - C_B\right|}{C_A + C_B} \times 100 \qquad (4\text{-}9)$$

For the calculation of compliance mercury emissions, Equations 4-3 to 4-7 are also applicable for sorbent trap monitoring based on the flow-proportional mass emission rate and concentration calculated in Eq. 4-2 and 4-8.

4.2.1.3 OHM stack testing

Laboratory analysis of liquid solutions (i.e. KCl, HNO_3/H_2O_2, $H_2SO_4/KMnO_4$) part of the procedure allows the quantification of total mercury mass (m_{Hg} in μg) captured during sampling. For replicated analysis, the average is considered in ensuing calculations. Discrete mercury emission concentration and hourly mass emission are obtained using Equation 4-8 and 4-2, respectively. For the calculation of compliance mercury emissions, Equations 4-3 to 4-7 are also applicable for OHM stack testing.

4.2.1.4 Average

For CEMS and dry sorbent trap monitoring, an arithmetic average of hourly or time-average mercury emissions should be considered according to the regulation specifications (i.e. daily average, 12-month rolling average, etc.).

$$\overline{E}_{Hg} = \frac{\sum_{1}^{n} E_{Hg}}{n} \qquad (4\text{-}10)$$

where

E_{Hg} is the specific mercury emission rate (as kg/TWh$_{th}$, kg/TWh$_e$ or % Hg capture) for individual time period

n is the number of time periods (hourly for CEMS, time-average for sorbent traps) in the average

4.2.1.5 Missing and invalid data

A missing data period occurs whenever the acquired measurement is not quality-assured due mostly to maintenance, system malfunction or invalid results from laboratory analysis. Standard procedures for the replacement of missing data were developed in the U.S. EPA CAMR according to the overall data availability and the specific length of monitor outage.[122] This matter is applicable for CEMS and dry sorbent trap monitoring.

An effort should be made to obtain valid data and avoid the use of substitutions. Data availability updated hourly of at least 90% for the previous year (or since certification) is deemed achievable.[123] In that case, for short term CEMS outage (< 24 hours), the mercury concentrations for the hour before and the hour after the missing data period should be averaged to replace the missing data. For longer outage, the average or 90th percentile, whichever is more restrictive, of previous 720 hours of quality-assured Hg measurements should be used to substitute missing data. This practice normally provides conservative mercury concentrations. For dry sorbent traps, the average of all valid measurements in the previous 12 months is applied when data availability is at least 90%. For lower data availability (<90%), stringent missing data procedures are considered for both CEMS and dry sorbent traps monitoring methods (Appendix B).[124] This procedure described herein was also considered for application in the CCME CWS monitoring protocol.

For CEMS, measurements that exceed the working detection scale are not representative of the actual concentration so long as the system is not malfunctioning. For every overscaling data, correction must be done by reporting 200% of the upper scale instead of the measured data. If overscaling occurs too frequently (normally >2% of the time), it is recommended to adjust the upper scale value on the CEMS.

[122] U.S. EPA, Standards of performance for new and existing stationary sources : electric utility steam generating units; final rule (40 CFR 75.32), May 2005.
[123] Clean Air Association of the Northeast States, Measurement and reporting of vapour phase mercury emissions, using continuous emission monitoring system, 2008.
[124] Ibid.

4.2.2 Report content

For any monitoring regime, compliance reports on mercury emissions from coal-fired EGUs should include the following elements. To our opinion, it should provide enough information to enable comprehensive auditing of mercury emission data. Distinctions between recommended monitoring regimes are noted (all, CEMS, DST, OHM).

1. Generalities (all) – should be updated annually at a minimum
   - Legal owner and operator
   - Plant address and other related identifications
   - Project personnel and responsibilities
   - Monitoring period covered by the report
   - Applicable mercury emission limit and regulation

2. Unit information (all) – should be updated annually at a minimum
   - Process flow diagram
   - Distribution of boilers per stack
   - Fuel and its main characteristics (as a minimum: type, blend, calorific value, moisture, ash, mercury)
   - Maximum rated heat input capacity
   - Air pollution controls

3. Activities during reported period (all)
   - Unit operation hours
   - Coal feed rate
   - Coal combustion residues tonnage and disposal/sale methods (if required)
   - Heat stream production rate, if available
   - Electricity production rate

4. Maintenance and corrective actions (all)
   - Report actions (i.e. start-up, shutdown, maintenance, coal input variations, etc.) that could affect mercury emission monitoring
   - Chronology of actions

5. Monitoring plan information for the unit (all) – should be updated annually at a minimum
   - Stack sampling location(s)
   - Methodology
   - Chronology
   - Measured parameters during monitoring (including, but not limited to, gas volumetric flow rate, moisture content, CO_2 content in flue gas, flue gas temperature)
   - Justification for the use of an alternate monitoring regime, if applicable

6. Mercury emission measurements
   - Hourly average mercury emission rates (kg/h) (CEMS)
   - Time-average mercury emission rates (as kg/h) (DST)
   - Discrete mercury emission rates (as kg/h) (OHM)
   - Corresponding percent mercury capture, if required by regulation (all)
   - Identification of substituted data (CEMS, DST)

7. Data reduction results (all)
   - Cumulative mercury emissions (kg/time period) for the monitored period covered by the report, if applicable
   - Average mercury emission rates (as kg/TWh_{th}, kg/TWh_e or % Hg capture) according to the regulation specifications, i.e. daily, monthly, yearly, 12-month rolling, etc.

8. Additional information
   - Report hourly data from auxiliary monitoring systems (i.e. temperature, moisture, flow rate, etc.) that are used in calculations (all)
   - Description (example) of the calculation method (all)
   - Report span and range information for mercury analyser and auxiliary systems (all)
   - For DST, report relative deviation between paired sorbent traps measurements + mercury analysis in 3rd section vs. spiked Hg concentration (DST)

9. QA/QC documentation (all)
   - System certification
   - Field data sheets and charts
   - Calibration procedure, frequency and results (on flue gas flow meter, mercury CEMS, dry sorbent trap gas sample monitor)
   - QA/QC test results demonstrating precision, accuracy and completeness including calibration error tests, linearity checks, system integrity checks, etc. (see Section 4.3)
   - Performance evaluation audits (RATA) + information about the consultant who did them
   - Certification of lab accreditation, when applicable
   - Other information confirming the system's performance

4.2.3 Frequency of reporting

The vacated CAMR recommended preparing semi-annual reports assessing the compliance of 12-month rolling mercury emission averages. The owner would have been also responsible for preparing quarterly reports of their mercury emissions from CEMS or dry sorbent trap monitors to the authority.[125] Reporting was to begin for the next calendar quarter after CEMS or dry sorbent trap system installation and certification, and to be submitted within 30 days following the end of each calendar quarter.

Accordingly, we recommend semi-annual reporting of CEMS and dry sorbent trap monitoring data for compliance duty that should be submitted within 60 days following the end of the calendar semester. For OHM stack testing, reporting should be synchronized with the sampling campaign frequency defined by the regulation. In any case, quarterly reporting of data should be considered as a maximum.

4.2.4 Method of reporting

Electronic submission based on a compliance report template should be considered except for supporting hardcopy information (i.e. certificates, field data sheets, etc.) which should be mailed to the regulatory body, preferably within 30 days of electronic submission.

[125] U.S. EPA, Standards of performance for new and existing stationary sources: electric utility steam generating units; final rule (40 CFR 60.4174, 60.51), May 2005.

4.3 Quality assurance and control (QA/QC) guidelines

This section provides specific QA/QC requirements for recommended mercury monitoring regimes regarding the operational procedures to ensure compliance with the reporting requirements, the periodic verification and auditing procedures of emission values, and record keeping provisions needed to demonstrate to the authority that the procedures were correctly followed. These measures allow for the control of the precision, accuracy and completeness of data as well as making sure the system is integral and information is traceable.

4.3.1 Operational procedures

The operational procedures described below are developed according to existing standards and regulations and are considered general. It does not discuss any calibration techniques or other QA/QC procedures that are specific to a commercial monitoring system. While applying the following operational procedures, the owner should also consider the operational specifications recommended by the supplier so as to achieve optimal results.

4.3.1.1 CEMS

Installation and operation of automated monitoring systems should ideally follow four levels of quality assurance to ensure that the monitor provide accurate, precise and reliable results (Fig. 4-1). Level 1 QA relates to the system certification, also known as a factory acceptance test, which investigates the suitability of the technology provided by the vendor according to established regulatory standards. It will not be covered in this report since it is not part of the QA/QC program for the CEMS operator. Level 2 QA, or performance warranty inspection, involves a multitude of system checks certifying that the system is performing properly after installation. Level 3 QA applies continuous QC procedures through the operating personnel assuring the system operation and data are always reliable. Finally, level 4 QA involves periodic surveillance audits thoroughly checking the level of certainty of measurements.

