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Mercury Emissions Control from Existing Utility and Industrial Boilers

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Abstract: Industrial, commercial, and institutional (ICI) boilers are one of the major sources of hazardous air pollutants (HAP), including mercury (Hg). Coal-fired electric power plants constitute the largest point source of anthropogenic Hg in the United States. The primary objective of this paper was to address the mercury side of the boiler maximum achievable control technology (MACT) of the national emission standards for hazardous air pollutants (NESHAP). This paper analyzed data collected by a research team at West Virginia University (WVU) as part of a Mercury Emissions Research project. The research focused on solid fuel (coal) fired boilers covered by the industrial boilers MACT. Hg emissions data along with coal and stack analysis were collected through a combination of surveys and personal contact with appropriate individuals at these facilities. The collected data were analyzed to determine the applicability of Hg control technologies to ICI boilers and their emissions reduction capabilities.

Keywords: ICI boilers, mercury emissions, control technologies.

INTRODUCTION

Boilers are an integral part of coal-fired electric power plants and any other plants that need a supply of steam for heating, drying, sterilization, and other purposes. About 50% of electricity generated in the United States comes from coal-fired electric power plants [1]. When coal is combusted in a boiler, it primarily produces carbon dioxide (CO_2), oxides of nitrogen (NOx), sulfur dioxide (SO_2), and particulate matter (PM). Industrial, commercial, and institutional (ICI) boilers are one of the major sources of hazardous air pollutants (HAP), including mercury (Hg). Coal-fired electric power plants constitute the largest point source of unregulated Hg emissions in the United States [2-4]. It has been estimated that about forty-eight tons of Hg is emitted from coal-fired power plants in the United States annually, which is about one percent of the total world wide Hg emissions [5].

Coal combustion in boilers produces Hg in three different forms in varying percentages. They are elemental mercury, oxidized mercury, and mercury that is adsorbed to particulates. Elemental mercury can travel a significant way in the atmosphere before being deposited to land and water bodies. Long term exposure to elemental mercury by humans has been shown to affect their central nervous system. Oxidized mercury in the presence of chlorine forms mercuric chloride ($HgCl_2$). Exposure to $HgCl_2$ has been shown to result in tumors in experimental animals. Organic Hg compounds are formed when Hg combines with carbon. Methyl mercury is the most common organic Hg compound found in the environment [6]. Americans are primarily exposed to methyl mercury by eating contaminated fish.

A number of steps have been initiated to reduce emissions of Hg and to limit its exposure. Both the Clean Air Act (CAA) and the Clean Water Act (CWA) regulate Hg by establishing technology based standards for sources that emit mercury. The U.S. Environmental Protection Agency (USEPA) on September 13, 2004, developed national emission standards for hazardous air pollutants (NESHAP) for ICI boilers and process heaters. The NESHAP focused on "the maximum degree of reduction in hazardous air pollutants (HAP), including Hg, that is achievable, taking into consideration the cost of achieving the emissions reductions, any non air quality health and environmental impacts, and energy requirements" [7]. This level of control is commonly referred to as maximum achievable control technology (MACT). The USEPA on March 15, 2005, also promulgated the Clean Air Mercury Rule (CAMR) to permanently cap and significantly reduce Hg emissions from coal-fired power plants in two phases. The first phase, which begins in 2010, aims to reduce Hg emissions down to thirty-eight tons a year and will take advantage of co-benefit reductions – that is Hg reductions achieved by reducing SO_2 and NOx from coal-fired power plants under the Clean Air Interstate Rule (CAIR) [8]. In the second phase, due in 2018, Hg emission is expected further to be reduced by 70% from the present level. During the second phase all coal-fired power plants will be subjected to a 'second cap' which will reduce Hg emissions to fifteen tons per year. New coal-fired power plants will also be subjected to stringent emission standards.

Hg emissions from ICI boilers are presently controlled by the existing conventional air pollution control devices (APCD) used to remove NOx, SO_2, and PM from combustion flue gas. This includes the capture of particulate bound Hg in PM control equipment and the capture of oxidized Hg compounds in wet flue gas desulfurization (FGD) systems [9]. In 1999-2000, USEPA conducted an Information Collection Request (ICR) to update the Hg emissions inventory for

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coal-fired power plants. It was found that the capture of Hg across existing APCD s varied significantly. Coal properties including chlorine content, sulfur content, flue gas temperature, ash content, and specific APCD configurations were likely to contribute to this variation. The level of control was found to range from 0% to more than 100% [10]. Therefore, there was clearly a need to determine if the existing fleet of ICI boilers can meet the new MACT regulations.

