Legislation, standards and methods for mercury emissions control

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Abstract

Mercury is an element of growing global concern. The United Nations Environment Programme plans to finalise and ratify a new global legally-binding convention on mercury by 2013. Canada already has legislation on mercury emissions from coal-fired utilities and the USA has recently released the new Mercury and Air Toxics Standard. Although other countries may not have mercury-specific legislation as such, many have legislation which results in significant co-benefit mercury reduction due to the installation of effective flue-gas cleaning technologies.

This report reviews the current situation and trends in mercury emission legislation and, where possible, discusses the actions that will be taken under proposed or impending standards globally and regionally. The report also reviews the methods currently applied for mercury control and for mercury emission measurement with emphasis on the methodologies most appropriate for compliance. Examples of the methods of mercury control currently deployed in the USA, Canada and elsewhere are included.

Acronyms and abbreviations

ACAP	Arctic Council Action Plan
ACI	activated carbon injection
APH	air pre-heater
BAC	brominated activated carbon
BAT	best available technique(s)
BEP	best environmental practice
BREF	BAT Reference Documents
Btu	British thermal unit
CAMR	Clean Air Mercury Rule, USA
CCICED	China Council for International Cooperation on Environment and Development
CEM	continuous emissions monitor
CEN	Comité Européen de Normalisation
CPC	carbon polymer composite
CSAPR	Cross-state Air Pollution Rule, USA
CWS	Canada-wide Standard
DSI	dry sorbent injection
EC	European Commission
EERC	Energy and Environmental Research Centre, ND, USA
ELV	emission limit value
ESP	electrostatic precipitator
EU	European Union
FBC	fluidised bed combustion
FF	fabric filter (baghouse)
FGD	flue gas desulphurisation
HELCOM	Helsinki Commission
HSBit	high sulphur bituminous coal
IED	Industrial Emissions Directive, EU
IPPC	Integrated Pollution Prevention and Control, EU
KTM®	KEMA Trace Model®
LCPD	Large Combustion Plant Directive, EU
LRTAP	long-range transboundary air pollution
LSBit	low sulphur bituminous coal
MACT	maximum achievable control technology
MATS	Mercury and Air Toxics Standard, USA
MMACF	million actual cubic feet
MEPOP	mercury and persistent organic pollutants
MHI	Mitsubishi Heavy Industries
MMACF	million actual cubic feet
NARAP	North American regional action plan
NEPM	National Environmental Protection Measures, Australia
NERP	National Emission Reduction Plan
NETL	National Energy Technology Laboratory, US DOE
NHMRC	National Health and Medical Research Council, Australia
NPI	National Pollutants Inventory
NSPI	Nova Scotia Power Inc, Canada
OSPAR	Oslo and Paris Commission
PEESP	plasma-enhanced electrostatic precipitation
POG	Process Optimisation Guidance Document, UNEP
PRB	Powder River Basin
SCR	selective catalytic reduction

SDA	spray dry absorber
SEA	sorbent enhancement additives
SED	Solvent Emissions Directive, EU
SNCR	selective non-catalytic reduction
UBC	unburnt carbon
US DOE	US Department of Energy
UNECE	United Nations Economic Commission for Europe
UNEP	United Nations Environment Programme
US EPA	US Environmental Protection Agency
VTI	All-Russia Thermal Engineering Institute
WFGD	wet flue gas desulphurisation
WGSR	Working Group on Strategies and Review, UNECE
WID	Waste Incineration Directive, EU

Contents

1 Introduction

Recent inventories indicate that coal combustion is the largest source of mercury emissions from human activities to the atmosphere worldwide. The United Nations Environment Programme (UNEP) carried out a review of global emissions of mercury to the atmosphere in 2008 and the results, as shown in Figure 1, indicated that coal combustion contributed around 46% of total emissions. Emissions from coal combustion could continue to rise for years to come in some rapidly developing areas. In 2013, UNEP will finalise a global, legally binding convention on mercury in an effort to reduce the impact of mercury on the environment. Considering the importance of coal combustion to global emissions, the control of mercury emissions from utilities will form a major part of this new convention.

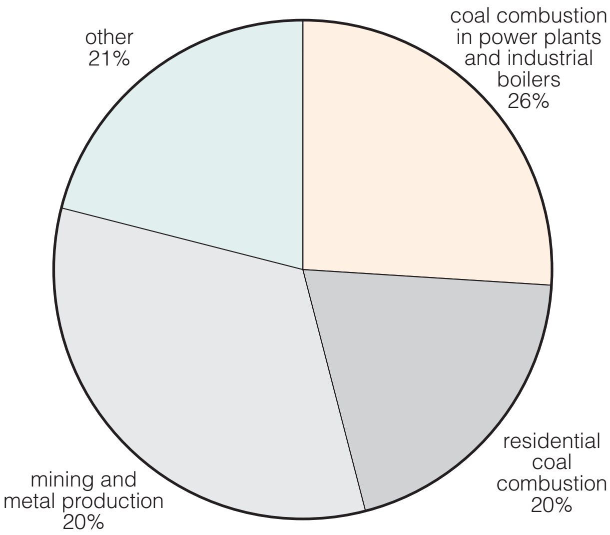


Figure 1 Proportion of global anthropogenic emissions of mercury to air in 2005

To date, there are only a few countries which have taken steps to set national standards specifically for mercury emissions from coal-fired plants. Canada has relatively stringent mercury control requirements which require significant investment in some plants in order to comply and the US EPA has recently finalised the 'MATS' – the Mercury and Air Toxics Standard, a challenging piece of legislation which must be applied within the next few years. Several states within the USA, such as New Hampshire, Maine and Massachusetts, have previously applied their own binding requirements for mercury reduction and have already achieved significant mercury control.

The European Union (EU) has updated the Large Combustion Plant Directive (LCPD) and Integrated Pollution Prevention and Control Directive (IPPC), replacing them in 2010 with the new Industrial Emissions Directive (IED). Although the IED does not set an EU-wide limit value for mercury emissions from coal-fired power plants, only annual monitoring requirements, further mercury reduction will be achieved through the co-benefit effects of pollution control systems installed for reducing particulate, SO_2 and NOx emissions in order to comply with the EU's limits set for those pollutants. Further, the IED requires that, for individual plants, emission limits are set for all relevant pollutant emissions and that those limits have to be based on the application of the best available techniques (BAT) as set out in the BAT conclusions (parts of BAT Reference Documents, or BREFs) adopted by the European Commission. A revision of the BREF on Large Combustion Plants is currently ongoing and should result in the adoption of BAT conclusions within a few years time. One of the key topics considered during the revision will be mercury emissions from coal-fired plants. Therefore, under the IED (as in under the IPPC regimes) plant-specific reduction or control requirements for mercury may still be required and, in addition, individual EU Member States may set stricter requirements than those applicable at the EU level. This appears already to be the case for several new plants in Germany and the Netherlands which could be facing a similar level of specific mercury control as that seen in Canada.

Many dozens of plants in Canada and the USA have already installed mercury-specific control technologies and are reporting mercury reduction efficiencies of 90% or more. In some situations, this level of mercury control can be achieved with existing control technologies, such as FGD and SCR systems; in others, retrofit options such as activated carbon injection are required. The variability of mercury in coal and the complexity of its behaviour in coal combustion systems means that there is no single best control strategy for mercury.

Chapter 2 of this report reviews the current and impending legislation for mercury control at coal-fired power plants internationally. Chapter 3 summarises the most relevant options for controlling mercury emissions and, where possible, gives example of where these technologies are being applied. Requirements for monitoring to ensure compliance with mercury emission standards are then discussed in Chapter 4.

2 Legislation and regulations

There are a number of international treaties, set by the United Nations Economic Commissions for Europe (UNECE), which include mercury. These are not challenging with respect to mercury limits and therefore do not currently require any action to be taken at coal-fired utilities. The United Nations Environment Programme (UNEP) Governing Council made a decision in February 2009 to further strengthen international action on mercury and has initiated negotiations towards producing a ‘Global legally binding instrument on mercury’ by 2013. The IEA CCC is acting as lead of the UNEP Coal Partnership providing information to the negotiations.

Canada and, more recently, the USA have set legally-binding requirements for mercury control at large-scale coal-fired power plants. In Europe, emissions are regulated mainly through the requirements to apply BAT, leaving some margin of discretion to the Member States and competent authorities to define the techniques and limit values set. EU limits for emissions of SO_2, NOx and partticulates have achieved co-benefits in also reducing mercury emissions. Other regions such as Australia and Asia are actively monitoring and partially controlling mercury emissions. However, they are currently doing so without the apparent urgency incurred by the national and regional binding legislation and specific mercury reduction targets that are being applied in North America.

This chapter summarises both international and national legislation. Mercury legislation is currently in a state of extreme flux and, as a result, the information included in this Chapter can only be regarded as a snapshot of the issue as this document is published. However, it is clear that many countries, not just those in North America, are moving towards more stringent control of all toxic emissions and so legislation for mercury control can be regarded as somewhat inevitable. It only remains to be seen what form this legislation may take in different regions and how soon it will be implemented.

2.1 International

There are a number of international agreements and action plans to co-ordinate action to reduce mercury emissions. These include (Sloss, 2003):

- the United Nations Economic Commission for Europe (UNECE) convention on long-range trans-boundary air pollution (LRTAP) through the Heavy Metals Prococol;
- the Oslo and Paris Commission’s programme (OSPAR) on reduction of land-based pollutants transported to the North Sea;
- the Helsinki Commission programme (HELCOM) covering the North Sea;
- the Barcelona Convention, a programme similar to OSPAR and HELCOM covering the Mediterranean Sea;
- MEPOP, a European political initiative studying the atmospheric cycling of mercury and persistent organic pollutants;
- the Arctic Council’s Environmental Protection Strategy;
- the North American Regional Action Plan between Canada, the United Mexican States and the USA;
- the Binational Toxics strategy between Canada and the USA.

None of these agreements or programmes includes guidelines on how the proposed reductions in emissions or concentrations should be achieved other than by recommending ‘best practices’. The Heavy Metals Protocol requires the use of BAT, listing options in the Annex, but does not set emission limits or reduction requirements. The agreements rely on the individual governments of each signatory country to produce a successful strategy to reduce mercury emissions. They therefore do not necessarily guarantee results. Action is rarely, if ever, taken against countries that are not as successful as others in reducing emissions.

For the moment, there is no international treaty which requires specific mercury control at coal-fired utilities. However, this may change with the introduction of the proposed UNEP Convention, mentioned above. In February 2009, the Governing Council of the United Nations Environment Programme (UNEP) agreed on Decision 23/9 defining the need to develop a global legally binding instrument on mercury. The instrument is to be completed by February 2013. This instrument is likely to be known as the 'Minamata' Convention, after the town in Japan where the worst incident of industrial methylmercury was discovered during the 1950s.

Concern has been expressed that the rapid increase in coal use in countries such as those in Asia may override reductions in emissions achieved elsewhere. It is therefore essential that any international mercury legislation is made both technically and economically viable in developing countries to ensure that the current upward trend in global mercury emissions is controlled effectively. These are the kinds of issues which will be addressed in the proposed UNEP convention which, it is hoped, will be accompanied by some form of financing mechanism.

2.2 Regional and national legislation – EU

This section summarises the legislation set at the EU level which is relevant to the control of mercury emissions from coal-fired power plants. EU Member States may set their own additional legislation as long as it is in line with, or more stringent than, that set by the EU.

2.2.1 European Union

At the moment there are no EU-wide limit values for mercury emissions from coal-fired plants except in the case of plant co-incinerating waste. However, the EU Directives on industrial emissions require competent authorities in the Member States to set emission limit values for all relevant pollutants within the permits of all installations. Those limit values have to be based on the application of BAT, defined at the EU level in the BREFs, adopted by the European Commission (EC). Under the new IED, the BAT conclusions from the BREF will take a more prominent role in the setting of emission limit values.

As a result of the current legislative framework, significant mercury reductions have been achieved, in particular as co-benefit effects through the stringent requirements for control of particulates, SO_2 and NOx (for which EU-wide emission limits apply) and this reduction is expected to continue for the next decade.

There are three established directives which are currently relevant to mercury emissions from coal-fired utilities (>50 MW rated thermal input) in the EU:

- the Integrated Pollution Prevention and Control (IPPC) Directive;
- the the Large Combustion Plant Directive (LCPD);
- the the Waste Incineration Directive (WID, only applicable to plants cofiring waste with coal).

These directives will all continue to apply until they are replaced by the Industrial Emissions Directive (IED), which enters into effect in January 2012 and will replace the IPPC and WID in January 2014 and the LCPD in January 2016.

It is therefore necessary to discuss each of these directives in turn to appreciate the ramifications for utilities in Europe.

EU Directive on **Integrated Pollution Prevention and Control** (IPPC; 2008/1/EC) applies an integrated environmental approach to the regulation of around 45,000 industrial facilities, including large combustion plants (>50 MWth), in the EU. The directive is based on plant-specific permits which detail the requirements relevant to each individual facility, which need to be based on the application of BAT, and meeting any international and national requirements (such as reduction targets for UNECE protocols and EU emission limits) while allowing permitting authorities to take into account regional and local considerations such as preservation of sensitive watershed areas. For particulates, the extensive EU BAT reference document for large combustion plants defines BAT as ESP (99.5% efficiency) in combination with wet FGD; or bag houses (fabric filters) (99.95% efficiency) in combination with wet FGD. For SO_2, the BAT options are either low sulphur fuel, wet FGD, spray dry FGD, seawater FGD, or combined SO_2 and NOx systems. For NOx, the BAT options are primary measures (air/fuel staging, low NOx burners, re-burn) in combination with SCR (selective catalytic reduction) or SNCR (selective non-catalytic reduction) in some cases; or combined SO_2 and NOx systems. However, the choice of which control combination is suitable as BAT for each individual plant has to be defined on a case-by-case basis under each permit.

The **Large Combustion Plant Directive** (LCPD; 2001/80/EC) applies to combustion plants with a thermal output of greater than 50 MW. According to the directive, all large combustion plants in Europe had to meet the following ‘minimum’ emission limit values (ELVs) for particulates, SO_2 and NOx:

- the 200 mg/m^3 SO_2 for new plant and 400–2000 mg/m^3 for existing plant (based on size);
- the 200–400 mg/m^3 NOx for new plant and 500–600 mg/m^3 for existing plant (based on plant size), from January 2016: 200 mg/m^3 for the largest existing plants (>500 MW).