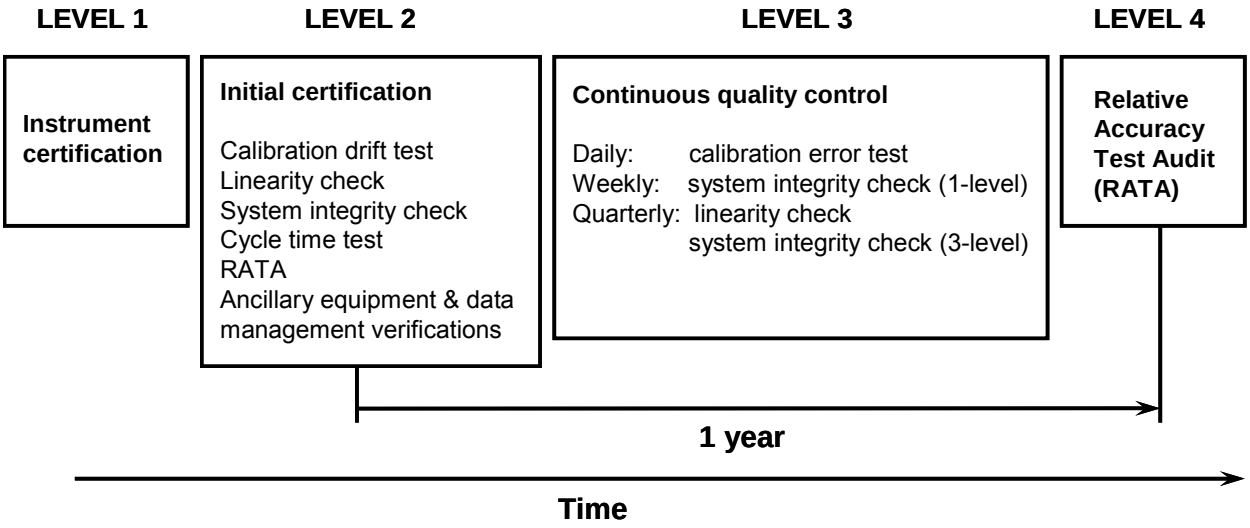

Figure 4-1: Overview of a typical QA/QC program for the installation and operation of mercury CEMS

Upon installation, the system must pass a performance warranty inspection through standardized methods to check for observance of preset measuring uncertainties regarding linearity deviation, reproducibility, response drift, response times, etc. These tests described below were recommended by the U.S. EPA CAMR and were applied in a recent investigation verifying the compliance of various commercial CEMS.[126] Recertification of the CEMS should be repeated every 5 years or more frequently if required by law. Recertification should also be considered if the CEMS is upgraded.

The proposed specifications have been developed to evaluate the acceptability of CEMS upon installation and periodically thereafter for systems installed downstream of the air pollution control devices of coal-fired boilers. It does not discuss specific calibration techniques adopted by the commercial CEMS. As experience is gained in operating and maintaining CEMS, it is expected that the specifications may be modified and the QA/QC procedures outlined below will have to change. The initial certification (and recertification) should be carried out in collaboration with the CEMS vendor.

Calibration drift test: Tests conducted once per day for seven straight days to verify the stability of the system's calibration. The response can not deviate for the zero level (i.e. Hg below detection limit) and upscale level (40–60 % of span) by more than 5 percent of the span value (i.e. if span = 100 $\mu g/m^3$, error should be < ±5 $\mu g/m^3$). Elemental mercury NIST certified calibration gas is used for this test.[127]

Linearity check: Test intended to verify if the measurement error is consistent across the detection span. It should consist of at least three injections of elemental mercury reference gas that cover the following concentration scales: zero-level (<0.1 $\mu g/m^3$), mid-level (40–60 % of span), high-level (80–100 % of span). This procedure should be repeated 3 times. For each concentration, the absolute error between the three responses average and the reference gas concentration should be less than 10% or 1 $\mu g/m^3$, whichever is less restrictive.

System integrity check (3-level): Test which should be designed in accordance with the installed system to verify the efficiency of oxidized mercury (Hg^{2+}) conversion into elemental mercury (Hg^0). It is carried out by injecting three reference samples (zero, mid-level, high-level) of a NIST certified source of oxidized mercury ($HgCl_2$). The test is passed if all three Hg^{2+} conversion efficiencies exceed 95%.

Cycle time test: Test intended to evaluate the response time of the CEMS to a mercury concentration change. The test is passed if the response time to a step change is less than 15 minutes. The time is stopped when the response has reach 95% of the mercury concentration step change. For example, for a step change from 50 $\mu g/m^3$ to 40 $\mu g/m^3$, less than 15 minutes should elapse to reach a response of 40.5 $\mu g/m^3$ or less.

Relative Accuracy Test Audit (RATA): see Section 4.3.2 for description

[126] U.S. EPA, Long-term field evaluation of mercury continuous emission monitoring systems: Coal-fired power plant burning eastern bituminous coal and equipped with selective catalytic reduction, electrostatic precipitator, and wet scrubber: Field activities from Nov. 2004–Sept. 2005, November 2006.

[127] *At the present time, there are no formal NIST traceability protocols for field mercury generators or cylinders for CEMS calibrations. Interim protocols for elemental and oxidized mercury generators are however available at this point and can be applied until the final forms are available.*

While performing initial certification, the owner should also inspect the reliability of auxiliary equipment like the flue gas flow monitor, CO_2 monitor, moisture monitor, probe controller, pumps, valves, mass flow controllers and data acquisition system to avoid unnecessary setbacks later on. Verification of the data handling procedure is also recommended to ensure that data management is appropriate for regulatory purposes. These verifications should be done in collaboration with recommendations from the vendor.

Following the initial certification, a continuous quality assurance program through the plant personnel must be pursued to control any operating anomalies. Several test procedures are recommended and should be applied at specified intervals and following preventive maintenance.

Calibration error test: Daily test conducted to validate the conformity of the calibration curve for the next 24 hours. It is carried out by injecting a reference mid- or high-level mercury concentration from an elemental mercury certified calibration gas. The error between the CEMS response and the reference concentration should be less than 5% of the span value. If the calibration is not in conformity, the instrument should be recalibrated according to the vendor's specifications.

System integrity check (1-level): Weekly test which should be designed in accordance with the installed system to verify the efficiency of oxidized mercury (Hg^{2+}) conversion into elemental mercury (Hg^0). It is carried out by injecting one reference sample (usually mid-level concentration) of a NIST certified source of oxidized mercury ($HgCl_2$). The test is passed if the Hg^{2+} conversion efficiency exceeds 95%. This weekly test is not required if the daily *calibration error test* is passed when using the source of oxidized mercury instead of prescribed elemental mercury.

Linearity check: Quarterly test intended to verify if the measurement error is consistent across the detection span. It should consist of at least three injections of elemental mercury that cover the following concentration scales: zero-level (<0.1 $\mu g/m^3$), mid-level (40–60% of span), high-level (80–100% of span). This procedure should be repeated 3 times. For each concentration, the absolute error between the three responses average and the reference gas concentration should be less than 10% or 1 $\mu g/m^3$, whichever is less restrictive.

System integrity check (3-level): Quarterly test equivalent to the 1-level system integrity check except that 3 mercury concentration levels (zero, mid- and high-level) are applied.

Continuous QA verifications of auxiliary monitoring systems should be performed at least on a weekly basis to ensure the quality of reported mercury data especially if the auxiliary equipment measurements are used for compliance.

4.3.1.2 Dry sorbent trap monitoring

For the initial certification of a sorbent trap monitoring system, a RATA with valid results must be passed according to the specifications defined in Section 4.3.2. Auxiliary monitoring systems must provide accurate results as well for certification.

- Dry gas meter: average measurement at 1 set point should be within ±5% of the prediction from the initial 3-point calibration curve. If not, the meter must be recalibrated;

- Temperature sensor: absolute temperature should be within ±1.5 °C of a reference sensor. If not, the sensor must be recalibrated or replaced;

- Barometric sensor: absolute pressure should be within ±10 mm Hg (1.33 kPa) of the reading from a mercury barometer. If not, the sensor must be recalibrated or replaced;

- Other sensors and gauges: calibrate according to the procedures specified by the instrument manufacturer.

Whenever the owner makes a replacement or modification to the certified sorbent trap monitoring system that may affect the accuracy of the measurement, recertification should be carried out unless otherwise specified in the regulation.

After initial certification, a QA/QC performance program should be respected to guarantee valid mercury emissions data. It includes system calibration and reliability checks, analytical method validation, sample check and sample manipulation check. More details on acceptance criteria and methodology are found in the U.S. EPA reference Method 30B.[128]

System calibration check: The performance of the gas flow meter, temperature sensor, barometer and other gauges should be checked once every 3 months at 1 set point. Recalibration or replacement should be considered if the test is not passed.

System reliability check: Pre-sampling and post-sampling leak checks across the system should be carried out to ensure that leaks will not and did not occur during sampling. The sampling can not begin if the pre-sampling leak check is not passed. The sample should be invalidated if the post-sampling leak check is not passed.

Analytical method check: A multipoint calibration of the mercury analyzer (i.e. CVAAS) with readings within ±10% of true concentration should be carried out on the day of the analysis. Following calibration, readings of an independent calibration mercury standard should lie within ±10% of true concentration in order to validate the calibration results. If not, calibration and mercury standard analysis should be repeated until successful.

Sample check (relative deviation, Hg breakthrough & flow proportionality): The relative deviation on readings from the paired sorbent traps according to Eq. 4-9 should be less than 10% for the sample to be valid. For a mean mercury concentration in flue gas of less than 1 $\mu g/m^3$, the maximum acceptable relative deviation raises to 20%.