This paper reports survey data collected by a research team at West Virginia University (WVU) as part of a Mercury Emissions Research project. The research focused on coal-fired boilers covered by the industrial boilers MACT. Hg emissions data along with coal and stack analysis were collected through a combination of surveys and personal contact. The collected data were analyzed to determine the applicability of Hg control technologies to ICI boilers and their emissions reduction capabilities. The unique findings of this survey are expected help the researchers and policymakers projecting the control technologies employed by ICI boilers to capture Hg emissions and their effectiveness.

INDUSTRIAL AND UTILITY BOILERS

Boilers burn fuel and produce steam, which acts as the working fluid for power plants. Power plants generally employ utility boilers for steam production, while industrial boilers are used to produce steam for heating, drying, sterilization, etc. According to a Council of Industrial Boiler Owners (CIBO) report published in 2003, there were about 4,000 utility boilers and about 70,000 industrial boilers in operation in the United State [11]. The major differences between utility and industrial boilers can be categorized in three distinct areas: boiler size, boiler steam production and its application, and boiler design. Industrial boilers are much smaller in size, as compared to utility boilers. A typical utility boiler can produce about 3,500,000 pounds of steam per hour while steam production from the majority of industrial boilers may range from 10,000 to 1,200,000 pounds of steam per hour. The size of the utility boilers allows them to have significant economies of scale, especially in the control of emissions that simply are not available to industrial boilers.

Utility boilers are primarily large field erected pulverized coal, oil, or natural gas fired high pressure, high temperature boilers with relatively uniform design and similar fuel combustion systems. In contrast, industrial boilers are large or small field erected or shop assembled package boilers designed to burn anything that can be burned alone or along with conventional fuels. Industrial boilers have different purposes in different industries and hence their operations are transient. Therefore, industrial boilers have much lower annual operating load or capacity factors than utility boilers. Utility boilers, on the other hand, generate steam at a constant rate to power turbines that produce electricity. Therefore, a utility boiler operates at a steady state rate close to its maximum capacity.

MERCURY EMISSIONS CONTROL

Controlling Hg emissions from boilers involves three separate steps; pre-combustion control, in-furnace control options, and post-combustion control options. Pre-combustion control options include coal cleaning and chemical addition while in-furnace control options include low excess air combustion, ammonia injection, and urea injection. The third controlling option, which takes place outside the combustion chamber, generally involves the use of selective catalytic reduction (SCR), electrostatic precipitators (ESP), fabric filters (FF), and mechanical separators (MS). Some power plants also use cold-side electrostatic precipitators (ESP-Cold Side), hot-side electrostatic precipitators (ESP-Hot Side), and particle scrubbers (PS). Plants use one or a combination of these post-combustion equipment options to reduce NOx, SO_2, and PM. Hg is also captured through these equipment as a co-benefit, although the degree of benefit varies depending on the type of coal burned and the control technology configuration [8]. EPA's Mercury ICR revealed that plants employing PM controls experienced Hg reduction from no reduction to more than 100%. A combination of ESP-Hot Side and FGD exhibited the highest average levels of mercury reductions, about 106% and 46% from bituminous and low rank coal, respectively [10]. FF alone showed better efficiency in Hg reduction when compared with other control technologies used alone. EPA's Mercury ICR also found that plants using both PM and SO_2 controls achieved 0 to 98% Hg emissions reduction. Some Hg specific emissions control methods are also used at present. Activated Carbon Injection (ACI) methods inject powdered activated carbon into the flue gas in a location before ESP or FF. The powdered carbon binds with Hg and PM in the flue gas and is subsequently captured by the PM reduction devices [12]. This method, however, would result in a significant increase in the cost of electricity from coal-fired power plants [3].

SURVEY METHODOLOGY

It was decided during the research project to collect boiler data through the use of a survey collection instrument. The survey contained two parts: identifying information and the necessary data. The items included in the survey were determined based upon appropriate input from boiler owners and operators, CIBO, and the U.S. Department of Energy (DOE). The data items were selected based upon their necessity for calculating the resultant information for the study. The survey form was distributed, with the assistance of the CIBO during 2004, to appropriate members of CIBO and other firms, whom it was felt would form a sufficiently large population for the data collection process. It was anticipated that this study would be able to obtain a large enough sample of data from this identified population to generate significant results and conclusions from the study. The final form of the survey is also available as supplementary material with this paper.