As an alternative, existing plants (those permitted before July 1987) could opt for one of the following compliance options:

- the be included in a National Emission Reduction Plan (NERP) defining overall emission ‘bubbles’ that are equivalent to the ELV reductions; or
- the ‘opt out’ of ELVs and NERP and commit to close by 2016, operating for no more than 20,000 hours over the period 2008-15.

There is also a peak-load derogation for plants operating <2000 hours up to 31 December 2015 and 1500 hours after that.

Therefore, to meet both the IPPC BAT requirements and the LCPD ELV with fuel switching alone, the larger plants would need to be firing very low sulphur coal to avoid having to install FGD. In simplistic terms, the IPPC and LCPD together mean that all larger plants must install wet FGD (or a technology with similar or greater SO_2 control) and make at least combustion modifications to reduce NOx (many of the larger plants require SCR or SNCR in addition to combustion modifications). Plants which could not comply with the limit values or are not covered by a NERP are to close by 2016 and run limited operating hours until that date.

As a result of the LCPD, almost 25 GW of coal units and 10 GW of lignite units did not install FGD and instead those plants chose to opt-out of the LCPD and close by 2016 (Kramarchuk and Brunetti, 2008).

If co-combustion of waste is to be applied at a coal-fired plant then the emission limits must be set in accordance with the EU **Waste Incineration Directive** (WID; 2000/76/EC) (Richers and others, 2002). The WID limits are generally more stringent than those in the LCPD. Using the ‘mixing rule’, waste co-incineration plants must calculate a specific emission limit based on the amount of waste material being cofired. However, this does not apply to mercury and its compounds, for which the WID limit is 50 µg/m^3 for all co-incineration plants. In addition to the more stringent emission limits, the WID also has more stringent monitoring requirements, including at least two measurements of mercury per year.

In 2007, in recognition that the EU legislation on industrial emissions at that time was somewhat piecemeal and confusing and that the application of BAT differed significantly amongst EU Member

States, the EC launched a review of the existing legislation. This review resulted in the new **Industrial Emissions Directive** (IED, 2010/75/EU) which merges seven existing directives (including the IPPC, WI and LCP Directives). The IED was adopted in November 2010 and was published in the Official Journal of the EU in December 2010. It entered into force on 7 January 2011. The IED must be transposed into international legislation within each of the Member States by 7 January 2013.

For coal-fired plants, the IED is effectively a combination of the IPPC and LCPD discussed above, containing aspects of both BAT-based permitting and plant-specific requirements including EU-wide emission limit values.

The new IED allows more limited flexibility in the application of BAT, according to the decisions of the local competent authority, and requires continued work by the EC on the development and revision of the BREFs and the adoption of their BAT conclusions. The IED includes the possibility for the competent authorities to give a derogation where achieving the emission levels associated with BAT is considered to be of a disproportionately high cost, as long as the ELVs are still met.

Table 1 Emission limit for SO_2 for plants permitted pre-2013, mg/m^3

Plant size, MWth	Coal, lignite and other solid fuels	Biomass	Peat	Liquid
50–100	400	200	300	350
100–300	250	200	300	250
>300	200	200	200	200

Table 2 Emission limit for SO_2 for plants permitted post-2013, mg/m^3

Plant size, MWth	Coal, lignite and other solid fuels	Biomass	Peat	Liquid
50–100	400	200	300	350
100–300	200	200	300	200
>300	150	150	150	150

Table 3 Desulphurisation rate for SO_2 for plants with challenging fuel, permitted pre-2013

Plant size, MWth	Plants permitted before 27 Nov 2002, %	Other plants, %
50–100	80	92
100–300	90	92
>300	90	96

As with the original LCPD, the IED allows alternative options instead of compliance with the ELV but these have again been tightened (opt-out is possible for plants operating less than 17,500 hours between 2016 and 2023) or have been limited in time (a Transitional National Plan may apply from 2016 to 2020).

The new ELVs for SO_2 for combustion plants granted permits before 7 January 2013 are shown in Table 1.

The remaining plants must then meet more stringent SO_2 limits after 2016 (*see* Table 2).

For those plants, originally permitted prior to 2013, which cannot meet the prescribed SO_2 ELVs due to specific fuel characteristics, there is still the option of meeting minimum rates of desulphurisation (*see* Table 3).

All other plants must meet tighter reduction requirements (*see* Table 4).

Both these reduction requirements and the ELVs listed above would require in most if not all instances, the use of FGD technologies.

For those plants firing low sulphur fuel, there is a potential derogation period of six months which will be permitted during instances of interruption in the supply of low-sulphur fuel (such as that resulting from a serious shortage).

The new NOx limits (mg/m^3) for combustion plants granted permits before 7 January 2013 are as shown in Table 5).

Table 4 Desulphurisation rate for SO_2 for plants with challenging fuel, permitted post-2013

Plant size, MWth	Required desulphurisation rate, %
50–100	93
100–300	93
>300	93

Table 5 Emission limit for NOx plants permitted pre-2013, mg/m³

Plant size, MWth	Coal	Lignite	Biomass and peat	Liquid
50–100	300	450	300	450
100–300	200	200	250	200
>300	200	200	200	150

Table 6 Emission limit for NOx plants permitted post-2013, mg/m³

Plant size, MWth	Coal	Lignite	Biomass and peat	Liquid
50–100	300	400	250	300
100–300	200	200	200	150
>300	150	200	150	100

Plants not permitted before 7 January 2013 must meet the following limits after 2016 (*see* Table 6).

For most plants, low NOx burning systems may not be able to reach these limits and additional SCR or SNCR technologies will be required.

There is a derogation limit for NOx of 1200 mg/m³ (until 2018) which applies to plants burning coals with high volatility. At the moment this applies to only a couple of plants in Spain and the Aberthaw plant in the UK.

Furthermore, plants may be exempt from the ELV if they agree to the following:

- to operate no more than 17,500 hours between 1 January 2016 and 31 December 2023;
- to report hours of operation on an annual basis;
- ELV values prescribed in the plant permit on 31 January 2015 shall be maintained for the remaining operation period of the plant.

There is also a peak load derogation for plants running <1500 hours until 2016.

The IED carries with it requirements for continuous emission monitoring of particulates/dust, SO_2 and NOx on all plants over 100 MW. Although the IED does not set an ELV for mercury from coal-fired utilities, it does introduce a requirement for annual monitoring of mercury emissions.

The IED will further enhance co-benefits of ‘traditional’ pollutant abatement measures on the reduction of mercury. Studies carried out in the EU and elsewhere have consistently shown that the installation of control technologies for particulates, SO_2 and NOx on coal-fired power plants can effectively reduce mercury emissions. For most plants and coals, the combination of particulate controls and wet FGD systems will mean at least 70% mercury reduction (Sloss, 2002, 2008). If SCR is also included, as will be the case at many EU plants, mercury capture can be up to and over 90%. Whilst this significant reduction rate is certainly not guaranteed, especially for some challenging coals, most plants will still achieve some co-benefit mercury control. By introducing the requirement for mercury monitoring at all plants, the European Commission will be able to gather data on just how effective the control systems required under the IED will be for mercury control and, based on this, may or may not set mercury specific legislation in the future. Although, for the moment, mercury emissions seem to be regarded as largely under control, the new IED BREFs, mentioned earlier, may well define BAT levels for mercury based on available information and reductions achieved so far and this could mean requirements for mercury on some plants in the future.

Individual member states within the EU must transpose EU legislation into national legislation within a set time period. Over and above this, each country may set its own legislation or reduction targets based on more local environmental challenges or concerns. The situation in Germany and the Netherlands is discussed in more detail in Sections 2.2.2 and 2.2.3.

The perceived lack of specific mercury legislation in the EU is the topic of debate. Weem (2011) has submitted an informal paper for the Working Group on Strategies and Review (WGSR) of the UNECE which proposes that the EC could introduce more stringent mercury limits and argues that 30 µg/m^3 set in countries such as Germany and China (*see below*), can be met by plants with little or no abatement technologies in place, and that plants fitted with ESP or baghouses, FGD and SCR (as required at many plants under the IED above) could easily meet a tighter limit of 3 µg/m^3. Those plants which do not meet this limit could do so with some investment which Weem (2011) argues would lead to a 'small' increase in the price of electric power (around 0.001 €/kWh, less than 1 €/y per family). Although this document is an informal submission and not endorsed by the EC, it is being discussed widely by industry.

2.2.2 Germany

The 13th Ordinance of the Federal Immission Control Act (13 BImSchV) set an emission limit of 30 µg/m^3 for mercury at all coal-fired plants (>50 MWth, 24-hour average). Continuous emission monitors for mercury are also required. Since all plants have FGD and SCR fitted, mercury is also captured efficiently and, as yet, no mercury-specific control technologies have been required at any plants firing coal alone (Thorwarth, 2011). Germany has around 20 plants cofiring sewage sludge with coal, as summarised by Fernando (2007), and these plants face a significant challenge with respect to mercury emissions and control.

Unpublished information suggests that at least one coal-fired power plant in Germany could be facing a mercury emission limit in the order of 3 µg/m^3. No more details are available at this time and this limit is regarded as speculative.

2.2.3 Netherlands

Similarly to Germany, the Netherlands has taken a pro-active approach to emission control and has often set legislation which is significantly more stringent than that set at the EU level.

KEMA in the Netherlands have developed the KEMA TRACE MODEL® (KTM), an empirical and statistical model developed from mass balance studies at all the coal-fired plants in the Netherlands over 25 years. The model can cope with cofiring secondary fuels such as biomass up to 30% on a mass base. The model covers 46 elements, including mercury. The calculated emissions, based on the fuel data, are compared to relevant emission regulations such as the LCPD or IED and any national regulations. The KTM is often used in impact statements and permit applications of coal-fired plants in the Netherlands (te Winkel, 2011) .

Although there has been nothing published as yet, it has been speculated that at least one coal-fired plant in the Netherlands could face plant-specific mercury regulations which would limit mercury emissions to below 2.4 µg/m^3 on an annual basis and 4.8 µg/m^3 on a daily basis.

2.3 Regional and national legislation – Asia

Asia contains some of the cleanest and some of the dirtiest coal-fired plants in the world. Several areas of Asia, such as Japan and South Korea, have already retrofitted most if not all of their plants with state-of-the-art emission control systems such as FGD, SCR and even, in some cases, activated carbon technologies. Other areas, such as China and India, have such rapidly growing populations and economies that the process of bringing all plants up to satisfactory emission limit standards is a challenge.

China has a range of plans and programmes to reduce emissions of SO_2 based on limits and emission fees and has recently tightened existing standards for SO_2 and NOx whilst introducing emission limits for mercury. Further, the Chinese Government has a policy based on the phasing out of smaller, less-efficient coal-fired units. These are discussed in more detail in Section 2.3.1.

Other Asian nations face their own local challenges. To date, the environmental performance of each plant in many developing Asian nations depends on the location (for example, whether it is causing noticeable local effects) or on the operator/utility (depending on the level of pro-activeness). Emission monitoring is not common in much of Asia and therefore it is hard to determine compliance with any applicable emission standards. It is also difficult to determine which plants should receive priority when it comes to investment for rehabilitation or retrofitting without emission information. A move towards increased measurement and monitoring in these areas would help evaluate areas of concern to produce the most effective national policies.

The following sections summarise the situation in selected countries in Asia.

2.3.1 China

Chinese emission legislation is defined within five and ten year plans. These plans are not law, but rather are targets that are achieved through agreements, performance, incentives or existing laws. Recently, the Chinese government's efforts have concentrated on sulphur emissions. Despite some missed reductions in the past, the reduction target for SO_2 under the Eleventh Five-Year Plan (2006-10; 10% reduction below 2005 levels) was met early and exceeded (a 14% reduction was achieved). This reduction was achieved largely due to the installation of FGD. The success has been somewhat limited due to the sheer number of plants in the country, especially older units and smaller industrial plants which are not currently targeted for control. The success of the Eleventh Five-Year Plan may be due to the strengthening of the approach with binding agreements with provinces and key emitters, economic and administrative incentives, performance audits and stronger enforcement of existing laws. There has also been an unprecedented installation rate of FGD in China. In 2005 only 14% of the installed coal-fired generating capacity had been fitted with FGD but this had increased to 86% by the end of 2010 (Zhang and Schreifels, 2011). This would no doubt have resulted in significant co-benefit mercury reduction. Further, China plans to invest a further $400 billion between 2011 and 2015 (Energy Central, 2011). Although it is not clear how this money would be spent, anything invested on energy efficiency or flue gas cleaning is likely to result in concomitant mercury reduction.

The *Emission Standard of air pollutants for thermal power plants* (GB 13223-2011) was adopted by the Chinese Ministry for Environmental Protection (MEP) on 18 July 2011 and was to be effective starting 1 January 2012 (ZHB, 2011). The standard applies to particulate, SO_2, NOx and mercury emissions from coal-fired plants but does not apply to plants cofiring waste or biomass. Emissions of mercury will be controlled from 1 January 2015. The limit for mercury is set at 30 $\mu g/m^3$. However, because of known co-benefit effects, the limits for SO_2 and NOx are also relevant. The full emission limits are listed in Table 7.

The limit set for mercury, 30 $\mu g/m^3$, is equivalent to the general emission limit for coal-fired units in Germany (*see* Section 2.2.2) and applies to both existing and new plants. It is therefore significantly less stringent than the limits set in the USA (*see* Section 2.4.2) and would be achieved by most modern plants fitted with ESP or baghouse systems firing standard coals. However, the limits set for SO_2 and NOx will be challenging and are likely to result in FGD on all plants and upgrades on many

Table 7 Emission limits for coal-fired boilers in China, from 2011 (for particulates, SO_2 and NOx) and 2015 (for mercury) (ZHB, 2011)

Pollutant	Conditions	Limit
Soot	All units	30 mg/m^3
	Plants in key regions‡	20 mg/m^3
SO_2	New boiler	100 mg/m^3
		200 mg/m^3*
	Existing boiler	200 mg/m^3
		400 mg/m^3*
	Plants in key regions‡	50 mg/m^3
NOx (as NO_2)	All units	100 mg/m^3
		400 mg/m^3†
	Plants in key regions‡	0.01 mg/m^3
Hg and compounds	All units	0.03 mg/m^3

* Applies in Guangxi Zhuang Autonomous Region, Chongqing Municipality, Sichuan Province and Guizhou Province

† W-type thermal power generation boilers, furnace chamber flame boilers, circulating fluidised bed boilers and boilers in operation before 31 December 2003

‡ Plants in 'key regions' are defined as those situated where development is concentrated and environmental capacity is low (such as existing weak environmental capacity, vulnerable ecological environment and major air pollution problems, as defined by the MEP)

existing FGD systems, SCR on almost all plants and upgrading of ESPs with potential retrofitting of fabric filters in some cases. This will mean that, although the mercury limit will not itself result in mercury control, the co-benefit effects of the new SO_2, NOx and particulate limits are likely to result in significant mercury reduction.