As explained in Section 3.3.5, the dry sorbent is confined in a tri-section trap, where the first section is designed to capture mercury, the second section for mercury breakthrough evaluation and the third for mercury spiking (cf. next paragraph). A performing sorbent should undergo minimum mercury breakthrough. Otherwise, it could point out to difficulties in capturing mercury. When analysing the mercury content in section 2, the reading should be less than 5% of mercury content measured in section 1. If not, the sample should be invalidated.

Providing a time-average mercury emission rate, it is important to maintain a steady flow-proportional extraction rate throughout the sampling campaign. At all time, the ratio between the

[128] U.S. EPA, Method 30B – Determination of total vapor phase mercury emissions from coal-fired combustion sources using carbon sorbent traps.

stack gas and sample volumetric flow rates should be maintained within ± 25% of the initial ratio. This factor should be verified every day.

Sample manipulation check (spike recovery): During analysis, the spiked mercury mass in section 3 for both sorbent traps should be recovered within 75–125% making sure that mercury loss or contamination between field sampling and laboratory analysis was effectively limited. It also validates the procedure for extracting the mercury from the sorbent matrix to the analyser. If the test is not passed, the sample should be invalidated. To achieve this task, pre-sampling mercury spiking in sorbent traps' third section should be performed in a controlled environment based on a standardized method. The spike level should range within ± 50% of the expected mercury mass captured during sampling. Validation of the spiking procedure should be confirmed during analysis by recovering between 85–115% of a known spiked mercury mass in specific sorbent evaluation traps. This test should be done daily prior to analyse field samples.

4.3.1.3 OHM stack testing

Periodical stack testing according to the OHM method is normally performed by a third party. Certification and quality assurance regarding the integrity of their sampling equipment is their responsibility as is mercury analysis which is carried out by an accredited laboratory. Certifications should be made available to the regulatory body when required. The owner should also perform on-going QA testing of auxiliary monitoring systems like the stack gas flow monitor and moisture monitor (if applicable) which values are used in calculations. The checks should be carried out in accordance with the recommendations of the equipment manufacturer.

For good results, the sampling campaign should be performed at a location that is representative of the mercury emissions to the atmosphere during the unit's normal operating load. For boilers sharing the same stack, normal operating loads for each boiler is required. Paired samples are required for each test run that should be long enough to ensure that sufficient mercury is collected for analysis. For each test run, the relative deviation (Eq. 4-9) between duplications must not exceed 10%. If the average concentration is less than 1 $\mu g/m^3$, the relative deviation must not exceed 20%. If unsuccessful, the reason explaining the discrepancy should be investigated and resolved before restarting a new stack test.

4.3.2 Periodic auditing procedures

A relative accuracy test audit (RATA) is required to complete the initial certification of CEMS and dry sorbent trap monitoring systems and should be repeated annually as part of a QA/QC program. Owners are advised to contract a third party to perform the RATA which consists of operating the CEMS (or dry sorbent trap system) together with a reference monitoring method (i.e. Ontario Hydro method, OHM) to confirm the accuracy of mercury measurements on actual flue gas conditions. Paired sampling trains for the reference monitoring method are required to consolidate its authenticity. A relative difference (Eq. 4-9) between sampling trains results below 10% validates the run. The two-point mercury concentration average should be reported and compared with the corresponding CEMS average or dry sorbent trap measurement.

A RATA program should comprise a minimum of 12 test runs carried out within 2 weeks in normal power load conditions. From that, nine valid runs are required for the performance assessment. The sampling period per run must be long enough to collect a sufficient mass of mercury to analyze. For the OHM reference method, this can be achieved within a few hours. For each run, the CEMS or dry sorbent trap data should be validated according to the quality assurance standards described in Section 4.3.1.

As a performance criterion, the relative accuracy (RA) between the stack sampling reference method (C_{OHM}) and the investigated system (C_{SYS}, CEMS or sorbent trap) should not exceed 20%. It is calculated according to Equations 4-11. Alternatively, if the mean reference method concentration for all valid runs (RM) is less than 5 $\mu g/m^3$ (low mass emitter), the RATA becomes successful if the difference between the reference method and tested method concentrations is maintained within ± 1 $\mu g/m^3$ for all valid runs. If proven unsuccessful, adjustments or modifications of the monitoring system must be done and revalidated following the initial certification program including a new RATA.

$$RA[\%] = \frac{\frac{1}{n}\left|\sum_{i=1}^{n}\left(C_{SYS,i} - C_{OHM,i}\right)\right| + CC}{RM_{avg}} \times 100 \qquad (4\text{-}11)$$

$$CC = \frac{t_{0.975}}{\sqrt{n}} \times \sqrt{\frac{\sum_{i=1}^{n}\left(C_{SYS,i} - C_{OHM,i}\right)^2 - \frac{1}{n}\left(\sum_{i=1}^{n}\left(C_{SYS,i} - C_{OHM,i}\right)\right)^2}{n-1}} \qquad (4\text{-}12)$$

where
i is the run number
n is the number of paired valid runs
C_i is the measured average concentration by either CEMS, DST or OHM
RM_{avg} is the average of all valid OHM reference mercury concentrations
$t_{0.975}$ is the 97.5% Student t-distribution value which is function of the number of valid runs

As part of the RATA, a bias analysis must be carried out to ensure that the mercury concentration from the investigated monitoring system is not under reported. The bias parameter must not exceed 5% of full detection scale or any other threshold defined by the regulation. If the test fails, a bias adjustment factor (BAF) must be applied to correct all subsequent CEMS or sorbent trap data.

$$Bias = \frac{1}{n}\left|\sum_{i=1}^{n}\left(C_{SYS,i} - C_{OHM,i}\right)\right| - CC \qquad (4\text{-}13)$$

$$BAF = 1 + \frac{RM_{avg}}{TM_{avg}} \text{ if Bias > 5\% of full scale} \qquad (4\text{-}14)$$

where
i is the run number
n is the number of paired valid runs
C_i is the measured average concentration by either CEMS, DST or OHM

CC is the confidence coefficient, Eq. 4-12
RM_{avg} is the average of all valid OHM reference mercury concentrations from the RATA
TM_{avg} is the average of all valid CEMS (or DST) mercury concentrations from the RATA

4.3.3 Record keeping provisions

Besides reporting their mercury emission results to the authority, the operator has the responsibility to keep a written record of data, calculations, and QA/QC test results demonstrating the validity of the monitoring system. A descriptive record of maintenance and repair activities should be kept in a suitable format as well. When possible, the schedule of events should be included. Hardcopy and electronic (when possible) versions of the following items should be accessible to the authority in an organised file. All recorded information should be retained for a minimum of 10 years. Distinctions between recommended monitoring regimes are noted in the list (all, CEMS, DST, OHM).

- Documentation and justification for any alternative method for mercury monitoring (DST, OHM)
- Coal characterisation (i.e. calorific value, moisture, ash, sulphur, mercury) results (all)
- Up-to-date power plant activities (incl. operation hours, coal feed rate, heat stream production, electricity production) (all)
- Written record (method, schedule, raw measurements, calculations) of the system's initial certification (and recertification, if applicable) (CEMS, DST)
- Documentation on the monitoring plan, schedule, procedural changes (i.e. detection span) and preventive maintenance actions (all)
- Written record of raw measurements including mercury and auxiliary parameter measurements (all)
- Written record of calculations and identification of missing data (CEMS, DST)
- Documentation (procedures, schedule) of the continuous QA/QC program (all)
- Written record of results (raw data, calculations) for the continuous QA/QC program (CEMS, DST)
- Documentation (procedures, results) on individual RATA (CEMS, DST)
- Laboratory accreditation (DST, OHM)
- Documentation regarding NIST-traceable mercury gas standards and other reagents (CEMS)

5. ESTIMATED COST OF MERCURY MONITORING REGIMES

This section addresses the cost implications to install, operate and maintain the mercury monitoring regimes recommended in Section 3 (CEMS, dry sorbent trap method and OHM stack testing). Cost estimates were derived on a per unit basis and globally for the Canadian coal-fired EGU sector according to their situation in 2009.

5.1 Approach

For each monitoring regime, cost estimates for specific cost items were reviewed from literature sources, internet data and personal knowledge. Order-of-magnitude cost estimates broken down as much as possible by cost items were made without detailed engineering data (not site-specific) which normally represent an accuracy of -30% to 50%.[129] All the costs in this report including hardware and labour are presented as 2009 Canadian dollars. The following cost parameters will be provided on a per unit basis:

- Capital costs including equipment and labour at year 0;
- Depreciation costs associated with installed capital equipment;
- Annual costs which include operation and maintenance broken down by cost item and labour reported here for the year 2009;
- First year costs (capital + O&M cost for year 0);
- Total costs over a 20-year operating life;
- Levelized annual cost over a 20-year operating life;
- Levelized busbar cost over a 20-year operating life.