RESULTS AND DISCUSSIONS

There were completed survey forms returned with data covering 232 boilers at 118 plants owned by twenty-five companies. Eighty-seven boilers out of these 232 boilers qualified to be included in the study based on the parameters identified in the survey form. Test results from these eighty-seven boilers have been presented in the following paragraphs.

Distribution of Boilers

Out of eighty-seven boilers reported in this survey, sixty-two units were stoker units, twenty-two boilers were pulverized units, two were fluidized bed combustors, and one was a cyclone unit. All pulverized boiler units used bituminous coal while fifty-nine of the stoker units and two of the fluidized bed combustors also used bituminous coal. Two stoker units and one cyclone type boiler used sub-bituminous coal and the remaining stoker unit used waste coal.

Geographically, boilers selected in this analysis came from six EPA regions as shown in Fig. (**1**). The majority of these boilers belonged to EPA region # 5, which constituted Indiana, Minnesota, Illinois, Ohio, Michigan, and Wisconsin. All these boilers used eastern bituminous coal. Eighteen boiler units were located in EPA Region # 4, which included Kentucky, Tennessee, Mississippi, and Alabama. These boilers also used eastern bituminous coal. On a state by state comparison, Michigan had the largest representation with fifteen boilers, followed by Tennessee with thirteen boilers.

These boilers were also grouped according to the purposes they served, by their Standard Industrial Classification (SIC) code as shown in Table **1**. Twenty-one boilers reported in this survey were used in the transportation equipment industries. Twelve boilers were used in chemical and allied products and ten boilers were used in organic chemical industries. Eleven boilers in this survey were used by universities. The remaining thirty-three boilers were used by salt manufacturers, prisons, hospitals, corn mills, paper mills, synthetic rubber manufacturers, pesticide and agricultural chemicals industries, electric services, combination utilities, and steam and air conditioning suppliers.

Mercury Content

Coal analysis performed by the facility owners yielded Hg contents in their fuel as a ratio of pounds of mercury to trillion (10^{12}) British thermal units (tBtu) of the fuel burned. Sufficient data for appropriate analysis was possible for Eastern Bituminous coal only. The amount of Hg in this type of coal ranged from 1.53 lb/tBtu to 13.64 lb/tBtu with an average value of 7.88 lb/tBtu and a standard deviation of 3.32 lb/tBtu. Fig. (**2**) presents a graphical representation of Hg content in Eastern Bituminous coal. It was observed that some coal analysis yielded Hg amounts well over the NESHAP standards of 9.0 lb/tBtu for existing large solid fuel-fired boilers.

PM Control Technologies

Boilers reported in this survey used a variety of post-combustion particulate control devices. Out of twenty-two pulverized coal-fired boilers, eight used ESP while six used FF and six used ESP-Hot Side as shown in Fig. (**3**). The remaining two used ESP with cyclones. Out of the sixty-two stoker-fired boilers, twenty-six ICI boilers used FF while twenty boilers used MS as presented in Fig. (**4**). Five of them used ESP while seven of them used FF's with cyclone. The remaining four ICI boilers used a combination of cyclone and ESP and PS.

Mercury Capture by Existing Post Combustion Control Technologies

Table **2** presents the average Hg capture by existing post combustion control technologies. It was found that pulverized coal-fired boilers with FF were more effective than boilers equipped with ESP in capturing mercury. This is reasonable because filter cake in FF acts as a fixed bed reactor and contributes to greater homogeneous oxidation and