The China Council for International Co-operation on Environmental Development (CCICED, 2011) has recommended that the Chinese mercury emission limit be lowered to 5 µg/m^3 by 2015 and to 3 µg/m^3 by 2020. If this recommendation were to be followed, Chinese emissions could be reduced from 2007 levels by an additional 10% by 2015 and an additional 30% by 2020, even with a 10% annual growth of coal consumption in this sector.

A report produced by Tsinghua University for MEP under a UNEP Coal Partnership project, included emission estimates for mercury from coal-fired utilities in China for 2005 and 2008 along with predictions for mercury reduction under future energy scenarios in 2020 (UNEP, 2011a). The scenarios are summarised in Figure 2 and the predicted reductions as a result of each of these are summarised in Figure 3. It is important to note that these scenarios were produced prior to the new 2011 standards and so the predicted mercury reduction may be even more significant now. As can be seen from these figures, the

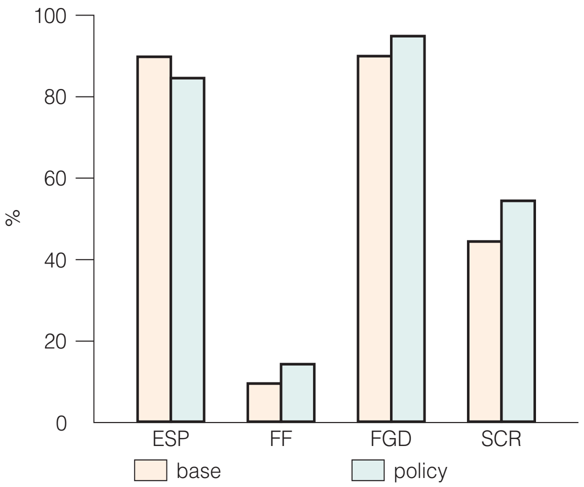


Figure 2 Chinese projections – application rate of emission controls in 2020 (UNEP, 2011a)

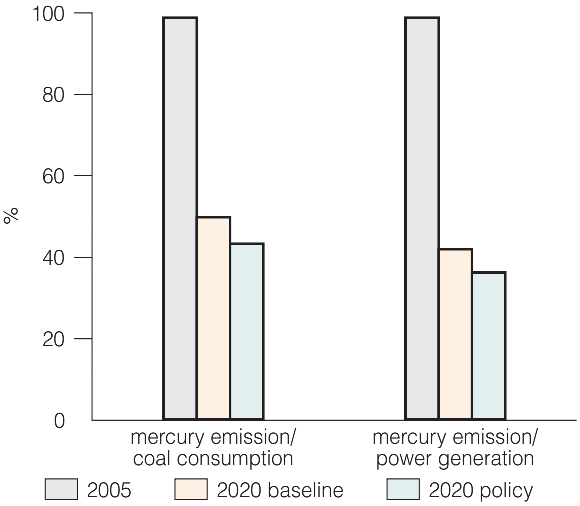


Figure 3 Chinese projections – predicted emissions to 2020 (UNEP, 2011a)

installation rate of FGD is impressive and therefore, due to the co-benefit effect of FGD on mercury control, it is not surprising to see predicted mercury emissions for 2020 at over 50% lower than the levels for 2005. It is important to note that these data relate to emissions from large (>50 MW) coal-fired units. Smaller units, industrial and domestic coal are not covered and emissions from these sectors could still be significant.

The new Chinese emission limits are challenging and are predicted to cost the Chinese economy at least 260 billion yuan ($40.74 billion) (PE, 2011). It is not clear whether this cost will include potential new monitoring requirements including CEM systems to ensure compliance. There has been speculation in the past as to whether the standards set in China are actually applied in practice, with suggestions that, although FGD systems are fitted, they are not actually turned on. However, it would seem that in many cases, plants are now being targeted for failing to comply with legislation. Recently eight coal-fired plants in seven provinces have been accused of violating pollution limits and, in some cases, falsifying emissions data. Emissions of SO_2 were exceeded, in some cases due to the pollution control systems being disabled. These plants are being fined and ordered to solve the problem by the end of 2012. During this time any subsidies for reducing carbon emissions have been withdrawn. Although the fines are relatively small (up to 100,000 yuan, about $15,800), it indicates that action is being taken and the authorities are taking a more stringent approach to compliance (YN, 2011).

2.3.2 Japan

Environmental legislation in Japan is set on a private individual company/plant basis and it is therefore not possible to summarise the requirements that apply. There is a very high priority based on social responsibility and most companies wish to enhance their public credibility by not exceeding any requirements set. Most, if not all, coal-fired units in Japan already have FGD and deNOx systems in place and many plants pride themselves in fitting the most up to date systems (Sloss, 2003). By 2000 over 90% of plants had wet scrubber systems installed and less than 3% had no flue gas treatment for sulphur. It is likely that these few remaining plants have been retrofitted since then. Over 75% of plants have both low NOx burners and SCR systems installed and the remainder had one or the other (Ito and others, 2006).

2.3.3 Other Asia

The **Philipines** have a mercury emission limit from any source of 5000 µg/m^3 which is not challenging when compared to the emission limits faced in North America (*see* Section 2.4). At the moment there are twelve coal-fired plants in the country, four of which are FBC systems (fluidised bed combustion) systems. New plants are required to install FGD systems and low NOx burners which could have a significant co-benefit effect on mercury emissions. There is also a fee levied which is proportional to emissions. However, some plants obtained a ‘grace period’ from these fees to help fund the installation of control technologies, for which tax credits are also available (Findsen, 2008).

Prior to 2010 there was no limit for mercury from coal-fired plants in **Korea** other than the general limit for mercury emissions for all industrial emissions set at an unchallenging 5000 µg/m^3. However, the new standards, promulgated in 2010, set an emission limit for mercury and compounds for all coal-fired facilities at 100 µg/m^3. As can be seen in Figure 4, this limit can easily be met by almost any plant fitted with an ESP system. For comparison, emission limits for Germany have been included. However, the limits shown for Germany seem somewhat high as the standards are currently 50 µg/m^3 for 30 minute averages and 30 µg/m^3 for 24 hour averages.

New legislated emission limits for SO_2 are set at 100 ppm for existing plants >100 MW (in operation before 1996) and 80 ppm for new plants in Korea. The limit for NOx is 150 ppm for existing plants

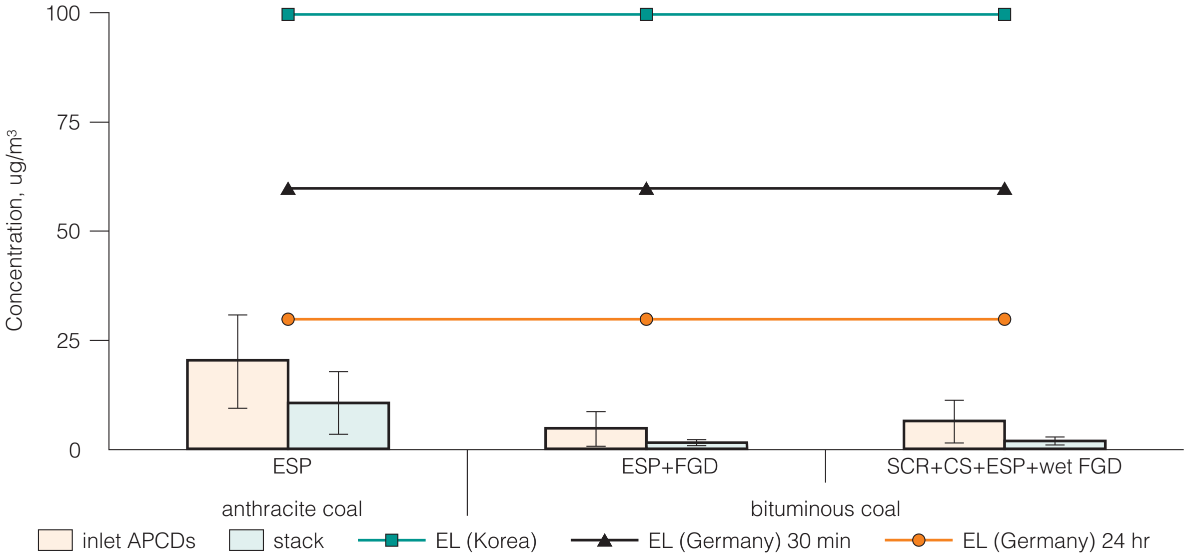


Figure 4 Measured mercury emission concentration and the permissible emission limit in current Korean and German regulations (Pudasainee and others, 2009)

and 80 ppm for new plants. This is equivalent to around 300 mg/m^3. This may require SCR systems on some plants which will improve mercury capture due to co-benefit effects. However, it has been proposed that mercury CEMs be introduced at plants in Korea to monitor the effectiveness of the potential co-benefit effects of the SO_2 and NOx control systems which would provide information for a future review of the legislation by policy makers to potentially tighten the mercury emission limit (Pudasainee and others, 2009).

With the current installation rate of FGD and SCR technologies on the capacity in Korea, Pudansainee and others (2009) estimate that emissions of mercury from coal combustion in utilities have already been reduced from around 10 t/y to under 4 t/y.

The majority of work in India to improve the environment is being undertaken under a national government programme to improve the efficiency of existing coal-fired plants. Significant improvements in efficiency can be achieved resulting in extended plant lifetime, reduced fuel consumption, increased energy output and reduced emissions. For most of the plants studied, this rehabilitation makes more economic sense than the construction of new plants. Increasing power plant efficiency means more energy for less coal burned and therefore a reduction in all emissions.

2.4 Regional and national legislation – North America

Canada and the USA are the two countries with current or impending legislation which applies specifically to mercury emissions from coal-fired power stations.

2.4.1 Canada

When the USA first introduced its Clean Air Mercury Rule (CAMR), Canada was quick to follow suit. However, the format the Canadian standard took differs from the CAMR and therefore, although the CAMR has now been annulled, the Canada-Wide Standard (CWS) still applies. The CWS sets stringent emission reduction targets, as shown in Table 8. There are caps for each province which apply to existing plants which require a total reduction of 60–70%. BAT is required on new plants. Individual provinces must decide the most appropriate means of meeting the required reduction

Table 8 Canada-wide Standard – provincial caps for 2010 (Gazette.ge, 2012)

Province	Estimated emissions (2003-04), kg/y	2010 cap, kg/y
Alberta	1802	590
Saskatchewan	710	430
Manitoba	20	20
Ontario	495	0
New Brunswick	140	25
Nova Scotia	150	65
Total	2695	1130

targets and the approaches vary from enhanced co-benefit controls, to activated carbon injection and even complete plant closure.

At the time of promulgation, there were 21 coal-fired plants in Canada. Four of these plants are in Ontario which has a challenging zero mercury emissions target. None of these plants had closed by the 2010 deadline, but, by the end of 2011, the Antikokan plant had converted to 100% wood firing, Thunder Bay had converted to gas firing, and both Nanticoke and Lambton were investigating biomass and gas options.

The CWS was put into place by the Province of Nova Scotia in January 2010. Nova Scotia Power Inc (NSPI) opted to install back-end activated carbon injection (ACI) systems combined with a front-end additive (unspecified) which was injected at the coal-feeders. Although the system worked well on all units, work has continued to optimise performance, including testing various feed rates and coal blends (Campbell, 2011).

NSPI asserted that there would be a significant economic impact of the requirement to immediately reduce emissions of mercury to below the 65 kg/y limit set by the Province. Although the company plans to move towards alternative, renewable, sources of energy for the province, this was planned over the extended 2011-20 time period. The CWS, however, applied immediately after 1 January 2010. In recognition of this issue, the Provincial target for mercury was adjusted to a step-wise reduction over several years: 100 kg/y in 2011 and 2012; 85 kg/y in 2013; 65 kg/y from 2014 to 2019 and a 35 kg/y limit by 2020. This means that the plants have more time to experiment with different ACI and coal blends (Campbell, 2011).

Table 9 Emission reduction requirements for new coal units under the CWS (Gazette.ge, 2012)

Coal type	Required capture, %	Emission rate, kg/TWh
Bituminous	85	3
Subbituminous	75	8
Lignite	75	15
Blends	85	3

The CWS applied to existing plants. Any new coal-fired plants brought into operation in Canada must meet new emission limits based on BAT, as listed in Table 9.

Results of the success of the CWS are currently being assessed and, based on reports on progress, the CWS may be reviewed by 2012 to explore the capture of 80% or more of mercury from coal burned for 2018 and beyond.

2.4.2 USA

Legislation in the USA is somewhat complex and the utility industry in the USA faces a future of significant investment for many plants that want to continue to operate. However, like many other countries, the USA has legislation for SO_2 and NOx which should provide co-benefit mercury reduction. The Clean Air Interstate Rule (CAIR) is now being replaced with the Cross-state Air Pollution Rule (CSAPR) which targets SO_2 and NOx in the Eastern and Central US states (such as Texa, Oklahoma, Kansas and Nebraska). There are also New Source Performance Standards (NSPS), MACT requirements, NAAQS and other individual state laws that mean that, much like the situation in the EU, individual plant permits are unique and can be challenging. In the USA as a whole SO_2 and NOx emissions from utilities have both dropped by around 70% since 1990. Mercury emissions are

Table 10 Mercury emission limits for existing and new coal-fired boilers under the US MATS (Hutson, 2012)

Input-based emission limits for existing facilities*	
Coal-fired unit (any coal other than lignite)	1.2 lb/TBtu (1.8 g/GWh)
Coal-fired unit (lignite units)	4.0 lb/TBtu (6.2 g/GWh)
IGCC unit (any fuel – coal or petcoke)	2.5 lb/TBtu (3.8 g/GWh)
Petcoke fired unit	0.2 lb/TBtu (0.3 g/GWh)
Alternative output-based emission limits for existing facilities†	
Coal-fired unit (any coal other than lignite)	1.3 x 10^{-2} lb/GWh (5 g/GWh)
Coal-fired unit (lignite units)	4.0 x 10^{-2} lb/GWh (17 g/GWh)
IGCC unit (any fuel – coal or petcoke)	3.0 x 10^{-2} lb/GWh (13 g/GWh)
Petcoke-fired unit	2.0 x 10^{-3} lb/GWh (0.8 g/GWh)
Output-based emission limits for new facilities	
Coal-fired unit (any coal other than lignite)	2.0 x 10^{-4} lb/GWh (0.08 g/GWh)
Coal-fired unit (lignite units)	4.0 x 10^{-2} lb/GWh (17 g/GWh)
IGCC unit (any fuel – coal or petcoke)	3.0 x 10^{-3} lb/GWh (1.3 g/GWh)
Petcoke-fired unit	2.0 x 10^{-3} lb/GWh (0.8 g/GWh)

* in units of pounds of Hg emitted per trillion Btu of heat INPUT from the fuel
† these are provided in units of pounds of Hg emitted per GWh of power OUTPUT from the facility

estimated to have dropped by around 50% in this time, despite the increase in electricity consumption of over 38% between 1990 and 2000 (Kinsman, 2011).