The levelized annual cost over a 20 year operating life is calculated according to Equation 5-1 based on a present worth discount rate of 10%. The levelized busbar cost over the same period corresponds to the levelized annual cost in function of the net annual electricity generation (based on a 500 MW plant at 80% capacity in this report). A sensitivity analysis on capital and annual cost items and some economic parameters will be carried out to identify critical variables, if any, that affect the levelized costs significantly. A ±30% variation on initial estimations will be considered.

$$\mathrm{LAC}[\$/a] = \mathrm{NPW}[\$] \times \frac{r(1+r)^{20}}{(1+r)^{20}-1} \quad (5\text{-}1)$$

$$\mathrm{LBC}[\$/\mathrm{MWh}] = \frac{\mathrm{LAC}[\$]}{8{,}760 \times P_E[\mathrm{MW}] \times C_E[\%]} \quad (5\text{-}2)$$

$$\mathrm{NPW}[\$] = \sum_{n=1}^{20} \frac{R_n - I_n - A_n}{(1+r)^n} \quad (5\text{-}3)$$

where
LAC is the levelized annual cost

[129] Vatavuk, W. M., Estimating costs of air pollution control, Lewis Publishers, Chelsea, MI, 1990.

NPW is the cumulative net present worth over 20 years
r is the present worth discount rate
LBC is the levelized busbar cost
P_E is the nameplate electric capacity
C_E is the annual relative capacity
R_n is the revenues at year n generated by the monitoring system
I_n is the capital costs at year n associated with the monitoring system
A_n is the annual costs at year n associated to the operation of the monitoring system

5.2 Continuous emission monitoring (CEMS)

One barrier to the installation of mercury CEMS besides technical issues is cost. CEMS can be expensive and often requires trained staff for maintenance to ensure accurate and reliable performance of the system. In fact, most power companies have dedicated staff to fulfill these tasks. Initial capital costs are a substantial portion of the overall costs, but in the long-run operational and maintenance costs including preventive and corrective maintenance, calibration, record-keeping, QA/QC tests and data reporting also require significant resources which can add hundreds of thousands of dollars annually.

5.2.1 Capital costs

Implementation of a mercury CEMS involves several phases including planning, equipment selection, site preparation, purchase, installation, initial certification and preparation of a QA/QC program. Globally, it represents the capital investment which comes from direct (i.e. purchased equipment) and indirect (i.e. installation, labour, start-up, testing) costs. Preliminary planning allows the owner to review the regulation specifications and determine, after inspecting the source, the specific constraints for operating a CEMS. An engineering report usually stems from that work. Engineering work is expected to last less than 2 weeks accounting for less than $5k in labour (Tab. 5-1). In this report, the hourly wage for power plant engineers and technicians are fixed at 35 $/h and 28 $/h, respectively (37.5 h/week, overhead factor of 1.6).

Once the decision to buy a CEMS is reached, the owner must select a vendor which involves several hours of administrative work to identify potential bidders, write the request for proposal, evaluate proposals and negotiate contracts. As the CEMS is being assembled, the plant engineer would normally review and approve the drawings and provide oversight of installation of support facilities (i.e. CEMS platform, c.f. next paragraph). Altogether, these tasks should monopolize around 6 weeks of the plant engineer's time (± $15k).

A suitable platform is required for the installation of mercury CEMS including a proper access to the sampling port (i.e. staircase, elevator), a CEMS shelter, a communication line as well as utilities like electricity, compressed air and water. Building an elevator is especially useful during setup and testing since the sampling ports are located several meters above the ground (typically >50 m). However, for a stack that does not have an elevator, the related cost can be significant in the vicinity of $250k[130] and should be considered only if it is judged essential by the vendor. Besides, it is often recommended by vendors to locate the CEMS in a shelter at ground level since it is difficult to lift shelters and CEMS to the stack platform and supply electricity, compressed air and other utilities at this elevation. The lack of space on the sampling

[130] Source Technology Associates, Monitoring emissions under a regulatory framework for the electricity sector, prepared for Environment Canada, April 2008.

platform and the cold Canadian weather also renders this setting precarious for CEMS. On the other hand, at ground level, installation of long heated umbilical lines to transport the flue gas samples are required which add significant costs that can be as high as $50k.[131] Another source reports a price tag of $30–50k for 100 m long umbilical line.[132] The overall price tag for a suitable CEMS platform obviously varies from site to site but in general, it is not expected to exceed $100k,[133,134] excluding the heated umbilical lines which are associated with the CEMS direct costs instead.

Table 5-1: Summary of capital and O&M costs for the installation and operation of a mercury CEMS

Capital cost		O&M cost	
Item	**Estimate**	**Item**	**Estimate**
Preliminary planning	$5 k	Day-to-day activities	$15 k
Equipment selection	$15 k	Maintenance	$10 k
Site preparation	$80 k (+250 k for elevator if required)	Recordkeeping and reporting	$7 k
Purchase	$175 k	Annual RATA	$20 k
Installation	$25 k	NIST traceable gas calibration audit	$15 k
Initial certification tests	$25 k	Technical review	$3 k
Preparation of QA/QC program	$10 k	*Annual overhead* [a]	*$5 k*
TOTAL	**$335 k**	**TOTAL**	**$75 k**

[a] Typical plant and payroll overhead usually covers 50–70 % of total plant labor.[135] The overhead cost specific to the Hg CEMS is however difficult to evaluate considering that most of these costs (i.e. taxes, insurance premiums, fringe benefits, plant offices, parking area, etc.) are already partly covered. Therefore, a 10% factor on CEMS O&M costs (excl. annual RATA) is applied.

The direct cost associated with the purchase of CEMS hardware has been estimated between $95 k and $135 k by the U.S. EPA in 2003 and has barely changed ever since. It is believed that increasing competition has kept these costs relatively stable. Including heating umbilical cords for ground level commissioning, the purchase cost should normally approach $175k. Commissioning of the mercury CEMS is not cost-intensive compared to other industrial equipment and normally approaches $20–$30k (or 15% of direct costs). This includes labour and equipment for the installation, start-up and training of the power plant personnel requiring

[131] Wilber, K.R. from Tekran Instruments Corp., Continuous mercury emissions monitoring feasibility and costs, presentation for the Lake Michigan Air Directors Consortium Emissions Controls and Monitoring Technologies, March 2010.
[132] Lehigh University Energy Research Center, Armstrong Project: Evaluation and comparison of U.S. and EU reference methods for measurement of mercury, heavy metals, $PM_{2.5}$ and PM_{10} emissions from fossil-fired power plants, February 2007.
[133] Source Technology Associates, Monitoring emissions under a regulatory framework for the electricity sector, prepared for Environment Canada, April 2008.
[134] Wilber, K.R. from Tekran Instruments Corp., Continuous mercury emissions monitoring feasibility and costs, presentation for the Lake Michigan Air Directors Consortium Emissions Controls and Monitoring Technologies, March 2010.
[135] Vatavuk, W. M., Estimating costs of air pollution control, Lewis Publishers, Chelsea, MI, 1990.

between 250–300 hours of labour.[136] The installation cost does not include any potential performance warranty agreement between the CEMS vendor and the owner that would ensure that the CEMS is working properly in the early stages and is suitable for the stack gas conditions. The costs associated with this agreement will depend of its scope (i.e. requirements, duration) and so, it can not be clearly identified at this point. In our opinion, this type of agreement should not be greater than 10% of capital cost in order to be competitive with other systems.

Following start-up, an initial certification test is required to confirm the integrity of the mercury CEMS for quality assurance purpose (see Section 4). For the plant owner, this means costs for the selection of the RATA consultant, the RATA test fee, the completion of other QA/QC tests and reporting. The RATA test using the OHM stack testing method (12 tests on 2 weeks span) covers most of the costs (normally $20–25k from the consultant, i.e. $1,500/day for testing and analysis + $2–5k for overhead and reporting) while other expenses should not exceed $5k.

Upon completion of the initial certification, the investment for purchasing, installing and commissioning the mercury CEMS should approach 335,000 CAD 2009 ($235–500k for a -30% to 50% order-of-magnitude accuracy) excluding the installation of an elevator, if required, which is valued at $250k. This corresponds to a constant annuity of $40 k ($29–59k) based on a 10% discount rate over a 20-year period.

5.2.2 O&M costs

Recurring annual costs excluding the capital recovery come from day-to-day activities regarding the QA/QC program, CEMS maintenance (parts & repairs), recordkeeping and reporting duty, annual RATA, calibration gas certification and annual technical review. These costs altogether can be highly variable depending upon how much of the instrument technician's time is accounted to the mercury CEMS. Most literature sources estimate the annual costs to range between $35k and $70k break down into:

- Day-to-day activities in regard to mandatory QA/QC tasks as defined in Section 4: $15k/annually incl. consumables for daily tests (0.5 h/day), weekly tests (2 h/week) and quarterly tests (5 h/quarter);

- Standard maintenance work for parts replacement including filters, catalysts, o-rings, etc.: $5–15k/annually. As a system ages (or struggles), electronic, optical or other major CEMS component will need to be repaired or replaced, adding to maintenance costs. A 5% annual escalation rate in maintenance cost is applied to represent this aspect;

- Recordkeeping and reporting duty (i.e. data reduction, 0.25 h/day; monthly review, 4 h/mo; quarterly, semi-annual or annual report, 10 h/report) typically requires $6–8k of the budget;

- RATA test from consultant: $20–25 k (see previous section);

- NIST traceable calibration gas audits: $10–20 k[137,138];

[136] U.S. EPA, CEMS cost model, 2007.
[137] Wilber, K.R. from Tekran Instruments Corp., Continuous mercury emissions monitoring feasibility and costs, presentation for the Lake Michigan Air Directors Consortium Emissions Controls and Monitoring Technologies, March 2010.
[138] U.S. EPA, CEMS cost model, 2007.