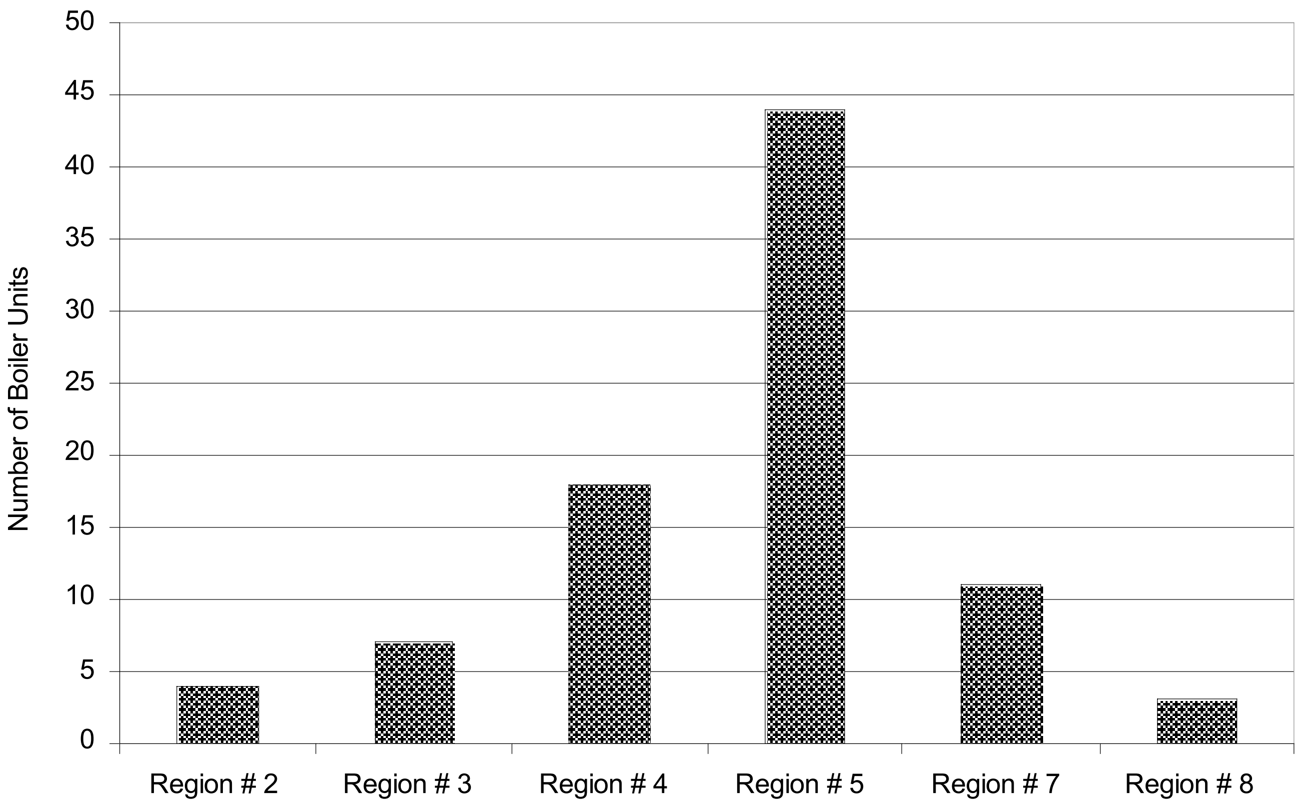

Fig. (1). Geographic distribution of boilers by EPA region.

Table 1. Distribution of Boilers by Standard Industrial Classification (SIC) Code and their Purpose

Primary SIC Code	Examples of Reporting Entities	Number of Boilers Reporting				
		Pulverized Coal	Cyclone Fired	Fluidized Bed Combustor	Stoker Fired	Total Number of Boilers Reported
28	Chemical & Allied Products	6	-	-	6	12
99	Prison (non-classifiable establishment)	-	-	-	3	3
806	IPP or Hospital	-	-	-	2	2
2046	Wet Corn Milling	3	-	-	5	8
2621	IPP – Paper Mill	-	-	-	2	2
2799	Salt Manufacturer	-	-	-	7	7
2822	Synthetic Rubber Manufacturer	2	-	-	-	2
2869	Industrial Organic Chemicals	8	-	-	2	10
2879	Pesticide and Agricultural Chemicals	-	-	-	2	2
3700	Motor Vehicle & Parts Manufacturer (Transportation Equipment)	-	-	1	20	21
4911	Electric Services	-	-	-	1	1
4939	Combination Utilities (gas, water)	2	-	-	1	3
4961	Steam and Air Conditioning Supplier	1	-	-	2	3
8221	University	-	1	1	9	11
Total Number Reporting		22	1	2	62	87