The original Clean Air Mercury Rule (CAMR) was annulled due to the legal decision that EPA's regulation was inconsistent with the requirements of the CAA as it relates to hazardous air pollutants. In view of the demise of CAMR and a court decision that EPA had to issue hazardous air pollutant emission standards for utility boilers, EPA developed the Mercury and Air Toxics Standards (MATS) rule. The new standard was developed for utility boilers and is broader than the CAMR. However, the new standard met with much opposition, with delays being proposed by the House of Representatives. The rule has gone under several names (such as the Utility Boiler MACT) but has the final title **Mercury and Air Toxics Standards (MATS)**. The standards apply to:

- metals (including mercury, arsenic, chromium and nickel and others);
- acid gases (including HCl and HF).

The MATS was signed on 16 December 2011.

The MATS is based on emission standards (similar to the EU ELV approach) set to achieve emission reductions that are at least as great as the emission reductions achieved by the average of the top 12% best controlled sources for the relevant source categories. The establishment of the limits therefore involved considerable data collection from numerous plants in the USA.

The rule concentrates on several air toxics: mercury, acid gases (HCl surrogate for all acid gases, with an alternate surrogate of SO_2), non-mercury metallic toxic pollutants (such as arsenic and chromium), with either individual metals, total metals, or filterable particulate matter (as a surrogate), and organic air toxics (including dioxins) (US EPA, 2011a). The emission limits for existing plants are shown in Table 10. The limits are based on coal input rates and plant power output rates and are in British

Imperial units which makes it difficult to compare these emission limits with the ELVs listed under the IED in the EU. The emission limits for new plants are also listed in Table 10 and these are based on outputs. Again the difference in units makes it difficult to compare with other standards. However, it has been estimated that the emission limit of 1.2 lb/TBtu is equivalent to around 1.7 µg/m^3, making it by far the most stringent national emission limit anywhere in the world at the moment. Individual states within the US, however, may set even more stringent standards if they wish. Emission limits at these concentrations can pose a significant challenge to emissions monitoring systems (*see* Chapter 4).

These limits are all 30-day rolling day averages (rolling operating days) and do not include periods of startup or shutdown. Two or more units within the same contiguous facility may meet the facility limit by averaging their emissions. Facilities that use multi-unit site-wide emissions averaging may alternatively meet a 1.0 lb/TBtu (around 1.5 ug/m^3) limit averaged over a 90-day period.

In order to clarify the standard for existing plants, it can be simplified (*see* Table 11).

Table 11 Hg reduction requirements under the MATs (Hendricks, 2011)

Coal	Typical Hg content, kg/GWh	Required Hg reduction, %
Bituminous	15.5–31	88–94
Subbituminous	7.75–23.25	76–92
Lignite	31–77.5	80–92

These values are based on mercury concentrations in US coals. As mentioned earlier, mercury concentrations in coals vary greatly, as do concentrations of other species such as ash and chlorine which will also affect mercury emissions. McCarthy (2011) states that the new mercury legislation will affect 1400 existing units at 600 plants when it comes into effect. Plants will have three years following the publishing of the rule in the Federal Register to comply, with a possible one-year extension in some circumstances.

The MATS is predicted to reduce mercury emissions by 20 t by 2016, a total of 70% reduction in emissions from the power sector. The cost of the standard is around $9.6 billion but mercury controls will only amount to around 20% of this cost. The monetary benefits, however, have been estimated at up to $90 billion per year, around ten times greater than the compliance costs. This would be achieved through health benefit effects such as reduced cases of chronic bronchitis (down 2800 by 2016), heart attacks (down 4700 by 2016) and asthma attacks (down 130,000 by 2016).

As has become common with most proposed US EPA legislation, there has been significant backlash from those who do not agree with the US EPA's approach. As recently as October 2011, 25 US states and the US Territory of Guam filed a brief urging the federal court to force the US EPA to delay the MATS by a year, until at least 16 November 2012. These states argued that the US EPA should take more time to consider the significant amount of comments received (Powernews, 2011a). It is possible that further legal interference could occur before the legislation is promulgated. For comparison, the CSAPR rule was issued in July 2011 and published in the Federal Register in August 2011 and yet in January 2012 implementation of the rule was blocked by the Federal Court. Petitioners listed 'unrealistic compliance deadlines, reliability and federalism concerns'. The power company Luminant had petitioned the court claiming that the CSAPR rule would cause the loss of 500 jobs and mean that two coal-fired plants had been forced to idle, meaning potential generation shortages. It is possible that this petition could force the rule start date to be delayed by at least a year. Similar action may be taken to delay or alter the MATS. One lawyer has been quoted as stating that 'the stay order contributes to regulatory uncertainty for power companies and power markets in a time of significant EPA rule-making activity. The order suggests that litigation will remain a wild card for compliance and market planning.' And so there may well be some more delay and controversy before rules such as the CSAPR and MATS come fully into force. However, ultimately, plants in the USA face challenging standards in the future (PowerNews, 2012).

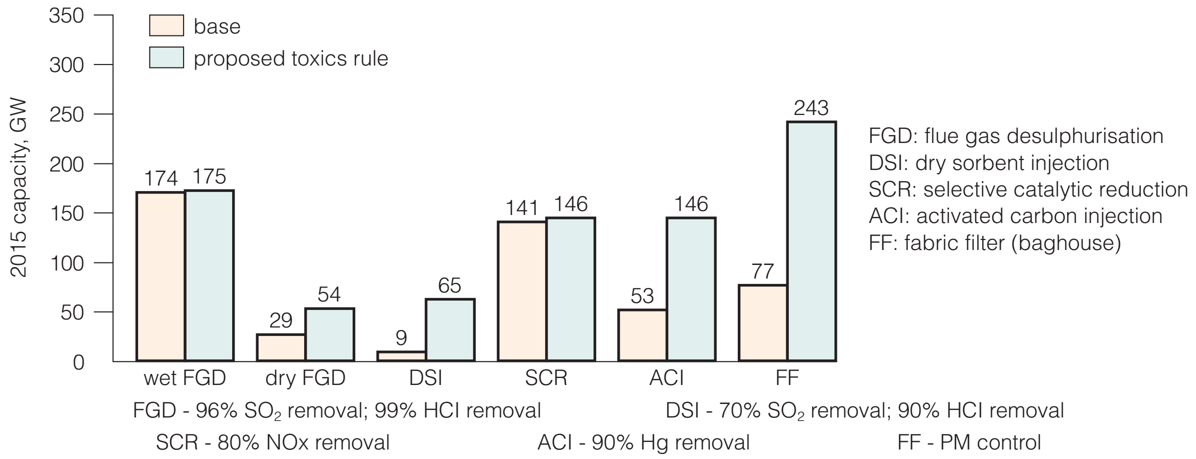


Figure 5 Technologies required to comply with MATS (Culligan, 2011)

At the moment, according to Hay (2011), 60% of the US coal-fired fleet either has scrubbers installed already or under construction, 35% have fabric filters/baghouses, 70% have ESP, and around 50% have some form of advanced NOx control (SCR or SNCR). These systems should already be helping some plants achieve significant mercury reduction.

The response to the MATS for many plants will be the installation of further co-benefit and mercury-specific control technologies. Figure 5 shows the predicted current base rate of technology installation and the predicted increase in each in response to the MATS. It seems that the majority of plants are expected to switch to fabric filters either instead of or in addition to any existing ESP systems and over half of these will also use ACI (Culligan, 2011). The technologies which can be used to control mercury emissions are discussed in more detail in Chapter 3.

Table 12 Installation of control technologies under MATS in 2015, GW (NRDC, 2012)

Control technology	Base capacity	Total capacity with MATS
Wet FGD	80	174
Dry FGD	29	51
FGD upgrade	–	63
Dry sorbent injection	9	52
SCR	146	146
ACI	49	148
Baghouse/fabric filter	90	191
ESP	0	34

Table 12 shows the installed capacity of control technologies estimated for 2015 under both a base case scenario (no MATS) and with MATS. There is a slight shift from wet FGD to dry sorbent options and a significant increase expected in both baghouse installation and activated carbon application. In fact, by 2015 under MATS it is estimated that almost half of the coal-generating capacity in the USA will be using activated carbon (NRDC, 2012).

Dominion plans to close down two of the four units at Salem Harbor Power Station in Massachussets by the end of 2011 and close the entire plant by June 2014 due to the tightening US regulations ‘making the power station uneconomical to operate’ (Patel, 2011). Similarly American Electric Power is planning to retire nearly 6 GW of coal-fired capacity and upgrade or refuel another 11 GW under an $8 billion plan to comply with the new US regulations (Power News, 2011b). These closures are as a result of a combination of regulations both at national and state level and are not due to the MATS alone. However, MATS is seen by some in the coal industry as the latest regulation in a line of regulations which makes compliance too challenging and expensive.

Table 13 **Pollution control systems on plants within the states with state-wide mercury standards** (Weiss, 2011)

State	Total units	Average age of units, y	% capacity with scrubbers	% capacity with ACI
CO	20	40	94	32
CT	2	33	35	65
DE	8	40	0	54
GA	26	44	60	29
IL	54	48	24	18
MA	4	50	89	100
MD	16	44	81	36
MI	59	44	16	2
MN	25	44	77	39
MT	8	31	92	5
NC	40	47	89	0
NH	5	53	0	0
NJ	7	39	80	69
NY	23	52	45	26
OR	1	31	0*	0*
SC	26	39	74	0
WI	29	50	32	7
Total	353	45	54	16

* unit being retired

Individial states within the USA have the power to set their own legislation and, as of 2011, seventeen states have legislation that requires action at coal-fired facilities. In some of these plants, existing pollution control systems (co-benefit effects) have proven sufficient to reduce mercury emissions whereas other plants have been required to install mercury-specific controls. Activated carbon injection has been installed at numerous plants, as shown in Table 13.

Although the legislation in the USA is complex and still in a state of relative flux, it is clear that coal-fired plants face a significant challenge and in many cases significant expense if they remain in operation in the future. Whilst it still remains possible, with MATS in place, to build new coal-fired power plants in the USA expected new regulations on SO_2, NOx, particulates and greenhouse gases will make it more difficult. New power plants in the USA will likely be based on cleaner fuels, or where coal remains the fuel of choice, these plants will likely employ advanced combustion systems and control technologies.

2.5 Other countries

Although **Australia** has a National Pollutants Inventory (NPI) for the quantification of emissions, there are no binding national emission standards for SO_2 or NOx. The guidelines issued by the National Health and Medical Research Council are very general and are set at levels which can be met relatively easily. Australian coals are generally low in sulphur and therefore SO_2 emissions are not regarded as a high priority for control and there are, to date, no FGD or similar controls on any Australian coal-fired plants. Although NOx limits have been specified in some states, it is thought that these are relatively lenient and have not required the installation of any NOx control technologies (Sloss, 2003). This means that the co-benefit mercury removal rate in Australia is likely to be relatively low, compared to North America, developed Asia and the EU. However, in the review by Morrison and Nelson (2004) of future strategies for energy in Australia towards 2050, most of the strategies considered related to the reduction of mercury and CO_2 emissions through the use of brown coal in IGCC (integrated gasification combined cycle) with and without CCS (carbon capture and storage). Australia's future energy strategies appear more concerned with greenhouse gas reductions and energy efficiency with SO_2 and NOx emissions taking much lower priority. It can therefore be assumed that there will be limited co-benefit reductions in mercury emissions, based on current legislation.

In March 2010, the **South African** Government established updated requirements for sulphur emission control. The limits are 3500 mg/m^3 for SO_2 from existing coal-fired power plants and 500 mg/m^3 for new plants (>50MW). The emission limits for NOx are 1100 mg/m^3 and 750 mg/m^3 for existing and new plants respectively (GG, 2010) . There is also a move towards requiring the installation of FGD on all large coal-fired units in the country. However, the financial constraints and, perhaps more importantly, the limited availability of water in the country, will make the installation of FGD within the required time period a significant challenge. But, once FGD or equivalent sulphur control is required, some level of co-benefit mercury control can be expected.

Russia has also completed its first inventory of mercury emissions from coal combustion (UNEP, 2011b). Although Russian coals have relatively low mercury concentrations, the lack of FGD and SCR systems mean that there is little or no co-benefit mercury reduction. UNEP, in conjunction with IEA CCC, are currently completing two full-scale demonstration projects at plants in Russia: one demonstrating sorbent injection and the other oxidant injection into a wet scrubbing system. The final reports will be available mid-2012.

2.6 Comments

At the moment, the majority of mercury control requirements apply in North America. The Canada-wide Standard for mercury has, to some extent, been responsible for the closure of some coal units and for the conversion of others to either gas or biomass. Many of the remaining coal units have retrofitted mercury control systems such as activated carbon. Similarly, the new MATS legislation in the USA is likely to result in older coal-fired plants closing, some switching fuel and the remainder using either co-benefit or mercury-specific control technologies to comply with the challenging emission limits for mercury and other pollutants.

Although there are international and national mercury emission limits outside North America, the majority of these are not currently set at levels which require any significant action to be taken. This does not, however, mean that mercury is not being controlled. In fact, mercury reduction rates of over 50% and even over 95% are being achieved at some coal-fired plants in countries which require state-of-the-art technologies for particulate, SO_2 and NOx control. Significant reduction in mercury emissions from the coal combustion sector has been achieved as a result of these co-benefit effects and is continuing in the EU and in countries such as Japan, Korea and, more recently, in China. And so, as a result, there is currently little or no perceived urgency to take specific action to control mercury. This may well change in the future if international and national bodies decide that current rates of mercury reduction in these regions are not sufficient.