- Annual technical review including meetings, update of the QA/QC plans, inventory, etc. takes less than 50 hours of technician and engineer time: < $3 k.

When including the capital recovery, the annualized cost for operating the mercury CEMS approaches $114,000 CAD 2009. These estimates are mostly applicable for a new mercury CEMS with 'normal' operability that does not require inordinate and unexpected amounts of corrective maintenance.

5.3 Dry sorbent trap monitoring

Dry sorbent trap for mercury monitoring is a relatively new concept for which few vendors were available until recently. However, considering the hardware is much less complex than CEMS and typically modular, the overall capital cost for implementing a dry sorbent trap system remains fairly marginal representing a fraction of CEMS capital cost. In contrast, the annual operating and maintenance cost can be significant owing to the extra costs for sorbent traps and laboratory analysis. In fact, annual expenses depend largely on the sampling frequency (i.e. typical sampling duration: 1–7 days) which is specific to the flue gas condition and sorbent trap mercury capacity.

5.3.1 Capital costs

The implementation of a dry sorbent trap mercury monitor involves the same phases as CEMS (planning, equipment selection, site preparation, purchase, installation, initial certification and preparation of a QA/QC program). Preliminary planning where the mercury monitoring approach is determined according to the regulation specifications normally requires less than a few weeks of work (<$5k in labour, Tab. 5-2). Once a decision is made, the owner must select a vendor which involves several hours of administrative work to identify potential vendors, write the request for proposal (if necessary), evaluate proposals and negotiate contracts. Owing to the relative simplicity of a dry sorbent trap monitoring system (modular hardware including probe, gas conditioner and sampling console), these tasks should demand less work than for CEMS selection (estimated 2 weeks of work, $4k). Dry sorbent trap monitors can be installed at elevation near the sampling port if it is well located against weather conditions and other potential stresses. Site preparation is therefore limited and varies from site to site. A $10k budget is believed more than enough for this job.

The direct cost associated with the purchase of dry sorbent trap monitor hardware includes the sampling probe assembly (± $1,000), the moisture removal device and gas conditioner (± $5,000) and the gas sampling console (± $10,000) which comes to $15–20k for the whole package. Sorbent trap system commissioning is normally very simple taking 1–2 days for the installation and start-up. Required training is also limited. Following start-up, an initial certification test is required to confirm the integrity of the sorbent trap system for quality assurance purpose (see Section 4). This implies costs for the selection of the RATA contractor, the RATA test fee, the completion of other QA/QC tests and reporting. The RATA test using the OHM stack testing method normally costs $15–25k while other expenses should not exceed $3k.

An alternative to reduce the important operating costs (cf. next section) attributed to the use of dry sorbent traps, the plant owner could also purchase a specialized sorbent trap mercury analysis system. However, this is conditional to the ability of the plant technicians to perform the analysis along the QA/QC guidelines established in Section 4. Although the purchase cost is

relatively important ($30–50k), this option would help reduce the expenses associated with subcontract lab analysis. On the other hand, some capital cost elements would slightly increase with the addition of the mercury analyser (see Table 5-3).

The global capital costs for purchasing, installing and commissioning the dry sorbent trap mercury monitoring system for compliance purpose should approach 60,000 CAD 2009 for option 1 with subcontract lab analysis and 100,000 CAD 2009 for option 2 with on-site mercury analysis. This corresponds to a constant annuity of $7 k ($5–11 k) and $12 k ($8–18 k) respectively, based on a 10% discount rate over a 20-year period.

Table 5-2: Summary of capital and O&M costs for the installation and operation of a dry sorbent trap mercury monitor (Option 1: with subcontract lab analysis, Option 2: with on-site mercury analysis)

Capital cost			O&M cost [a]		
Item	Estimate		Item	Estimate	
	Opt. 1	Opt. 2		Opt. 1	Opt. 2
Preliminary planning	$3 k	$3 k	Trap consumables and analysis	$70 k	$40 k
Equipment selection	$4 k	$6 k	Day-to-day activities	$20 k	$30 k
Site preparation	$10 k	$10 k	Maintenance	$2 k	$4 k
Purchase	$17 k	$55 k	Recordkeeping and reporting	$5 k	$5 k
Installation	$2 k	$3 k	Annual RATA	$20 k	$20 k
Initial certification tests	$20 k	$20 k	Technical review	$3 k	$3 k
Preparation of QA/QC program	$5 k	$5 k	*Annual overhead* [b]	*$3 k*	*$4 k*
TOTAL	**$61 k**	**$102 k**	**TOTAL**	**$123 k**	**$106 k**

[a] Cost approximated for 150 samples/a (~60 h or 2.5 days sampling duration).

[b] Typical plant and payroll overhead usually covers 50–70 % of total plant labor.[139] The overhead cost specific to the dry sorbent trap system is however difficult to evaluate considering that most of these costs (i.e. taxes, insurance premiums, fringe benefits, plant offices, parking area, etc.) are already partly covered. Therefore, a 10% factor on dry sorbent trap monitoring O&M costs (excl. trap consumables and annual RATA) is applied.

5.3.2 O&M costs

The purchase of mercury-spiked sorbent traps and their analysis after sampling represents the largest annual expense which is highly variable depending on the system's operating setup. The cost per sampling campaign typically ranges between $400 and $500, consisting approximately of $60 per trap (×2), $60 per trap for pre-spiking with mercury and $100 per trap for the analysis of the three-section sorbent media after sampling.[140] With the on-site mercury analyser option, the global cost for sorbent traps would be reduced to $200–$300. Based on an average sampling duration of 1–7 days, the annual expenditure for traps theoretically varies between $20k and $180k. However, most literature sources estimate these costs to range between $60k and $120k[141,142] which also include:

[139] Vatavuk, W. M., Estimating costs of air pollution control, Lewis Publishers, Chelsea, MI, 1990.
[140] U.S. EPA, The Environmental Technology Verification Program: Mercury emissions monitor, 2007.
[141] Canadian Electricity Association, Mercury Information Clearinghouse – Quarter 8: Commercialization aspects of sorbent injection technologies in Canada, October 2005.

- Day-to-day activities in regard to mandatory QA/QC tasks as defined in Section 4: $20k/annually (based on 150 samples/a) for daily checks (0.25 hr/day) and pre- & post-sampling tests and management (2 hr/test). An additional $10k/a would be required to operate the on-site mercury analyser by plant technicians;

- Standard maintenance work on the sorbent trap assembly is minimal: $2k/annually. A similar situation is expected for the on-site mercury analyser. A 5% annual escalation rate in maintenance cost is applied to represent the extra maintenance for older systems;

- Recordkeeping and reporting duty (i.e. data reduction, 1 h/week; monthly review, 4 h/mo; quarterly, semi-annual or annual report, 10 h/report) typically monopolizes $5–8k of the budget;

- RATA test from consultant: $20–25k;

- Annual technical review including meetings, update of the QA/QC plans, inventory, etc. takes less than 50 hours of technician and engineer time: < $3k.

When including the capital recovery, the annualized cost for operating a dry sorbent trap mercury monitoring system with subcontract lab analysis approaches 130,000 CAD 2009. For the second option with on-site mercury analyzer, it would be somewhat reduced to 118,000 CAD 2009. These estimates are mostly applicable for a new system with 'normal' operability (1 sample per 60 hours or 2.5 days) that does not require inordinate and unexpected amounts of corrective maintenance.

5.4 Wet chemistry stack testing

Periodic stack testing with a sampling train (OHM, ASTM D6784-02) necessitates the extraction of a gas sample manually from the stack, usually over a few hours. In contrast to other recommended mercury monitoring regimes, this method does not require any capital investment other than ensuring that the infrastructures (platform and sampling port) are acceptable for the consultant. Most Canadian coal-fired EGUs have participated to the CEA mercury program in 2002 (except Grand Lake and H.R. Milner facilities) which demanded stack testing as part of the evaluation. Therefore sampling infrastructures exist and further investment for implementing this monitoring regime for compliance purpose is considered negligible. Test fees and labour cost for assistance, recordkeeping and reporting covers most of the expenses.

[142] U.S. EPA, Standards of performance for new and existing stationary sources: electric utility steam generating units; final rule (40 CFR 60, 72 and 75), May 2005.

5.4.1 O&M costs

As mentioned, recurring costs per stack test trial comes from consultant fees and related plant labour. Triplicate runs lasting a few hours can normally be carried out within 2 days with fees extending between $3–5k (i.e. $1,500/day for testing & analysis + $1–2k for overhead and reporting). Pre- and post-test administrative work (i.e. contacting the consultant, assistance to the consultant, recordkeeping and reporting) by the plant representatives typically requires the equivalent of 3 days of work ($1–1.5k). Accordingly, overall expenses for the realization of one triplicate stack test campaign are estimated between $4–6.5k. For a regulation that requires quarterly testing, annual expenses should approach $25k including annual overhead.