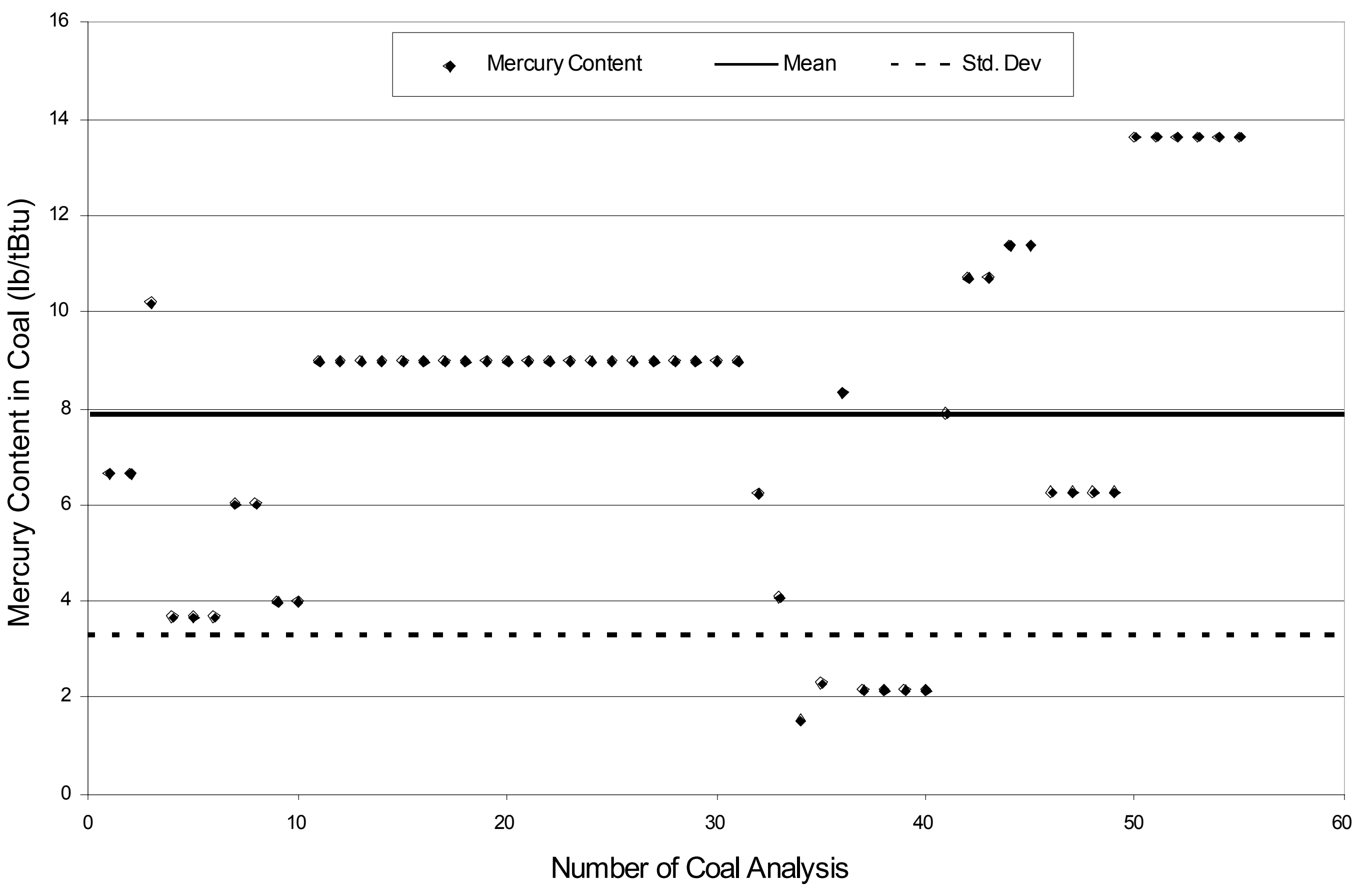

Fig. (2). Mercury content in eastern bituminous coal used in ICI boilers.