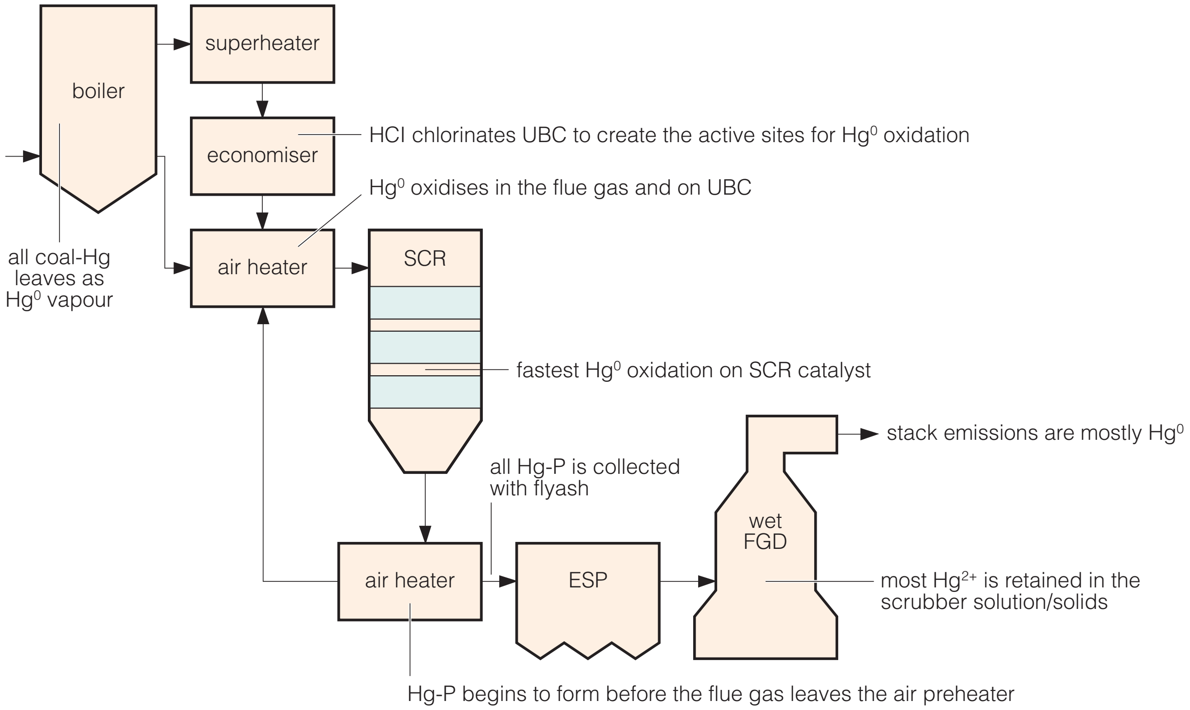
3 Options for controlling emissions

Mercury concentrations in coal are variable and the behaviour of mercury in coal combustion systems is complex. Figure 6 demonstrates the locations in a power plant where mercury behaviour can be affected by coal and in-plant variables, including other species such as chlorine and ash, and also with combustion conditions. Unabated emissions (with only controls for particulates such as ESP or baghouses) have been estimated as ranging from 2 to 27 $\mu g/m^3$ (Weem, 2011). This means that many plants can achieve the emission limits or reductions set in some general legislation (such as that in the EU, China and Korea, *see* Chapter 2).

The behaviour of mercury is so variable that there is no single control technology or strategy which would achieve mercury control in all coal-fired systems. Mercury control options are therefore determined on a case-by-case, plant-by-plant basis.

Because of the emerging mercury legislation discussed in Chapter 2, there are now a large number of commercial companies offering mercury control systems. This Chapter is not intended to provide a summary of all commercially available control options but rather to provide a brief guide to the different types of methods available.

The information in the sections below is summarised from previous reports (Sloss, 2002, 2008) and from the POG – the Process Optimisation Guidance Document – produced by the UNEP Coal Partnership under IEA CCC lead (UNEP, 2010). The POG is discussed in more detail in Section 3.5.



Hg speciation changes from pure Hg^0 vapour at the furnace exit to changing mixtures of Hg^0, Hg^{2+}, and Hg-P as the flue gas moves through the APCDs depending on the levels of Cl and UBC, whether an SCR is present, and many other clearing conditions.

Figure 6 Mercury behaviour in a coal-fired power plant (UNEP, 2010)

3.1 Coal treatment – washing and blending

One of the simplest ways of reducing emissions from coal combustion is to burn less coal or to burn the coal more efficiently. To improve economics, plant efficiency and coal consumption rate should be a priority at any plant. Some coal plants are moving to cofiring biomass or other materials with coal as a move towards lowering CO_2 emissions. This can have an effect on mercury emissions, usually achieving mercury reduction due to the lower concentration of mercury in most biomass materials and due to the change in combustion and ash conditions. This is discussed in more detail in a separate IEA CCC report (Sloss, 2010). As discussed in Section 2.4.1, fuel switching is being carried out at some plants in Canada in order to comply with mercury reduction requirements.

Coal washing is standard at many mines and plants to reduce the ash content and increase the calorific value of the coal. Conventional coal washing can remove mercury associated with non-combustable mineral materials but will not remove any mercury associated with the organic fraction of the coal. The amount of mercury removed by coal washing varies considerably from coal to coal from virtually no mercury removal up to 64% (in unique cases). The average mercury removal with standard coal washing is around 20–30%. More specialised coal washing treatments using chemicals or special physical parameters can remove up to 78% of the mercury in the coal but, again, this is very coal specific (UNECE, 2010).

Beneficiation of coal with physical or thermal treatments can also reduce mercury emissions. For example, the K Fuel process is a commercial system based on both physical separation and thermal processing which can be used to upgrade subbituminous or lignite coal. This system is reported to be able to achieve 28–66% mercury reduction (UNECE, 2010).

Bland and others (2011) report on the WRITECoal™ coal upgrading process for high-moisture coals which can remove up to 87% of the mercury from some coals. The process is a two-stage system of heating where the first phase drives off the moisture and the second phase drives off the mercury. Demonstrations at pilot scale have shown that between 50% and 80% of the mercury in lignite and PRB coals can be removed with this system, the mercury being captured in a solid sorbent system.

As discussed previously, the behaviour of mercury in coal combustion systems is complex. However, it is known that the presence of species such as halogens, unburnt carbons and the burn characteristics of some coals can have a significant effect on mercury emissions – some coals, regardless of the average coal mercury content, tend to release less mercury than others during combustion. It is therefore possible to blend coals to maximise mercury capture in the particulate control devices and FGD system. Bituminous coals typically produce more oxidised (soluble and easy to capture) mercury than subbituminous coals and lignite. This is largely due to the greater halogen content of the bituminous coals. Blending up to 20% western bituminous coal with subbituminous coal can increase mercury capture in an FGD system from virtually zero to around 80% in some cases. The effect can be even more dramatic in plants which have both FGD and upstream SCR systems. The oxidising power of the SCR system converts even more mercury into the soluble oxidised form resulting in up to 97% mercury capture with some blends (UNECE, 2010). Coal blending is therefore an inexpensive option for many plants in North America and this approach could also be an economic approach which could be used in developing countries and emerging economies.

3.2 Co-benefit effects

Co-benefit effects refer to the capture of mercury in pollution control systems which were not designed to remove mercury but rather were installed to control other pollutant species such as particulates, SO_2 and NOx. ESP systems tend to be less effective at controlling mercury emissions. The average mercury removal in particulate control systems is shown in Table 14.

These results are based on data from several plants in the USA and do not in any way imply guaranteed or even predicted mercury capture rates in different particulate control systems. However, from the data it is clear that the choice of particulate control system can have a significant effect on mercury emissions. Those plants in North America fitted with baghouses and firing bitumunous coal

Table 14 Mercury reduction efficiency with different pollution control systems

Control technique	Mercury reduction, %
Coal washing	30
water scrubber	6.5
Cyclone dust collector	0.1
ESP	29
FF	67
ESP + wet FGD	62
FF + wet FGD	87
ESP and wet FGD and SCR	66
ESP + wet FGD + SNCR	62
ESP + ACI	40 (mid-high S coals); <80% (PRB blends)
FF + ACI	>95%

Data accumulated from CCICED (2011), Hendricks (2011), Wang and others (2012)

face much less of a challenge than those fitted with ESP and/or firing subbituminous coal or lignite when it comes to complying with the new emission legislation.

The mercury capture in particulate control systems is dependent upon several factors including the efficiency of the particulate control system, the temperature and the presence of unburnt carbon. Making minor alterations to some particulate control systems, especially those which are not operating at full efficiency, could make a significant difference to mercury emissions.

Wet FGD systems for SO_2 control can also be extremely effective at reducing mercury emissions. Oxidised mercury is soluble and is therefore captured in FGD solutions to be removed from the plant in the liquid or solid waste. Maximising the proportion of mercury in the oxidised form maximises its capture in the FGD. Oxidation, discussed in greater detail in Section 3.4, works extremely well at plants fitted with FGD systems. There can be a problem with re-emission of mercury in some FGD systems but this can be dealt with by using appropriate additive materials. Mercury capture in wet FGD systems can be up to and over 90%, depending on other plant and coal parameters (UNECE, 2010).

The catalysts used in SCR systems for NOx reduction have the co-benefit effect of converting some of the elemental mercury into the oxidised form, thus making it easier to capture in baghouses and FGD systems. The combination of SCR and FGD systems often means that plants can achieve over 90% mercury control. This, as always, is not guaranteed and varies with plant and coal characteristics (UNECE, 2010).

Co-benefit effects can be considered as the most popular method for mercury control for many plants, mainly because these plants already have these systems in place and are saving significant amounts of money that would otherwise be required for mercury-specific control technologies. The presence of FGD systems reduces emissions significantly in some cases (down to 2–7 $\mu g/m^3$), and the combination of FGD and SCR can generally reduce emissions to below 2 $\mu g/m^3$ (Weem, 2011). Obviously there will be some exceptions to the rule, especially at plants firing challenging fuels such as lower grade coals. Weem (2011) states that, because of the requirements for FGD and SCR under the new IED (*see* Chapter 2), ‘new coal-fired plants in the EU can reach emission levels for mercury of 3 $\mu g/m^3$ without additional costs’. If EU plants were not fitted with FGD or SCR the estimated cost of mercury specific control (using sorbent based approaches) has been estimated at 128,000 €/kg of mercury removed. Co-benefit effects are therefore saving the EU millions in potential mercury reduction costs.

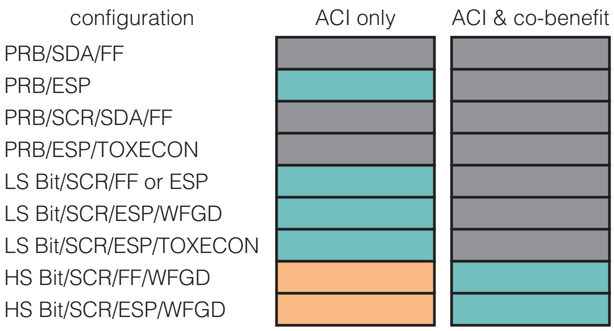
Maryland, USA, has state-wide reduction targets for mercury of 80% by 2010 and 90% by 2013. The first phase of reductions of 80% was achieved primarily with co-benefit effects and ACI is being installed for the second phase (Aburn, 2011).

3.3 Sorbent Injection

Sorbents can be used to capture mercury on particles which are then caught in a particulate control device. Cold-side ESPs are less effective than baghouses (fabric filters, FF) for this and hot side ESPs are very limited in efficacy. This is due to the shorter time for reaction between the mercury and particulates in ESP systems and also for the potential for the interference of SO_3, used in some ESPs. There are numerous sorbent types available; however, the majority are activated carbon based, often with halogen enhancement to improve the mercury capture. ACI with fabric filters is regarded as the best basic combination.

The US Department of Energy (US DOE) National Energy Technology Laboratory (NETL) carried out extensive research on mercury control at coal-fired plants during the 1990s and early 2000s. Phase I of the programme concentrated on ACI and the improvement of mercury capture in FGD systems while Phase II moved on to chemically treated ACI, sorbent enhancement additives (SEA) and sorbents designed to preserve fly ash quality. During both phases, the NETL carried out full-scale field tests at almost 50 coal-fired plants. Phase III had the longer-term goal of developing advanced control technologies that can achieve >90% mercury capture at cost of 50–75% less than 60,000 $/lb (around 20 £/t) of mercury removed. By March 2009, over 130 full-scale ACI systems had been ordered by US coal-fired generators, representing over 55 GW in installed capacity (around 13% of the total US coal-fired capacity) (Feeley and others, 2009).