5.5 Levelized costs

Calculation of levelized costs over a 20-year operating life period (Eq. 5-1 to 5-3) was carried out in accordance with the capital and annual operating costs developed in previous sections. The levelized busbar cost is based on a 500 MW unit operated at 80% of its capacity annually. The following assumptions were considered as well:

- Present worth discount rate of 10%;
- Capital costs are considered for year 0 only (not annualized over the 20-year period);
- Time for commissioning (from planning to initial certification) CEMS and dry sorbent trap monitors is set at 4 and 1 month, respectively;
- Annual RATA and technical review costs are not relevant to year 0 (not included in first year costs);
- Maintenance cost escalation rate set at 5%;
- Inflation rate (construction and labour) of 2% is applied over the 20-year period;
- Revenues associated to a monitoring regime come from the avoided costs from the previous monitoring regime. The mass balance approach with $20k annual expenses is considered in the analysis;
- Potential taxes, credits or interests not included.

A summary of important cost parameters including levelized costs are presented in Table 5-3 for each monitoring regime while Table 5-4 provides an overview of potential first year costs and levelized costs for the Canadian coal-fired EGU sector according to their situation in 2009. It confirms that mercury CEMS, although the investment is considerable at first (first year cost: $369k vs. $150k–$176k for dry sorbent trap), becomes economical on the long run compared to dry sorbent trap monitoring (levelized cost: $111k/a for CEMS vs. 134$k/a for dry sorbent trap with subcontracted lab analysis or $118k/a for dry sorbent trap with on-site analysis) as long as the system operates without major difficulties. However, due to the novelty, complexity and fragility of mercury CEMS today, there is no guarantee that it would not require major repairs over a 10–20 years operating life. Periodic repair or even CEMS replacement should not increase the levelized costs significantly. For example, the replacement of a mercury CEMS by another one after 10 years will increase the 20-year levelized cost by 15% to $130k/a, all other things being equal.

Table 5-3: Summary of cost parameters for the installation and operation of recommended mercury monitoring regimes

Parameter	CEMS	Dry sorbent trap		Stack testing
		Opt. 1 [a]	Opt. 2 [a]	
Capital cost	$335,000	$61,000	$102,000	N/A
Annualized capital cost [b]	$39,000/a	$7,200/a	$12,000/a	N/A
Depreciation cost	$9,000/a	$1,000/a	$2,800/a	N/A
Annual O&M cost [c]	$77,000/a	$122,000/a	$105,000/a	$25,000/a
First year costs [d]	$369,000	$150,000	$176,000	$25,000
Total costs [e]	$2,340,000	$3,120,000	$2,750,000	$645,000
Levelized annual cost	$111,000/a	$134,000/a	$118,000/a	$6,400/a
Levelized busbar cost	3.2 ¢/MWh	3.8 ¢/MWh	3.4 ¢/MWh	0.2 ¢/MWh

[a] Opt.1: with subcontracted lab analysis; Opt. 2: with on-site analysis.
[b] Annuity over a 20-year period at an 10% discount rate.
[c] Estimation for full year operation (2009).
[d] Include the capital cost and applicable annual operating cost for year 0.
[e] Sum of non levelized costs over the 20-year period.

For sorbent trap monitoring, the sampling frequency greatly affects its economics (see Section 5.6). For a sampling duration of 3.5 days (default value is set at 2.5 days in Tab. 5-2 and 5-3), the levelized cost for dry sorbent trap sampling with subcontracted lab analysis would become equivalent to the CEMS's levelized cost. For a 7 days sampling period, it would further drop to $78k but the quality of long-term mercury emissions projections would become questionable for compliance purposes.

The operation of mercury CEMS would cost annually about $4M levelized over 20 years to Canadian coal-fired EGUs (as of 2009) on condition that every flue gas stack is operating one (Tab. 5-4). For dry sorbent trap monitoring, it increases to $5M annually while periodic stack testing would require levelized financial resources below the $300k mark. These costs are marginal though compared to the global economics of a coal-fired power plant. In fact, the estimated levelized costs (< 4 ¢ per MWh generated, Tab. 5-3) for operating a mercury emission monitoring regime are trivial when compared to the fixed and variable operating and maintenance costs required for operating a coal-fired power plant (typically 20–30 USD per MWh generated[143]).

[143] U.S. Energy Information Administration, 2016 levelized cost of new generation resources from the annual energy outlook 2010, January 2010.

Table 5-4: First year costs (FYC) and levelized costs (LC) by province (according to their situation in 2009) for the installation and operation of the recommended mercury monitoring regimes

Province	CEMS		Dry sorbent trap [a]		Stack testing	
	FYC $k	LC [b] $k/a (¢/MWh)	FYC $k	LC [b] $k/a (¢/MWh)	FYC $k	LC [b] $k/a (¢/MWh)
Alberta	4,060	1,225 (2.8)	1,650	1,450 (3.3)	275	70 (0.2)
Manitoba	370	110 (19.8)	150	135 (23.9)	25	6 (1.1)
New Brunswick	740	220 (5.0)	300	270 (6.1)	50	13 (0.3)
Nova Scotia	2,220	670 (6.9)	900	805 (8.3)	150	39 (0.4)
Ontario	3,325	1,000 (3.1)	1,350	1,210 (3.7)	225	58 (0.2)
Saskatchewan	2,960	890 (7.3)	1,200	1,075 (8.8)	200	51 (0.4)
Canada	**13,675**	**4,115 (4.0)**	**5,550**	**4,945 (4.8)**	**925**	**240 (0.2)**
Future facilities	1,480	445 (3.2)	600	540 (3.8)	100	26 (0.2)

[a] Option with subcontracted lab analysis.
[b] Annual electricity production is based on reported data in 2003 (UDCP).

5.6 Sensitivity analysis

A sensitivity analysis exploring the impact of various cost items and parameters on the economics of recommended mercury monitoring regimes was carried out. It was assessed by calculating the specific linear variation of the levelized annual cost for each variable (in $k per % deviation of the variable).

Figure 5-1 exposes the results for the operation of a mercury CEMS. It shows that each capital and annual cost items covered in Section 5.2 have some influence on the levelized cost ranging between 0.04 and 0.25 $k per % deviation. Most sensitive items are equipment direct cost, day-to-day activities and annual RATA. As expected, the sensitivity of total annual costs (0.89 $k/% deviation) is about twice as significant compared to total capital costs (0.39 $k/% deviation). For example, a 10% increase in the annual costs will increase the levelized cost from 111 $k/a (see Tab. 5.3) to 120 $k/a. A similar increase in the capital costs will raise the levelized cost to 115 $k/a. The extent of costs avoided by installing the new mercury CEMS is also an important parameter as is the discount rate adjusting the worth of money over the 20-year period.

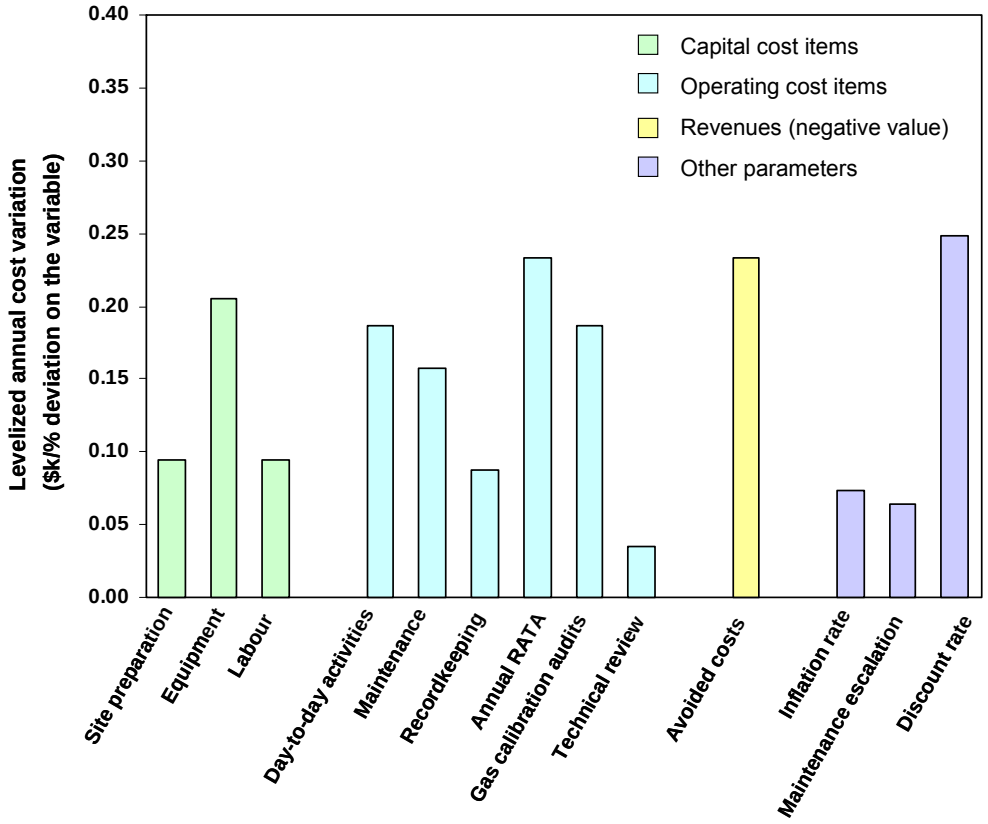

Figure 5-1: Impact of cost items and economic parameters on the levelized annual cost for the mercury CEMS

Figure 5-2 exposes the sensitivity analysis results for the operation of a dry sorbent trap mercury monitoring system including subcontracted lab mercury analysis. As expected, the sensitivity of capital costs on the 20-year levelized cost is almost negligible (0.07 $k/% deviation) compared to annual operating costs (1.47 k/% deviation). Most sensitive items are day-to-day activities, annual RATA and most important, the cost for purchasing sorbent traps and their analysis. For a 10% increase in annual sorbent trap expenses, the levelized cost would increase to 143 $k/a (default value: 134 $k/a, see Tab. 5.3). Like mercury CEMS, the costs avoided by installing the new monitoring system is a significant variable in the levelized economics of dry sorbent trap monitoring.