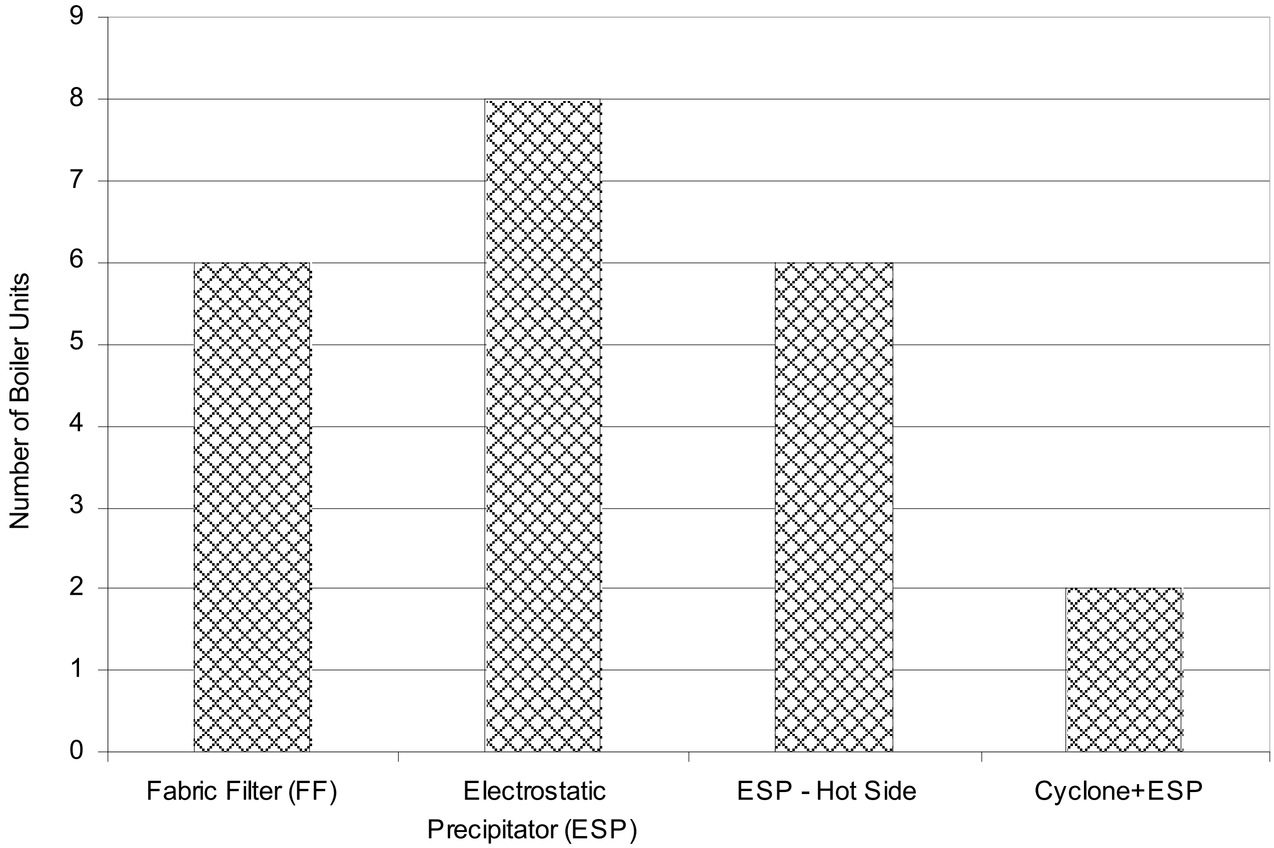

Fig. (3). Type of particulate control devices used by twenty-two pulverized coal-fired boilers.