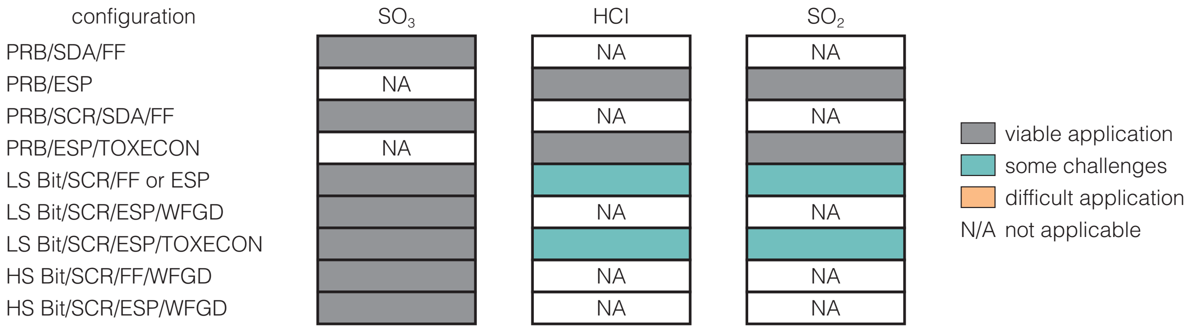
According to Bustard and others (2011), prior to the US MATS, around 155 coal-fired boilers (totalling 58 GW) had awarded contracts for sorbent-based mercury control systems. This number is expected to triple in the three years between the issuance of the MATS and the compliance date. ACI is ‘expected to be the primary technology of choice for controlling mercury emissions’. Taking the requirements of both the MATS and the CSAPR could mean that over 1000 ACI and DSI (dry sorbent injection) systems will be needed within the next four years. This is a large amount of equipment within a very short time frame. Bustard and others (2011) have produced an excellent paper outlining the challenges this brings to the industry and the interested reader is recommended to consult this paper for further information. Figures 7 and 8 show the ACI and DSI technologies that will be most applicable for different plant configurations in the USA taking the coal type into account.



configuration	ACI only	ACI & co-benefit
PRB/SDA/FF	■	■
PRB/ESP	🟦	■
PRB/SCR/SDA/FF	■	■
PRB/ESP/TOXECON	■	■
LS Bit/SCR/FF or ESP	🟦	■
LS Bit/SCR/ESP/WFGD	🟦	■
LS Bit/SCR/ESP/TOXECON	🟦	■
HS Bit/SCR/FF/WFGD	🟧	🟦
HS Bit/SCR/ESP/WFGD	🟧	🟦

Figure 7 Technology potential matrix for ACI systems to meet new mercury, SO_3, SO_2, and HCl emission standards required in MATS and CSAPR (Bustard and others, 2011)

It has been reported that SO_3 can affect ACI performance, since it competes for the adsorption sites on the sorbent surface. For example, the mercury removal at the high sulphur (3–4%) bituminous coal-fired



configuration	SO_3	HCl	SO_2
PRB/SDA/FF	■	NA	NA
PRB/ESP	NA	■	■
PRB/SCR/SDA/FF	■	NA	NA
PRB/ESP/TOXECON	NA	■	■
LS Bit/SCR/FF or ESP	■	🟦	🟦
LS Bit/SCR/ESP/WFGD	■	NA	NA
LS Bit/SCR/ESP/TOXECON	■	🟦	🟦
HS Bit/SCR/FF/WFGD	■	NA	NA
HS Bit/SCR/ESP/WFGD	■	NA	NA

■ viable application
🟦 some challenges
🟧 difficult application
N/A not applicable

Figure 8 Technology potential matrix for DSI systems to meet new mercury, SO_3, SO_2, and HCl emission standards required in MATS and CSAPR (Bustard and others, 2011)

Conesville Station Unit 6 was limited to around 30%. At another plant, Labadie Station Unit 2 (Powder River Basin, PRB-fired), turning the flue gas conditioning system off increased the mercury capture efficiency with DARCO from 50% to 80% at 8 lb/MMACF (million actual cubic feet); around 128 mg/million m^3). The injection of alkali such as magnesium oxide or sodium sesquicarbonate (trona) can mitigate SO_3 issues and improve mercury capture. The Merrimack Station Unit 2 fires bituminous coal (around 1% sulphur) and has SCR and two ESPs in series. Without SO_3 mitigation the mercury removal rate was only 22% (chemically treated ACI at 8 lb/MMACF, 128 mg/million m^3). However, the addition of trona upstream of the air preheater at 500 lb/h (227 kg/h) increased this to 50% (with DARCO at around 4 lb/MMACF, 64 mg/million m^3) (Feeley, 2009).

The NETL study indicated that ACI is of limited use at plants firing low-rank coals. Initial results at plants such as the Pleasant Prarie Unit 2 firing PRB subbituminous coal, showed that untreated ACI achieved only up to 65% mercury removal. However, chemically treated sorbents are far superior and have demonstrated over 90% mercury removal at Great River Energy's Stanton Station Unit 10 (lignite fired, with a fabric filter), Stantin Station Unit 1 (PRB fired with an ESP) and Basin Electric's Leland Olds Station Unit 1 (lignite fired with an ESP). Relatively low ACI injection rates of <3 lb/MMACF (< 48 mg/million m^3) were required to achieve these capture rates. The improved performance of treated ACI means lower injection rates are required which helps to keep sorbent and operation costs down (Feeley and others, 2009).

Brominated activated carbons (BACs) are popular as bromine has a far greater oxidation effect on mercury than chlorine. BACs were tested at Xcel Energy's Comanche Unit I which fires PRB and is fitted with a lime spray dryer and a baghouse. The BAC reduced the mercury emissions below the required 0.15 lb/GWh (70 g/GWh) reaching to as low as 0.004–0.005 lb/GWh (1.8–2.3 g/GWh), although the emission rates were variable. The cost of compliance for the plant using this approach was estimated at somewhere between $200,000 and $1million (assuming a BAC cost of 1.05 $/lb, equivalent to 2.3 $/kg, and a factor of 2–3 uncertainty in the required feed rate) (Magno and others, 2011).

One concern with ACI is the effect it may have on fly ash. The presence of carbon in the ash affects the performance of the concrete and has meant that many plants must consider the loss of fly ash sales when they move to ACI injection. This is discussed in a previous report (Sloss, 2007). However, companies are now developing sorbents which do not result in loss of fly ash sales. These include C-PAC™, which achieve reasonable fly ash removal efficiencies whilst maintaining fly ash sales (Feeley, 2009). Bierman and others (2011) report on the use of the MinPlus, non-carbon based sorbent for mercury capture in high temperatures without the need for halogen addition. MinPlus is a mixture of metakaolinite and calcium compounds which can be produced from waste sludges and paper recycling processes. The sorbent has been demonstrated at two full-scale plants in the USA where it was injected just after the furnace at temperatures of 1100–1200°C and achieved mercury reduction rates of 70–98%. Different coals were noted to give different results with PRB coal resulting in significantly poorer mercury capture in the sorbent.

Injecting sorbents into the flue gas can lead to issues with ash contamination and particulate emissions. EPRI have evaluated several alternative fixed-structure sorbents which would avoid these issues, such as carbon beds, honeycombs, plates cloth and composite materials. In particular, a carbon-polymer composite (CPC) produced by W L Gore and Associates showed promise. Slipstream tests were carried out at Georgia Power's Plant Yates which fires low sulphur Eastern bituminous coal and is fitted with a cold-side ESP. Initial results suggest that the modules would last over six months and possibly over a year whilst maintaining over 90% mercury removal. The cost of the system would be, as with many mercury systems, plant-specific based on the plant itself and the systems already in place. The capital costs for the CPC system, $1.54 million per year (amortised cost per year for a 500 MW plant) are greater than for ACI with an ESP or baghouse ($0.3 million per year) but the operation and maintenance costs are comparable (all around $0.1–0.2 million per year). Machalek and others (2011) argue that the cost is competitive as the lifetime of the fixed-bed sorbent may prove to be longer than anticipated.

TOXECON™ is a system designed by EPRI which involves removal of the fly ash in an ESP upstream of the sorbent injection system, thus preserving fly ash sales. The TOXECON system has been tested successfully at the We Energies Presque Isle Power Plant in Marquette, MI, since 2006, maintaining >90% mercury removal with both untreated and brominated ACI (DARCO). The TOXECON II™ is a modification of the original system which involves the injection of the sorbent into the downstream collection fields of the ESP. Fly ash sales are preserved since the majority of the fly ash is collected in the upstream fields. Initial tests at the PRB-fired plant Independence Station Unit 1 (Entergy Inc) achieved 90% mercury removal with DARCO injection at 5.5 lb/MMACF (around 88 kg/million m^3). However, concerns were raised over effects on the residence time of the sorbent in the ESP and possible associated increases in particulate emissions (Feeley and others, 2009).

An electron beam-based process, known as E-Beam, can be installed downstream of an ESP to remove SO_2 and NOx and, at the same time, leads to oxidation of up to 98% of the mercury in the flue gas. The process involves flue gas cooling (to 60–70°C), injection of ammonia and irradiation with high-energy electrons. The E-Beam process has been tested on slipstream scale at several plants and is running at full scale at a 90 MWe unit in Szczecin, Poland, where the by-product of the process is sold to a local fertiliser manufacturer. No information was given on the fate of mercury in the system (UNECE, 2010).

There are many other commercial systems breaking into the market place, such as the Enviroscrub/Pahlman closed-loop DSI system, electro-catalytic oxidation, Lo-TOx (low temperature oxidation), PEESP (Plasma-enhanced ESP), discussed in more detail in the UNECE (2010) report.

3.4 Oxidants

As mentioned previously, oxidised mercury is much easier to control than elemental mercury, and therefore the conversion of mercury to the oxidised form increases mercury control in any system. Oxidation can be achieved in various ways, including coal blending (*see* Section 3.1). Alternatively, chemical additives can be used to enhance the oxidation of the mercury during combustion. This can be a relatively simple and inexpensive approach for mercury reduction at some plants as it requires only the installation of a dosage system at the coal feed site and the purchase of relatively inexpensive halogen-based consumables.

Honjo and others (2011) reported on the use of a NH_4Cl oxidant based system developed by

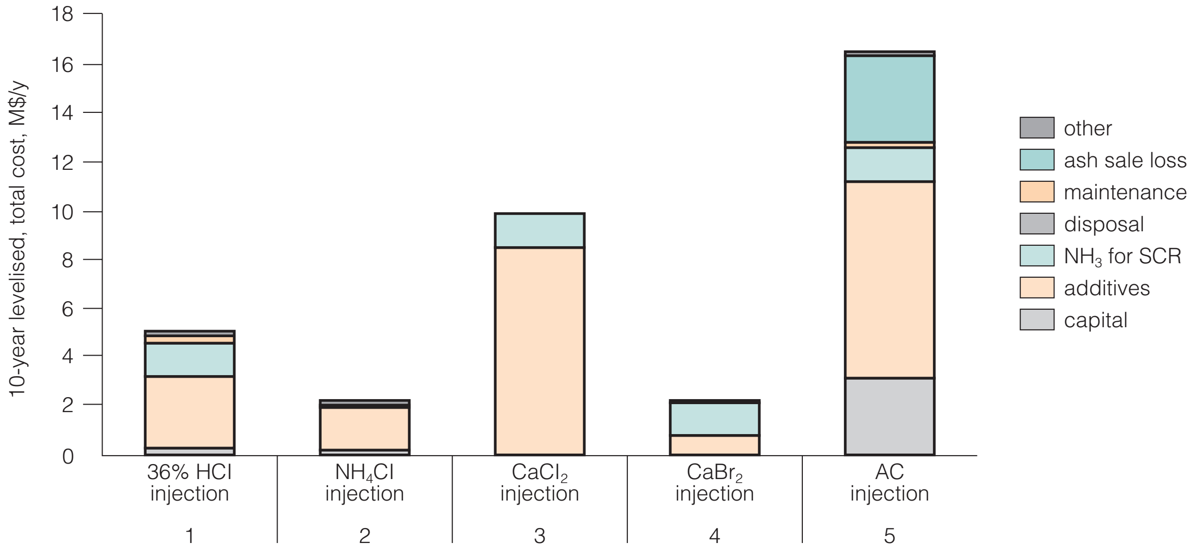


Figure 9 Cost comparison of mercury control technologies (Honjo and others, 2011)

Mitsubishi Heavy Industries (MHI) to be used in conjunction with FGD and SCR. The system was tested at pilot scale at Gulf Power's Plant Crist in Pensacola, FL, USA and then at full scale at Alabama Power's Plant Miller. The oxidant is delivered to the plant as a solid powder which is then mixed with water prior to injection. The NH_4Cl has the added advantage that it replaces the anhydrous ammonia needs of the SCR system, thus saving on total costs. A comparison of the costs of NH_4Cl injection versus $CaCl_2$ injection and ACI is shown in Figure 9 (Honjo and others, 2011).

Although chlorine is used in some systems, almost an order of magnitude less bromine than chlorine is needed due to the higher oxidation potential of bromine (UNECE, 2010). $CaBr_2$ injection was tested at Luminant Power's Monticello Station which fires a blend of PRB and Texas lignite. An 86% mercury removal could be achieved at a $CaBr_2$ injection rate of 113 ppm. To achieve >90% mercury removal required an injection rate of 330 ppm (Feeley and others, 2009).

Bromine addition was tested at an unnamed site in the USA with a 750MW boiler, high dust SCR, cold-side ESP and wet FGD system firing 100% Appalachian eastern bituminous coal. Before the addition of the bromine to the coal, the mercury emissions from the stack were around 1.9 lb/TBtu (around 0.86 kg/kJ) which is low, but higher than would be expected in such a plant. Addition of the bromine to the coal (100–500 ppmw Br equivalent) resulted in a reduction of the mercury emissions to 0.7 lb/TBtu (around 0.32 kg/kJ). This was reported to be due to the accumulation of Br in the FGD system which helped to sequester the mercury in the FGD solution and inhibit re-emission (Tyree and others, 2011).

KNX™ is a commercially bromine-containing additive (such as sodium bromide or calcium bromide as a dry salt) which can be added to coal during its passage through the feeders in the wet or dry form. The bromine is released in the combustion zone where it converts the mercury to the easily captured oxidised form. KNX has been tested at the Lewis and Clark plant in Montana, USA. The 45 MWe plant fires northern lignite. KNX has been tested for over a year at the plant on its own and in conjunction with ACI and, with the latter combination, has kept mercury emissions from the stack at around 1.5 lb/TBtu (around 0.68 kg/kJ) or below (Pearson and Sago, 2011).

EERC (Energy and Environmental Research Centre, USA) have developed SEA™, sorbent enhancement additives which can improve the efficiency of mercury capture in sorbents at challenging plants. The additives work well with subbituminous coals in units with ESP systems, with some plants achieving over 90% mercury control without any significant negative balance-of-plant effects (Pavlish and others, 2011).

3.5 Selection process

As can be seen from the previous sections in this chapter, there are a number of options for mercury control but none is guaranteed to achieve the 90–95% reduction in mercury emissions required at some coal-fired plants in North America. The choice of control technique or technology varies with both the coal and plant characteristics and is therefore being determined on a plant by plant basis. Some plant managers are facing a difficult challenge to work through the different commercial systems which are available to determine which will be most suitable at their plant.

In the EU, emission legislation is accompanied by BREFS (BAT reference documents) to help competent authorities set permit conditions and operators decide what techniques to use to comply with legislation. Most of the BREFs are developed for a particular industrial activity, covering all key environmental issues. For power plants, the LCP BREF produced in 2006 defines the BAT and this document is mainly focused on particulates, SO_2 and NOx emissions, only briefly touching upon mercury abatement. However, a revision of this BREF has recently been started in order to develop BAT conclusions that will apply under the new IED (*see* Chapter 2) and it can be expected that techniques to abate mercury emissions will be discussed in more detail in the revised document.