For wet chemistry stack testing, an increase by 30% of annual costs (incl. consultant fee, assistance and reporting, overhead) will increase the levelized annual cost by an equivalent factor (0.32 $k/% deviation) to 16.1 $k/a. The most significant cost item is the consultant annual fee. Avoided cost is another important variable to consider (-0.26 $k/% deviation).

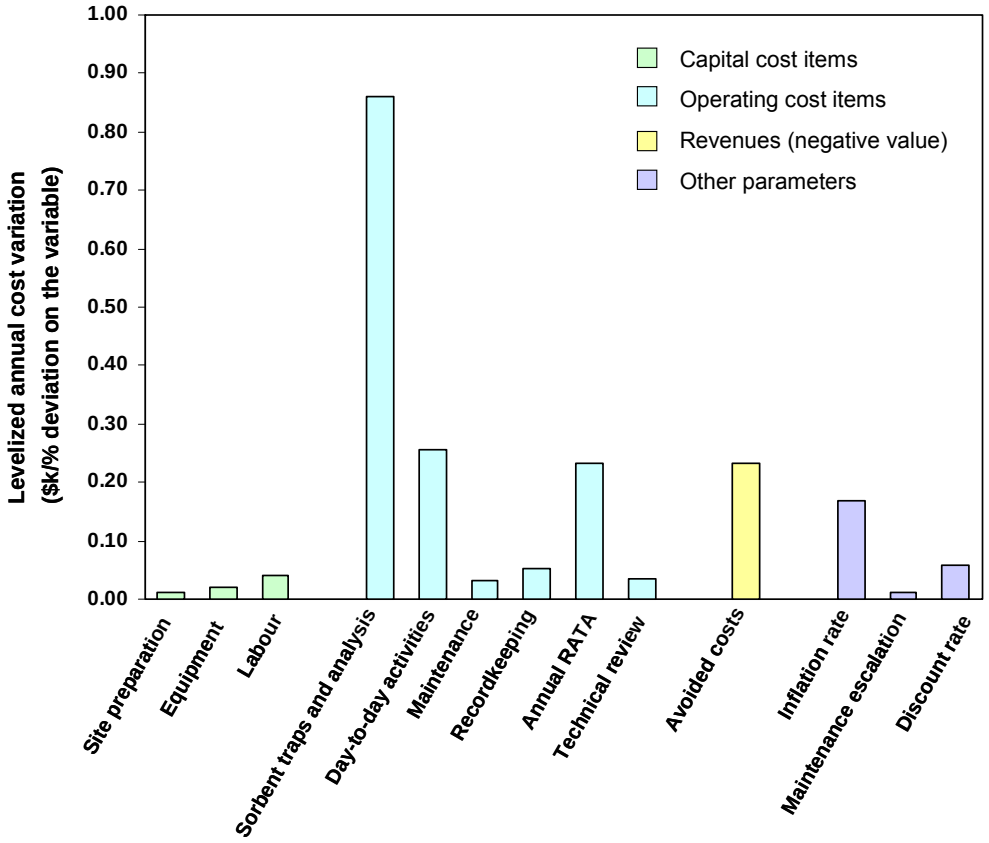

Figure 5-2: Impact of cost items and economic parameters on the levelized annual cost for the dry sorbent trap mercury monitoring system

6. CONCLUSION

The objective of this work was to provide Environment Canada with a better understanding of available methods for measuring and quantifying mercury airborne releases and the technical and economic implications they would have on the Canadian coal-fired electricity generation sector. This work was carried out in 3 phases:

1. Review currently available mercury monitoring techniques for air and soil/water emissions according to the following criteria: measurement frequency, accuracy and uncertainties, detection limit, reliability, practicality and extent of application, costs, advantages and limitations. Following this analysis, propose the optimal airborne mercury monitoring regime for the Canadian coal-fired EGU sector. Propose two alternative monitoring methods that would be appropriate for use by Canadian low-mass mercury emitters (LME) and peaking units.

2. Identify and describe the reporting requirements for compliance purpose (compliance data reduction method, report content, frequency of reporting and method of reporting) of mercury emissions extracted from the recommended mercury monitoring regimes. Identify the QA/QC requirements that would consolidate the exactness of measurements from the recommended monitoring regimes.

3. Estimate the installation, annual and levelized costs for operating the recommended mercury monitoring regimes as a per unit basis and globally for the existing and hypothetical future Canadian coal-fired power generation facilities.

Recommended mercury monitoring methods

Several airborne mercury monitoring (predictive approach, mass balance approach, wet chemistry stack testing, CEMS, dry sorbent trap, semi-continuous CEMS) and soil/water mercury monitoring (automatic, manual sampling and analysis) methods were reviewed. The CEMS was considered the best monitoring option for the following reasons:

- Method proven accurate if an appropriate QA/QC program is followed rigorously;
- Only real-time method that can detect and represent inherent fluctuation in power plant's operation and can provide an evaluation of mercury control strategies;
- Low detection limit for mercury allows for the implementation of high and low-mass mercury emitters (not ultra low-mass emitters depending on the circumstances);
- Although technical issues have plagued mercury CEMS, rapid development and efficient troubleshooting (in part due to the instauration of the U.S. EPA mercury rule in 2005 but vacated in 2008) is currently improving their potential for the near future;

The dry sorbent trap monitoring regime was considered the second best option owing to its very low detection limit and the fact that other gases do not interfere with the measurement. Time-average mercury concentrations on a 1–7 days period is deemed appropriated for compliance purpose as long as the power plant's operation (i.e. coal input, heat stream, APC operation) remains mostly undisturbed during that time span. The third recommended mercury monitoring option is periodic stack testing using the standardized Ontario Hydro method (OHM) which is in fact more appropriate for use on peaking units.

Reporting and QA/QC requirements

Quality assurance and quality control requirements allowing control of the precision, accuracy and completeness of data vary for each recommended monitoring regimes:

- CEMS: Installation and operation of a CEMS should follow four levels of QA including system certification (vendor's responsibility), initial certification (incl. calibration drift test, linearity check, system integrity checks, cycle time test, RATA, auxiliary equipment conformity), continuous QC program (incl. calibration error test, system integrity checks, linearity check, auxiliary equipment verification) performed during operation and an annual audit (RATA);

- Dry sorbent trap: Installation and operation of a dry sorbent trap mercury monitor should follow three levels of QA including initial certification (incl. ancillary equipment verification, RATA), continuous QC program (incl. system calibration and reliability tests, mercury analysis control, sample quality control) and an annual audit (RATA);

- OHM stack testing: Periodical stack testing according to the OHM method is performed by a consultant. Certification and quality assurance regarding the integrity of their sampling equipment is their responsibility since mercury analysis is carried out by an accredited laboratory. The owner should perform on-going QA testing of auxiliary monitoring systems like the stack gas flow monitor which values are used in calculations.

For any mercury monitoring regime, compliance reports in response to specifications from a regulation should be submitted preferably using an electronic template containing the following items: plant identifications, plant information, plant activities, mercury monitoring plan, mercury emissions measurements, data reduction results, QA/QC documentation and supplemental information. Semi-annual reporting of CEMS and dry sorbent trap monitoring data is recommended.

Cost analysis

Economic assessment of the recommended mercury monitoring regimes has revealed that both mercury CEMS and dry sorbent trap monitoring requires over $100k of levelized dollars per year (LAC) for installation and operation over a 20-year operating life. This price tag will increase, especially for mercury CEMS, if the operating life is reduced due to important capital costs (± $335k vs. $60–100k for dry sorbent trap monitoring). Installation and operation of these monitoring regimes costs between 3–5 ¢ per unit for each megawatt-hour of electricity generated by a standard power plant (i.e. 500 MW). This is negligible compared to the operating and maintenance costs required for operating a coal-fired power plant. For quarterly stack test campaigns, the annual costs drop to less than 1 ¢ per MWh (LAC = $6.4k/a).

The sensitivity analysis has shown that most capital (site preparation, equipment, labour) and annual (day-to-day, maintenance, RATA, gas calibration audits, recordkeeping and reporting) cost items for mercury CEMS have comparable influences on the levelized cost. Most sensitive cost items are equipment purchase, day-to-day activities and annual RATA. For dry sorbent trap monitoring, the most sensitive parameter is the sorbent trap consumables and analysis which covers most of the annual costs. Sampling frequency is therefore a vital element in defining the economics of dry sorbent trap monitoring.