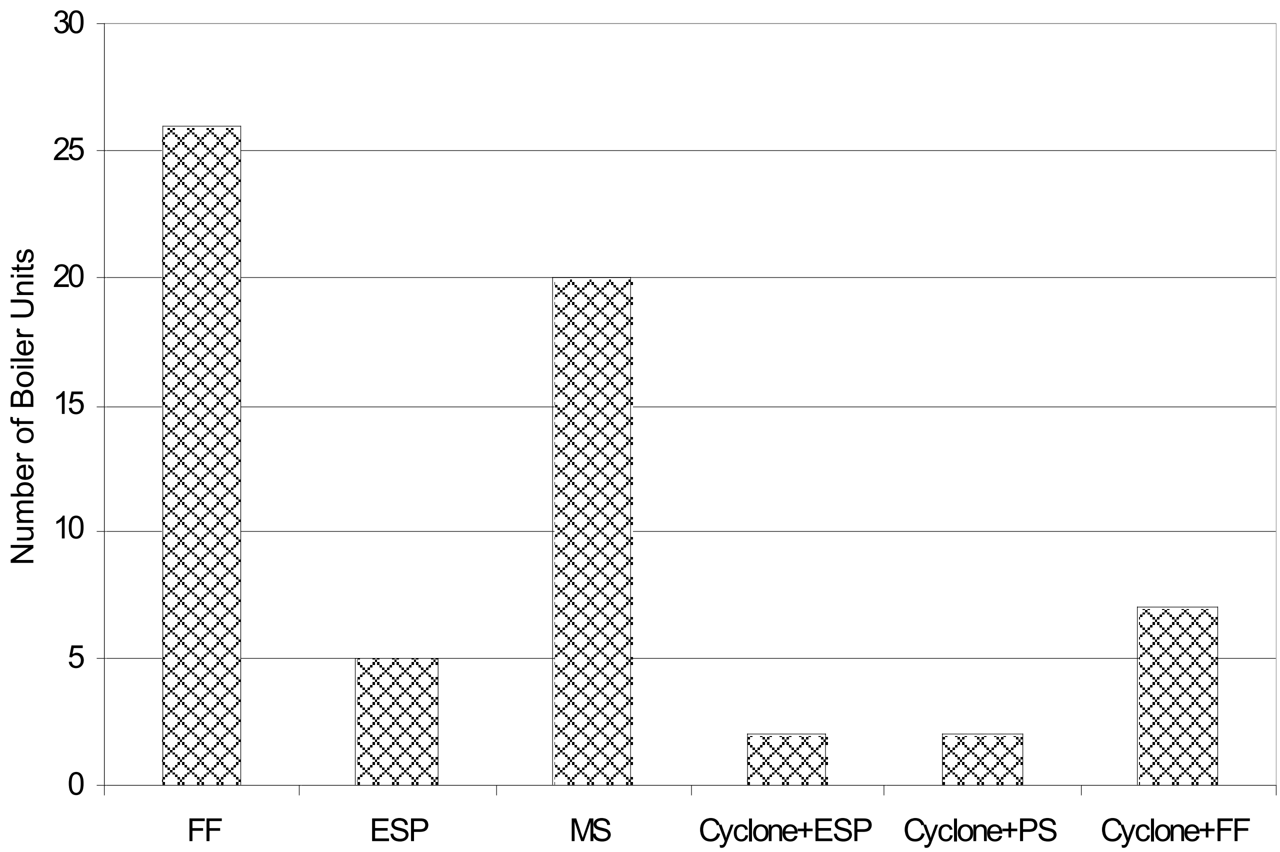

Fig. (4). Particulate control devices used by stoker-fired boilers.

Table 2. Average Mercury Capture by Existing Post Combustion Technologies

Post Combustion Control Strategy	Post Combustion Emission Control Device	Average Mercury Capture by Control Configuration	
		Coal Burned in ICI Boiler Units	
		Bituminous	
		Stoker Fired	Pulverized Coal Fired
PM Control Only	Electrostatic precipitators (ESP)	-155.6%	5.7%
	Fabric Filters (FF)		96.4%
	Mechanical Separators (MS)+FF	45.8%	
Wet SO_2 Scrubber System	MS+ Venturi Wet Scrubbers (VWS)	-4.0%	

adsorption of Hg [8]. These results supported the findings of the EPA's Mercury ICR. The negative emission reductions shown for stoker-fired boilers presented cases for which the outlet Hg concentration was higher than that of the inlet concentration. This was believed to result from one or a combination of factors. For example, negative emission reductions could have occurred when temperature changes within the test unit increased the desorption of Hg, ESP rapping cycles resulted in the re-entrainment of Hg, or small differences between inlet and outlet Hg concentrations were not accurately quantified because of imprecision in the measurement instruments.

CONCLUSIONS

Hg emissions data were considered in this research for eighteen different boiler units, which included sixteen stoker-fired boilers and two pulverized coal-fired boilers. It was found that ten out of the eighteen boiler units would have passed the present NESHAP Hg emissions standards for existing large boilers. Even though coal analyses were available for fifty-five of the original eighty-seven surveyed boiler units, Hg contents in the coal used were not available for all of the eighteen boilers discussed here. Both of the pulverized coal-fired boilers had stack Hg emissions below NESHAP standards for existing boilers. One pulverized and four stoker-fired boilers had Hg emissions below NESHAP standards for new boilers. The lowest Hg emission was observed for one stoker-fired unit employing a MS in series with a FF along with wet SO_2 scrubbing and one pulverized coal-fired unit employing just a FF.

Emissions results and coal analysis showed that Hg emissions were affected by the type of coal used and hence its Hg content, type of particulate control technique used, and the type of control devices used by the boilers. Analysis of two boilers from the same facility, but employing different boiler and particulate control devices, revealed that control technique and control device could have produced different Hg emissions. Two boilers, with the same heat input rate and burning the similar coal, yielded different Hg emissions.

The lack of completeness in Hg emissions data and corresponding coal analysis data does not allow for any concrete conclusions from the current survey. The effect of fuel type, control technology, and control device on Hg emissions was observed. Additional data covering a wider range of boiler type, fuel type, and control device type will help to better quantitatively understand the extent to which each of these factors contribute to Hg emissions reduction.