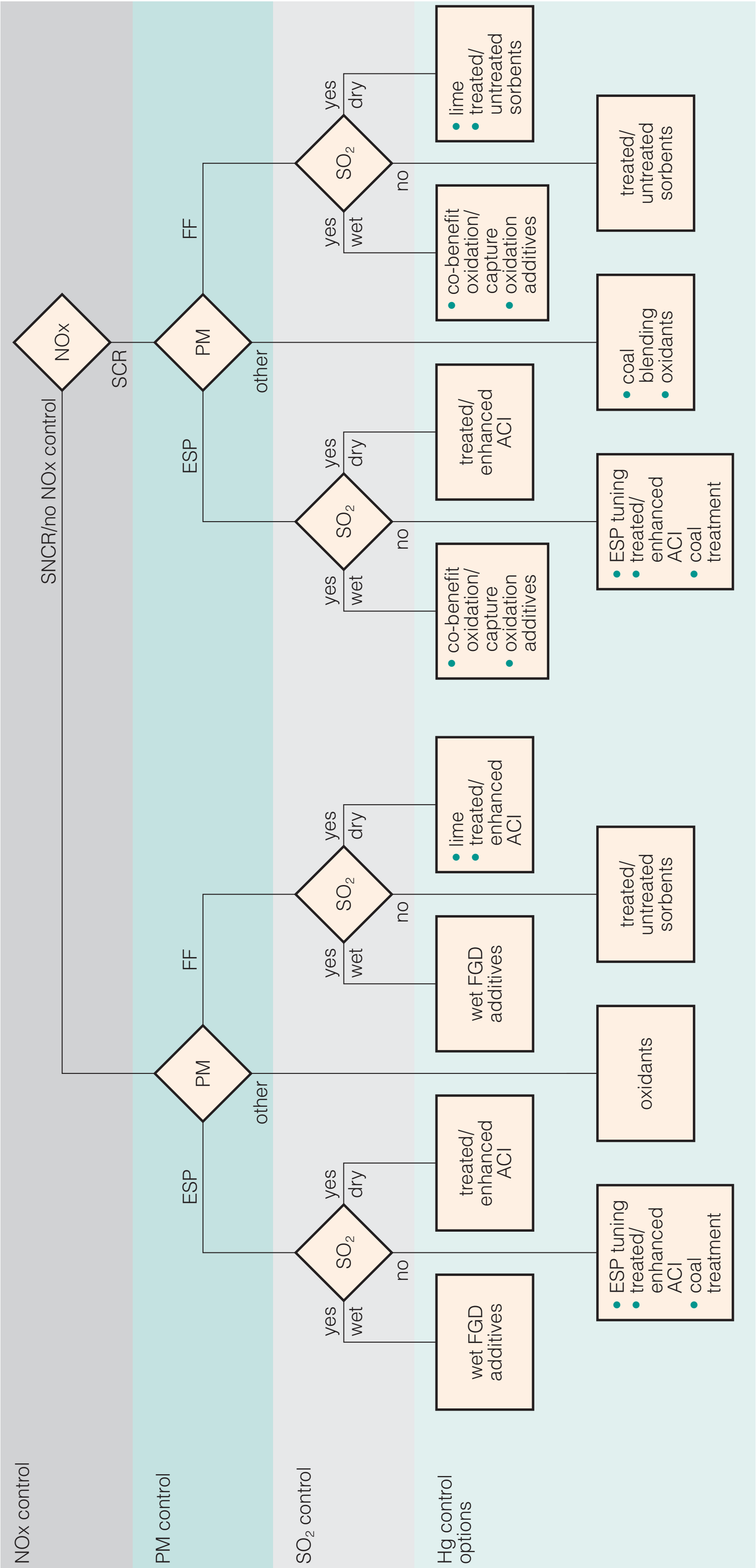
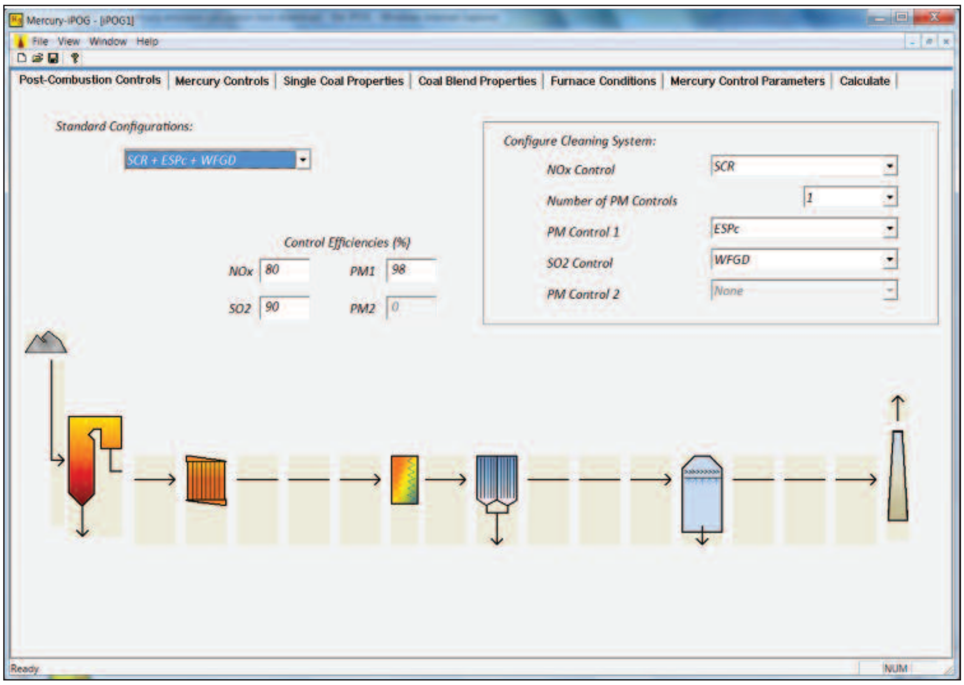


Figure 10 Flow chart to determine most appropriate mercury control options (UNEP, 2011)

In order to help plant operators determine the mercury control options which are most likely to be relevant to them, but without any commercial bias, the UNEP Coal Partnership has produced the Process Optimisation Guidance (POG) document (UNEP, 2010) under IEA CCC lead. The POG includes a comprehensive summary of all options for controlling mercury emissions, from coal cleaning and fuel switching through to activated carbon injection. The POG has been translated into Russian and Chinese and is available free of charge from both the UNEP and IEA CCC websites. The POG document is quite lengthy and detailed and therefore includes a flow chart, as shown in Figure 10. This chart is intended to act as a guidance to plant operators to focus on those areas of the POG document which are most relevant to them. Although the flow-chart may be of use to some plants in North America, it is aimed more at plants in developing nations and emerging economies to help them focus on the most economic mercury control options in these regions. The POG does not lists costs of the various options, as these are likely to vary with location and to reduce over time. However, it does include a table ranking relative costs of different control options.

The POG and the flow chart have been discussed during the negotiations towards the UNEP global convention on mercury control (as mentioned in Section 2.1) and have been found to be extremely useful. As a result, the POG has been further developed into a downloadable calculation tool/model. The iPOG allows users to input plant-specific data on coal and plant characteristics (as shown in Figure 11) and then use the model, which is based on a significant amount of data from real plant and coal studies, to predict the emissions from the plant (as shown in Figure 12). The iPOG can take a significant amount of coal and plant specific data (for those who wish to consider a single plant) or can be operated by selecting very generic parameters (for those who wish to understand coal mercury behaviour in different types of coal plant). The tool is therefore useful both to individual plant managers and to those working within local



Standard Configurations: SCR + ESPc + WFGD

Control Efficiencies (%)

NOx 80 PM1 98

SO2 90 PM2 0

Configure Cleaning System:

NOx Control: SCR

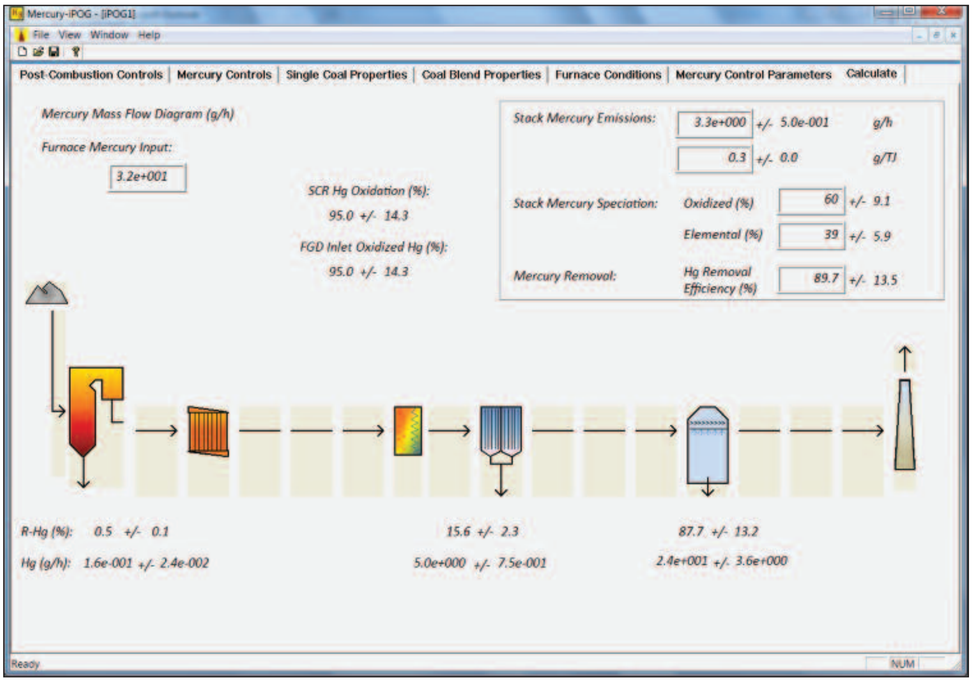
Number of PM Controls: 1

PM Control 1: ESPc

SO2 Control: WFGD

PM Control 2: None

Figure 11 Inputing information into the iPOG (screen capture from iPOG – see download details in text)



Mercury Mass Flow Diagram (g/h)

Furnace Mercury Input: 3.2e+001

SCR Hg Oxidation (%): 95.0 +/- 14.3

FGD Inlet Oxidized Hg (%): 95.0 +/- 14.3

Stack Mercury Emissions: 3.3e+000 +/- 5.0e-001 g/h

0.3 +/- 0.0 g/TJ

Stack Mercury Speciation: Oxidized (%) 60 +/- 9.1

Elemental (%) 39 +/- 5.9

Mercury Removal: Hg Removal Efficiency (%) 89.7 +/- 13.5

R-Hg (%): 0.5 +/- 0.1 | 15.6 +/- 2.3 | 87.7 +/- 13.2

Hg (g/h): 1.6e-001 +/- 2.4e-002 | 5.0e+000 +/- 7.5e-001 | 2.4e+001 +/- 3.6e+000

Figure 12 iPOG output information (screen capture from iPOG – see download details in text) government, for example. By changing the parameters used in the iPOG, users can 'play' with options such as adding bromine or ACI to determine the most appropriate control technologies for different case studies. The tool is not recommended to be prescriptive – it should not be used to select a mercury control option without expert assistance. However, it can be a very useful means of comparing options to allow the user to focus on those which are most relevant.

The POG can be downloaded free of charge from the UNEP website in English, Russian or Chinese:

http://www.unep.org/hazardoussubstances/Mercury/PrioritiesforAction/Coalcombustion/Reports/tabid/4492/language/en-US/Default.aspx

The iPOG can be downloaded free of charge from the IEA CCC website:

http://www.iea-coal.org.uk/site/2010/news-section/news?latestNewsPage=1&IEAInNewsPage=2

3.6 Case studies

Some plants in Canada have opted to close, or to switch fuels to comply with the Canada-wide Standard (*see* Chapter 2). Some plants have found that co-benefit effects of existing control systems are also sufficient to control mercury. The same will be seen in the USA under the new MATS. For example, the state of Maryland believes that it will achieve the first phase of its mercury reduction targets (80%) purely with co-benefit effects. However, the second phase target of 90% will require ACI. Overall six new FGD units, six new baghouses, two limestone injection systems, seven SCRs and SNCRs and six ACI systems will have been installed across the fleet over a three- to four-year window to comply with the current and impending US legislation. In addition sixteen mercury CEMs and nine sorbent trap systems have been installed for monitoring compliance (*see* Chapter 4). The result is clear with a reduction in mercury emissions from 1614 lb/y (730 kg/y) in 2008 to 142 lb/y (64 kg/y) in 2010 (Aburn, 2011).

Similarly, Merrimack, the 445 MW coal-fired plant in New Hampshire, is considered able to comply with the new US MATS standard as a result of the installation of the new $450 million scrubber installed recently (Brooks, 2011).

Other plants do not have such prospects with many plants opting to switch fuels or close entirely. For example, AEP in West Virginia plans to close the 1105 MW Philip Sporn plant in Mason County and the 439 MW Kanawha River Plant in Kanawha County, while Ohio Power plans to close the 713 MW Kammer Plant in Marshall County (Kasey, 2011). However, these closures are likely to be as a result of a combination of regulative factors as well as economic and technical factors and are not due to the MATS regulation alone.

The following sections look at challenging plants which have installed mercury-specific control technologies.

3.6.1 Edgewater Unit 5, Sheboygan, WI, USA

The 380 MW Edgewater Unit 5 plant in Sheboygan, WI, owned by Wisconsin Power and Light (WP&L), was one of the first commercial installations of ACI in the USA. The plant fires PRB and is fitted with a cold-side ESP. The installed ACI system can inject either upstream or downstream of the air preheater (APH). The initial target for mercury removal was 70% (of mercury and compounds present in the flue gas). The total installed cost of the ACI injection system was around 8000 $/MW (around $3.04 million).

Figure 13 Edgewater Unit 5 ACI system silo (Starns and others, 2011)

Figure 14 Installation of process equipment model at Edgewater Unit 5 (Starns and others, 2011)

The plant was fitted with a silo to hold 14 days' worth of the halogenated powdered ACI, assuming the designed feed rate of 820 lb/h (370 kg/h) or 8 lb/MMACF (128 kg/million m^3) on an APH outlet basis. As an indication of the scale of an ACI installation, Figures 13 and 14 show the silo for activated carbon storage and the feeder and blower rooms. Injection was recommended at the APH inlet to allow distribution of the ACI through the flue gas as the gas is heated through the APH, since mercury removal is optimal at temperatures above 450°F (232°C). The injection rate of the ACI was adjusted according to the measured mercury output to maximise efficiency and avoid wastage.

Prior to installation of the ACI system the mercury emissions from the plant ranged from 4–8 µg/m^3 with an average value of 6.4 µg/m^3. To meet 70% mercury removal, an injection rate of around 100 lb/h (45 kg/h) or 1.15 lb/MMACF (18.4 kg/million m^3) of sorbent (Norit DARCO Hg-LH) would be required. This would require (at 90% capacity factor) 789,000 lb/y (360 t/y) sorbent. The power consumption of the entire ACI system, including duplicate trains and silo space heaters) is around 142 kW. If 90% removal was required, this would require an injection rate of 210 lb/h (110 kg/h) or 2.45 lb/MMACF (39.2 kg/million m^3). In either case, the silo fitted was large enough to cope with the required sorbent.