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Appendix A

U.S. states regulations

Table A-6-1: U.S. states strategies for addressing mercury emissions according to a NACAA census

State	Regulation/strategy overview	Hg emission target (~: estimation)
Colorado	• Regulation adopted in February 2007. • Phase I target: 0.0174 lb/GWh or 80% mercury capture by 2014. • Phase II target: 0.0087 lb/GWh or 90% mercury capture by 2018. • Continuous mercury monitoring is required with QA/QC provisions that are different to CAMR provisions.	~1.3–2.6 kg/TWh$_{th}$ 3.9–7.9 kg/TWh$_{e}$
Connecticut	• Regulation adopted in 2003, effective in July 2008. • Target: 0.6 lb/TBtu or 90% mercury capture. • Affects 2 bituminous coal power plants. • Compliance is determined through quarterly stack testing.	0.9 kg/TWh$_{th}$ ~2.8 kg/TWh$_{e}$
Delaware	• Regulation adopted in 2006, effective in July 2008. • Phase I target: 1.0 lb/TBtu or 80% mercury capture by 2009. • Phase II target: 0.6 lb/TBtu or 90% mercury capture by 2013. • Intra-state trading not allowed.	0.9–1.6 kg/TWh$_{th}$ ~2.8–4.7 kg/TWh$_{e}$
Illinois	• Regulation effective in July 2009. • Phase I target: 0.008 lb/GWh or 90% mercury capture (2009-12) on a system-wide basis. • Phase II target: 0.008 lb/GWh or 90% mercury capture by 2012 on a plant by plant basis. • Continuous emission monitoring is required by the regulation. Specifications are based on the vacated federal CAMR.	~1.2 kg/TWh$_{th}$ 3.6 kg/TWh$_{e}$
Maryland	• Maryland Healthy Air Act on NO_X, SO_2 and Hg control effective in 2007. • Phase I target: 80% mercury reduction by 2010 according to the 12-month rolling average. • Phase II target: 90% mercury reduction by 2013. • Mercury emission baseline is based on 2002 measurements and is specific to each facility.	
Massachusetts	• Rule adopted in 2004, effective in January 2008. • Phase I target: 0.0075 lb/GWh or 85% mercury capture by 2008. • Phase II target: 0.0025 lb/GWh or 95% capture by 2012. • Affects 4 bituminous coal power plants. • Requires continuous monitoring by 2008 but rulemaking on that aspect is under development. It will be derived from similar provisions included in the vacated CAMR.	~0.4–1.1 kg/TWh$_{th}$ 1.1–3.4 kg/TWh$_{e}$
Michigan	• Developing a state rule that requires mercury reduction starting in 2015. • Target: 0.008 lb/GWh or 90% mercury capture. • LME units (< 9 lb per 12-month rolling average): application of an alternative compliance demonstration project.	~1.2 kg/TWh$_{th}$ 3.6 kg/TWh$_{e}$
Minnesota	• Legislation requires 6 units to reduce mercury emissions by 90% starting in 2015.	
Montana	• Regulation adopted in October 2006. • Target (a): 0.9 lb/TBtu by 2010 for non-lignite facilities. • Target (b): 1.5 lb/TBtu by 2010 for lignite facilities. • Mercury monitoring requirements are being developed based on the vacated CAMR.	1.4–2.4 kg/TWh$_{th}$ ~4.2–7.1 kg/TWh$_{e}$
New Jersey	• Regulation adopted in 2004, effective in December 2007.	~1.0 kg/TWh$_{th}$

State	Regulation/strategy overview	Hg emission target (~: estimation)
	• Target: 3 mg/MWh or 90% mercury capture by 2008 on annual basis. • Affects 10 units all using bituminous coal. • Intra-state trading not allowed (except for multiple units on the same site).	3.0 kg/TWh_e
New York	• Regulation adopted in 2007, effective in 2010. • Phase I target: annual facility-wide emissions based on state mercury budget proposed by the CAMR (0.393 tons/a) until 2014. • Phase II target: 0.6 lb/TBtu starting in 2015.	0.9 kg/TWh_{th} ~2.8 kg/TWh_e
North Carolina	• Regulation NC Clean Smokestacks Act requires control of NO_X and SO_2 co-benefiting mercury control as well. • NC mercury rule requires a control plan by January 2013, for application in 2017.	
South Carolina	• State version of CAMR was developed but is now in the process of being removed. • Agreement with EGUs to either install Hg monitors or perform stack testing by July 2009.	
Wisconsin	• Regulation effective in December 2008. • Phase I target: 40% mercury emissions reduction by 2010. • Phase IIa target: 0.008 lb/GWh or 90% mercury capture (based on mercury content in coal) by 2015 for large coal-fired power plants (150+ MW). • Or phase IIb target: 0.019 lb/GWh or 70% mercury capture by 2015 for large coal-fired power plants if multi pollutant control is required. The final standard is 0.013 lb/GWh or 80% mercury capture by 2018 in this case.	~1.2–2.9 kg/TWh_{th} 3.6–8.6 kg/TWh_e
Maine, Kentucky, Mississippi, Tennessee, Oklahoma, Iowa, Kansas, Missouri, Nebraska, North Dakota, Alaska, Washington, Arkansas, Georgia, Virginia, West Virginia, California, South Carolina		Waiting for new federal standards.
Rhode Island, Vermont, Idaho		Not applicable. No EGU.
States that are not covered in this table did not provide information to the NACAA census as of April 2010.		

Appendix B

Missing data procedure

Table B-6-2: Standard missing data procedure when operating a mercury CEMS or dry sorbent trap monitoring system

Data availability	Outage duration	Standard missing data procedure	
		CEMS	Dry sorbent trap
≥ 90%	≤ 24 h	Two-point average of the immediate previous and following hours to the outage	Average of all valid data obtained from analyses in the previous 12 months
	> 24 h	The greater between the average and the 90th percentile on 720 hrs of valid data from no earlier than 3 years prior to the missing data period	
80–90 %	≤ 8 h	Two-point average of the immediate previous and following hours to the outage	95th percentile of all valid data obtained from analyses in the previous 12 months
	> 8 h	The greater between the average and the 95th percentile on 720 hrs of valid data from no earlier than 3 years prior to the missing data period	
70–80%	> 0 h	Maximum of 720 hrs of valid data from no earlier than 3 years prior to the missing data period	Maximum of all valid data obtained from analyses in the previous 12 months
<70 %		Maximum potential concentration should be reported • Bituminous coal combustion: 9 μg/Nm^3 • Sub-bituminous coal combustion: 10 μg/Nm^3 • Lignite coal combustion: 16 μg/m^3	

Appendix C

Mercury monitoring detection range

Table C-6-3: Estimation of the applicable detection range per facility for recommended mercury monitoring regimes.

Facility	2008 reported Hg emissions (kg)	Applicable detection range (kg)		
		CEMS [a]	Sorbent trap [b]	Wet chemistry stack testing [c]
Sundance	145	5.8 – 873	1.7 – 5800	29.1 +
Keephills	22	2.4 – 362	0.7 – 2400	12.1 +
Wabamun	41	0.6 – 91	0.2 – 610	3.0 +
Genesee	105	4.0 – 604	1.2 – 420	20.1 +
Sheerness	90	2.4 – 361	0.7 – 2400	12.0 +
Battle River	67	1.8 – 269	0.5 – 1800	9.0 +
H.R. Milner	4	0.4 – 56	0.1 – 380	1.9 +
Brandon	10	0.2 – 34	0.1 – 220	1.1 +
Belledune	11	1.6 – 238	0.5 – 1580	7.9 +
Grand Lake	33	0.2 – 27	0.1 – 180	0.9 +
Lingan	95	1.9 – 281	0.6 – 1900	9.4 +
Point Aconi	3	0.5 – 81	0.2 – 540	2.7 +
Point Tupper	24	0.5 – 71	0.1 – 470	2.4 +
Trenton	41	0.8 – 124	0.2 – 830	4.1 +
Atikokan	18	0.4 – 57	0.1 – 380	1.9 +
Lambton	58	4.0 – 595	1.2 – 4000	19.8 +
Nanticoke	84	7.9 – 1191	2.4 – 8000	39.7 +
Thunder Bay	31	0.6 – 88	0.2 – 580	2.9 +
Boundary Dam	285	2.4 – 367	0.7 – 2500	12.2 +
Poplar River	244	1.8 – 267	0.5 – 1800	8.9 +
Shand	99	0.8 – 123	0.2 – 820	4.1 +

Applicable detection range calculated according to the following equation:

Detection limit (kg/Nm^3) × 4 Nm^3/kWh_e[144] × annual electricity generation (kWh_e/a, see Tab. 2-2)

[a] CEMS detection range = 0.1–15 μg/Nm^3.
[b] Sorbent trap detection range = 0.03–100 μg/Nm^3.
[C] Wet chemistry stack testing minimum detection = 0.5 μg/Nm^3.

[144] Sargent & Lundy LLC, Flue Gas Desulphurization Technology Evaluation, Dry Lime vs. Limestone FGD, prepared for National Lime Association, March 2007.

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