DEFINITIONS, ACRONYMS, ABBREVIATIONS

ACI	=	Activated Carbon Injection
APCD	=	Air pollution control devices
Btu	=	British thermal units
CAA	=	Clean Air Act
CAIR	=	Clean Air Interstate Rule
CAMR	=	Clean Air Mercury Rule
CIBO	=	Council of Industrial Boiler Owners
CO_2	=	Carbon dioxide
CWA	=	Clean Water Act
DOE	=	U.S. Department of Energy
ESP	=	Electrostatic precipitators
FF	=	Fabric filters
FGD	=	Flue gas desulfurization
HAP	=	Hazardous air pollutants
Hg	=	Mercury
$HgCl_2$	=	Mercuric chloride
ICI	=	Industrial, commercial, and Institutional Boilers
ICR	=	Information Collection Request
MACT	=	Maximum achievable control technology
MS	=	Mechanical separators
NESHAP	=	National emission standards for hazardous air pollutants
NOx	=	Oxides of nitrogen
PM	=	Particulate matter
PS	=	Particle scrubbers
SCR	=	Selective catalytic reduction
SIC	=	Standard Industrial Classification
SO_2	=	Sulfur dioxide
USEPA	=	U.S. Environmental Protection Agency
VWS	=	Venturi Wet Scrubber
WVU	=	West Virginia University

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SUPPLEMENTARY MATERIAL

This article also contain supplementary data and it can be viewed at www.bentham.org/open/towmj

REFERENCES

[1] "Energy Information Administration (EIA), Generation and Consumption of Fuels for Electricity Generation", *Electric Power Monthly*, July 2006, Available: http://www.eia.doe.gov/cneaf/electricity/epm/epm_sum.html

[2] J. Ravi, "Coal-Fired Power Plants – Science, Technology, and Environmental Policy Issues", *Clean Technol. Environ. Policy*, vol. 6, pp. 73-74, February 2004.

[3] C. E. Romero, Y. Li, H. Biligren, N. Sarunac, and E. K. Levy, "Modification of Boiler Operating Conditions for Mercury Emissions Reductions in Coal-Fired Utility Boilers", *Fuel*, vol. 85, pp. 204-212, January 2006.

[4] T. M. Sullivan, F. D. Lipfert, S. M. Morris, and S. Renninger, "Assessing the Mercury Health Risks Associated with Coal-Fired Power Plants: Impacts of Local Depositions", *Proc. Air Qual. IV Conf.,* Arlington, VA, September 2003.

[5] J. Kilgroe, C. Sedman, R. Srivastava, J. Ryan, C. Lee, and S. Thoreloe, "Control of Mercury Emissions from Coal-Fired Electric Utility Boilers: Interim Report", *EPA-600/R-01-109*, *U.S. Environ. Protect. Agency,* April 2002.

[6] U.S. Environmental Protection Agency, "Mercury Study Report to Congress", *EPA-452/R-97-003*, 1997.

[7] U.S. Environmental Protection Agency, *Code of Federal Regulations (CFR) 40*, Part 63, Federal Register/ vol. 70, no. 248, December 28, 2005.

[8] R. K. Srivastava, N. Hutson, B. Martin, F. Princiotta, and J. Staudt, "Control of Mercury Emissions from Coal-Fired Electric Utility Boilers -An Overview of the Status of Mercury Control Technologies", *Environ. Sci. Technol.*, vol. 40, pp. 1385-1393, March 2006.

[9] *U.S. Environmental Protection Agency*, "Mercury: Controlling Power Plant Emissions: Controlling Mercury with Existing Controls", Available: http://www.epa.gov/mercury/control_emissions/tech_exist.htm

[10] C. L. Senior, "Behavior of Mercury in Air Pollution Control Devices on Coal-Fired Utility Boilers", Power Production in the 21st Century: Impacts of Fuel Quality and Operations, Engineering Foundation Conference, Oct-Nov 2001.

[11] "Energy Efficiency and Industrial Boiler Efficiency – An Industry Perspective," *Counc. Ind. Boiler Owners (CIBO)*, March 2003.

[12] "Mercury: Controlling Power Plant Emissions: Mercury Specific", *U.S. Environmental Protection Agency*, Available: http://www.epa.gov/mercury/control_emissions/tech_exist.htm

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