Use of the Norit DARCO activated carbon meant that the fly ash produced was not acceptable for concrete use. Since fly ash sales are important to the plant budget, an alternative sorbent is being tested – Calgon concrete-friendly FLUEPAC® CF PLUS, which had approximately the same mercury removal rate as the Norit sorbent.

3.6.2 Wet scrubber plant in Russia

As part of an EU-funded project for the UNEP, the IEA CCC has been involved in project work in Russia designed to demonstrated economic options for mercury control in plants with challenging characteristics. The project was operated by VTI (the All-Russian Thermal Engineering Institute) under the ACAP (Arctic Council Action Plan) Programme. One part of the project concentrated on the Kuznetsk coal-fired Togliatti cogeneration plant in the Volga River area. The plant controls particulate emissions with a wet centrifugal scrubber rather than the ESP or baghouse systems seen elsewhere. The scrubber system is shown in Figure 15. Under normal plant operation, the mercury capture ranged from 25% to 45%, depending on the rate of water spraying in the system. As would be expected, almost all of the mercury captured was oxidised mercury. Various oxidising salts were tested to see if

Figure 15 Centrifugal water scrubber at Togliatti Power Plant, Russia (from an as-yet unpublished UNEP report)

the mercury capture rate could be improved. Laboratory studies indicated that injection of potassium permanganate and sodium hyperchlorite with the irrigation water of the scrubbers can cause mercury oxidation and thus improve mercury capture. Potassium permanganate is a controlled substance and more expensive than sodium hyperchlorite and so, as a result, full scale testing at the Togliatti plant concentrated on the latter. The oxidising solution (19% NaClO) was injected with the spray water at different flow rates (ranging from 90 to 250 L/h). Initial results from the full-scale study indicate that the oxidant solution increased the capture of elemental mercury by up to 20%, increasing the total mercury capture to 55–60% at rates of under 0.3 kg NaClO/t water/h (results as yet unpublished).

3.7 Comments

There are many ways to reduce mercury emissions from coal. These vary from coal treatment and maximising the operation of existing pollution control systems (co-benefit effects of ESP, baghouses, FGD and SCR) to, in some cases, more expensive mercury-specific options such as sorbent or oxidant addition. Because of the complexity of the behaviour of mercury in coal combustion and its variability with coal type and combustion conditions, there is no single method which will achieve maximum mercury reduction at all plants. Plants such as those in North America which face challenging mercury reduction requirements will have to invest in both expertise and development to ensure that the method chosen for their units are the most appropriate. The market for mercury control in North America is now vast and therefore it is not surprising that new technologies are being developed to move into the market place as quickly as possible.

UNEP have developed guidance tools – a document, flow-chart and interactive computer tool – which aim to help plant operators and regulators determine the most appropriate methods for mercury control on a plant by plant basis. These are available free of charge from the IEA CCC.

4 Monitoring

Emission limits and reduction targets are only successful if emissions can be measured and compliance assured. Mercury is a particular challenge for monitoring because of the low concentrations in flue gases and the two main forms it can take (oxidised and elemental). Detection limits for many systems are in the µg/m^3 range which means that very specialised systems will be required to ensure compliance with the emission limit values being set in the USA. Mercury monitoring systems are therefore relatively expensive compared to those for SO_2 and NOx. And so, over and above the expense that the utilities in the USA are facing with the control requirements of the MAT, the expense for installing mercury monitoring systems will also be high.

Monitoring methods commonly evolve to provide data in response to exacting requirements of emission standards or limits. This has been discussed in a previous report on monitoring and reporting (Sloss, 2011). As is often the case, methods have developed separately around the world but, for the ease of understanding, the most commonly used systems for measuring mercury are discussed in the following sections.

4.1 Wet chemical/manual methods

In the EU CEN (Comité Européen de Normalisation, European Standards Institute) 13211 defines the standard wet chemical method for mercury which is very similar to US EPA Method 29. US EPA Method 29 is the best known and most used method for trace metal, especially mercury, measurement from sources such as coal-fired plants. The Ontario Hydro Method is a similar wet chemical method based on a number of alkali and acidic impingers in sequence. These methods are not simple and it is well recognised that they should only be performed by qualified specialists. Method 29 is a relatively complex wet chemical method involving the passing of the flue gas through several impingers containing different solutions, including nitric acid. Each of these solutions must be collected and analysed separately using chemicals which must be shipped from the field for off-site analysis. The method is time-consuming and costly and is not an option in North America where the legislation requires either continuous monitoring or monitoring on a regular (monthly) basis. In the past, wet chemical methods have been required to calibrate automatic (CEM) systems. However, more modern CEMs are self-calibrating using mercury standards. They must still be validated against a separate system (CEM or other), however, to ensure that they are functioning correctly.

4.2 Sorbent tubes

As discussed in Chapter 3, mercury attaches to activated carbon and similar materials and, in addition to their use in control technologies, sorbents can also be used to capture mercury for quantification by monitoring systems.

The US EPA has developed a mobile mercury monitoring toolkit based on sorbent tubes. This is known as the US EPA Mercury Measurement Toolkit. Mercury passes through the sorbent tube and is captured according to its speciated form over an extended period of time. The material in the tube is analysed using thermal desorption to measure the mercury content. These measurements, combined with process information (flow rate, fuel calorific value and feed rate), are used to calculate total mercury mass emissions (µg/m^3) or mass emissions per unit of heat input (kg/trillion Btu, kg/GJ). The process for using the toolkit is outlined in Figure 16.

The robustness and simplicity of the sorbent tube system makes it ideal for short-term sampling as well as long term. UNEP-sponsored projects, lead by the IEA CCC, have deployed the toolkit in

Mobile mercury monitoring toolkit
four steps to measuring mercury from coal combustion

1 - transport and set up equipment
- all equipment fits in a van
- set-up typically takes 2-3 hours

2 - collect samples
- collect samples of coal, ash, flue gas and discharges from the pollution control devices

3 - analyse samples
- on-site results
- self validation

4 - evaluate results
- mercury emissions
- pollution control co-benefits
- emission factors

plant A

unit	flue gas (µg/m³)
unit 1	8.4
unit 2	3.1
unit 3	2.9

plant B

unit	flue gas (µg/m³)
unit 1	31.3
unit 2	36.9
unit 3	35.1

plant C

unit	coal (µg/m³)	flue gas (µg/m³)
unit 1	106	2.64
unit 2	69	3.20
unit 3	27	9.57

the toolkit includes necessary equipment, methodologies, procedures, and calculation tools.

US Environmental Protection Agency
Contact: Reynaldo Forte at
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Figure 16 US EPA Mercury Monitoring Toolkit – sorbent trap (Forte, 2012)

several countries, including Russia and South Africa, to successfully measure mercury emissions from large coal-fired power plants.

EERC (Energy and Environmental Research Centre, ND) in the USA have developed their own ME-ST sorbent tube based system for mercury measurement. They have successfully demonstrated it on pilot-scale standard pulverised coal fired systems but also on oxycombustion and gasification systems. The ME-ST system can be used for all of the MATS-specified metals (those covered by the US legislation as discussed in Chapter 2) and not just mercury, with detection levels significantly lower than those possible with Method 29 (Lentz and Pavlish, 2011).

4.3 CEMs

Mercury CEMs must measure total mercury from flue gases at elevated temperatures and often containing acidic and interfering species. Mercury CEMS must therefore be robust and well designed. Over and above this, in order to determine total mercury emissions, these systems must be able to detect and quantify both elemental and oxidised mercury. This requires some sort of conversion system, which is often the feature causing problems with mercury CEM maintenance.

In Europe, EN 14884 is the standard for mercury CEMs. The standard is quite general, outlining the methods for calibration, positioning and so on. It does not prescribe any type of CEM, rather requiring that the system meet defined performance standards.

There are numerous commercial CEM monitoring systems available, the most popular of which appear to be the Tekran, the ThermoFischer, the Lumex and the PS Analytical systems. Mercury CEM systems typically cost from around $150,000 up to over $350,000 and site preparation can add another

£200,000–350,000 to the total cost. There are ongoing costs associated with maintenance and upkeep but, in the long term, the manufacturers report that these should generally be no more than would be associated with any standard CEM (such as SO_2 and NOx – around $50–90 thousand per year). By 2010, around 600 mercury CEM systems had been installed in the USA (NESCAUM, 2010).

Mercury CEMs have been prone to problems with reliability. In the past operators reported problems with low availability, interference, high maintenance costs and issues with heated sample lines. (Kietzer, 2011). Although manufacturers suggest that mercury CEMs can be easy to maintain, users have reported that, in practice, they require far higher levels of maintenance than other CEM systems with some systems requiring man hour levels of 20 hours per week or more. Some operators switched from CEMs to sorbent traps because of these issues. Older systems were reliant on consumables, solutions such as tin chloride or a heated catalyst, to convert mercury oxides to the elemental form to obtain total mercury measurements. Many systems now use extreme heat (>800°C) to crack the mercury compounds into the elemental form thus avoiding the need for any consumables (Kietzer, 2011).

Cross-interference from other species such as SO_2 was also an issue. This could be avoided by using a gold-trap to capture the mercury, move it and analyse it in a clean gas zone. This, however, made the system more of a batch-process than a CEM. Many systems now avoid this by using the ‘Zeeman effect’ which uses two magnetically separated wavelengths to exclude cross-interferences (Kietzer, 2011).

Mercury CEMs have improved significantly in the last few years with maintenance intervals in the range of 3–6 months and relative accuracy results of >5%. NIST standards have also been developed to provide a level of calibration which was not available before 2010 (Kietzer, 2011)

The emission limits set in the US MATS and at some plants in Europe, at the $\mu g/m^3$ level or lower, will prove a challenge for some monitoring systems. Thompson and Laudal (2011) tested several mercury CEMs and sorbent traps in a natural gas system with low (near ambient) mercury levels to determine how well the systems worked at low concentrations. The Tekran and Thermo CEM systems worked well with the Tekran having a lower detection limit than the Thermo system.

4.4 Monitoring and reporting

As mentioned in Chapter 2, the EC has recently introduced, under the IED, a requirement for annual mercury measurements at coal-fired plants. It is likely that many plants will opt to carry out this test with wet chemical methods as, although the method can be challenging, it is significantly cheaper than installing a CEM system. Sorbent traps would also be a cheaper option to CEM systems for the plants in the EU at this time.

The cap-based system for mercury emissions under the CWS in Canada means that mercury emissions can be estimated from emission factors and plant performance. However, provincial standards may require CEMs on some units.

Mercury monitoring is most challenging in the USA where the new MATS is based on an emission per energy input or output basis. These limits are all 30-day rolling day averages (rolling operating days) and do not include periods of start-up, shut-down, or malfunction. Compliance can be demonstrated either with CEM data or with quarterly testing, depending on the form of the limit chosen. If CEM data are to be used then the data are averaged hourly and all of the hourly averages are then summed and divided by total hours of operation over a 30-day operating period. That average is updated daily. Two or more units within the same contiguous facility may meet the facility limit by averaging their emissions. Facilities that use multi-unit site-wide emissions averaging may alternatively meet a 1.0 lb/TBtu (around 1.5 ug/m^3) limit averaged over a 90-day period.

A typical sorbent trap system costs around $130,000–150,000 if the analysis system is included and only $80,000–100,000 if the tubes are sent to a commercial lab for analysis. Consumables and labour are then around $20,000–25,000 per year, significantly lower than the CEM systems discussed earlier (Siperstein, 2011). It would appear (from unpublished data) that many US plants have opted to use the cheaper and simpler sorbent trap approach to mercury monitoring rather than installing CEM systems. However, CEMs may be preferable for those plants which wish to maintain a watch on trends in mercury emissions and be able to act on any increases before the limit is breached. CEMs are also suitable for situations where there are any concerns with operator error or potential tampering, since these systems are fully automated and can be controlled and monitored remotely.

4.5 Comments

Mercury monitoring methodologies have evolved from complex wet chemical methods to simpler and more portable CEM and sorbent tube methods. The significant expense and maintenance requirements of CEMs will mean that these systems are likely only to be used by plants which need to keep a close watch on fluctuations in emissions in order to ensure compliance. Sorbent traps are regarded as cheaper and simpler. As a consequence, sorbent traps are also the method of choice in countries such as South Africa and Russia for producing more accurate emission factors and inventories.

5 Conclusions

Awareness of the issue of mercury as a global pollutant is growing and, as a result, emission reduction requirements are becoming more common. Canada and the USA have set stringent emission limits for coal-fired plants which require many plants to install mercury-specific control technologies. Other countries, such as those in the EU and some countries in Asia (Japan, Korea and, more recently, China) are taking a less stringent legislative approach since their existing or impending requirements for reductions of other pollutants (particulates, SO_2 and NOx) will mean the continued deployment of pollution control systems such as baghouses, FGD and SCR which are known to achieve significant mercury co-benefit reduction. Countries such as India, which have very limited controls for SO_2 and NOx will face a significant challenge if mercury reduction is required. However, the regional and national policies which have been implemented or are being implemented now have helped mercury control technologies progress, resulting in improved and more cost-effective mercury control options now being available globally.

Mercury behaviour in coal-fired power plants is affected by many factors, from the chemical and physical characteristics of the coal through to the combustion conditions and the presence of other species in the flue gas. There is therefore no single solution to the mercury problem and mercury reduction requirements force plant operators to face the challenge of having to determine which method of control is most appropriate for them. Some plants may be able to comply with even the most stringent of emission limits due to the fact that they have already installed co-benefit control systems and happen to burn coal that tends to produce mercury in the oxidised form. Other plants may need to install expensive mercury-specific control technologies. Once these technologies are in place, these plants must also invest in monitoring systems to ensure that they can demonstrate compliance with emission limits on a continual basis.

UNEP is working towards a global legally binding convention on mercury in 2013 and, although it is not known yet what form this will take, it is likely to lead to increasing global awareness and action on mercury control. The areas of greatest mercury increase tend to be those countries with growing coal use and which do not currently have pollution control systems installed which would provide co-benefit mercury reductions. It is in these areas that mercury control will be most challenging. UNEP, under the guidance of the IEA CCC, have produced free documents such as the POG and calculation tools such as the iPOG to assist these areas in determining simple and economic methods of mercury reduction.

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