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Trace Emissions from Coal and Oil Combustion

How real is the threat from trace emissions of metals and organics? Here are experimentally based national estimates.

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Due to the need of national energy self-sufficiency and increasing energy demands in the United States, coal is supplanting imported oil as a fuel supply. Combustion of coal and oil results in varying quantities of trace pollutant emissions, many of which may be harmful to human health.

The U.S. Environmental Protection Agency is currently engaged in a program to assess the environmental, economic, and energy impacts of stationary conventional processes firing coal, oil, and other fuels [*1*]. The program focuses on the assessment of trace pollutants in the gaseous emission streams from conventional combustion sources.

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This article presents background information on atmospheric emissions of certain trace metals and hazardous pollutants from coal and oil combustion based on a review of the existing literature.

The following four principal categories of conventional stationary combustion systems are analyzed in this summary:

- Utility boilers
- Industrial boilers
- Commercial/institutional boilers
- Residential boilers

A minimum size of 264 GJ/hr (250 × 10^6 Btu/hr) heat input was selected for the utility category in accordance with EPA's guidelines for New Source Performance Standards (NSPS). The industrial category includes both industrial and commercial boilers with a minimum heat input of 26 GJ/hr (25 × 10^6 Btu/hr) while those with capacities below 26 GJ/hr (25 × 10^6 Btu/hr) are included in the commercial/institutional category. Residential boilers studied had a maximum size of 422 MJ/hr (0.4 × 10^6 Btu/hr) heat input.

The boiler categories are further divided into subcategories according to a classification scheme based on fuel type and firing technique, as shown in Table 1. The choice of the various categories is based on representativeness and data availability of boiler population and emissions.

PRIORITIZATION OF TRACE POLLUTANTS

Several trace elements and organic species have received individual attention in the literature with regard to the environmental and health impacts of their emission from coal- and oil-fired plants. In order to limit the number of trace pollutants considered in this study, a preliminary prioritization technique was employed using the following criteria for selection of pollutants:

- Known or suspected carcinogens
- Substances listed by EPA as hazardous to human health
- Elements preferentially enriched in the fly ash as compared to the bottom ash
- Elements showing pronounced concentration trends with decreasing particle size

Based on the above considerations, the following list of pollutants comprising 10 trace metals and 4 organic species was developed.

Trace Metals

1. Arsenic (As)
2. Beryllium (Be)
3. Cadmium (Cd)
4. Chromium (Cr)
5. Lead (Pb)
6. Manganese (Mn)
7. Mercury (Hg)
8. Nickel (Ni)
9. Selenium (Se)
10. Vanadium (V)

Organic Species

1. Benzo(a)pyrene (BaP)
2. Dioxins
3. Formaldehyde (HCHO)
4. Polycyclic organic matter (POM)

Among the trace metals, arsenic, beryllium, cadmium, chromium, and mercury are either known or suspected carcinogenic agents [2, 3]. With respect to organic emissions, a number of POM compounds have also been identified as active carcinogens. It should be noted that BaP is listed separately from POM even though BaP is a POM compound, since analysis is generally specific for BaP and reported emission data for other POM compounds are sparse by comparison [4]. Formaldehyde has been listed as a suspected carcinogen in the literature [3], and is therefore included in the list of trace pollutants. The acute toxic nature which has been reported [5] for a number of dioxin isomers supports the inclusion of dioxins in the trace pollutant list.

Arsenic, cadmium, chromium, lead, nickel, and selenium have been found to have a tendency to preferentially concentrate in the fly ash from coal-fired plants [6]. The above elements in addition to beryllium, manganese, and vanadium, show pronounced concentration trends with decreasing particle size. This is an important consideration since pollutants present in respirable particulates may pose an environmental hazard. Principal trace elements in oil include cadmium, chromium, nickel, and vanadium [7].

TABLE 1. COMBUSTION SOURCE CATEGORIES

Category	Fuel type	Firing type
Utility	Bituminous coal	Pulverized dry bottom Pulverized wet bottom Cyclone Stoker
	Anthracite coal	Pulverized dry bottom Stoker
	Lignite coal	Pulverized dry bottom Pulverized wet bottom Cyclone Stoker
	Residual oil	Tangential Wall
Industrial	Coal (all types)	Pulverized Stoker
	Residual oil	Tangential Wall
	Distillate oil	Tangential Wall
Commercial/institutional	Coal (all types)	Pulverized Stoker
	Residual oil	Tangential Wall
	Distillate oil	Tangential Wall
Residential	Bituminous coal	All types
	Anthracite coal	All types
	Lignite coal	All types
	Distillate oil	All types

EXISTING EMISSIONS DATA BASE

An extensive literature search was conducted to obtain emissions data for the 14 trace pollutants from the combustion source categories described earlier. Available data and statistical reports from Federal Government agencies, e.g., Bureau of Census, Bureau of Mines, Bureau of Domestic Commerce, National Institute of Health, etc., were surveyed. Other significant sources of information included the Combustion Emissions Analysis Catalog System, computerized data bases, technical papers and reports by trade organizations, such as the Electric Power Research Institute. A concentrated effort was made to assess the trace emissions in terms of the type of particulate control device employed. Decisions as to the adequacy of the existing data base involved a consideration of both the reliability and variability of the data.

A brief discussion of the emissions data base is presented below for each of the four boiler categories.

Utility Boilers

Despite the widespread application of control devices, particulate emissions from utility boilers still pose a significant environmental problem, accounting for approximately 25 percent of the total particulate emissions from all stationary sources [8]. The literature is abundant in emissions data for the trace pollutants from bituminous coal-fired boilers equipped with electrostatic precipitators and from uncontrolled residual oil-fired utility boilers. Relatively less information, though, is available on trace emissions from lignite-firing, while data on emissions from anthracite-firing sources are almost nonexistent. For coal combustion in general, the data base characterizing gaseous emissions primarily represents sources equipped with electrostatic precipitators for pulverized and cyclone-fired boilers, and multicyclone-equipped stoker units. Trace emissions data are seldom available for oil-fired boilers equipped with particulate control devices.

Industrial Boilers

The existing trace emissions data base for industrial boilers is inadequate, particularly for coal-fired units. Most of the existing data on coal-firing is for bituminous coal pulverized units equipped with multicyclones or scrubbers, and for stoker units equipped with multicyclones. No data on dioxin emissions, though, were found.

In the case of oil-firing, the data base covers uncontrolled as well as scrubber-equipped units.

Commercial/Institutional Boilers

The data base on commercial/institutional boilers is similarly limited for trace emissions; all reported data are for uncontrolled emissions.

Residential Boilers

Available literature contains extensive data on trace organic emissions, with the exception of dioxins, from both coal- and oil-fired residential units. The variability in the data, however, is significant since these emissions vary widely depending on boiler combustion efficiency. Data on trace metal emissions from residential units, though, are relatively sparse.

EMISSION FACTORS

Based on a review of the existing emissions data base and employing engineering judgement where needed, emission factors were estimated for the trace pollutants from the various combustion-source categories, as a function of particulate control device. The emission factor estimates for utility, industrial, commercial/institutional, and residential boilers are presented in Tables 2 through 5. As with all emission factors, these are only general estimators of the actual emissions and could vary widely from plant to plant.

Importance was given to the reliability of reported emissions data in estimating the emission factors. Average trace-element removal efficiencies reported in the literature were used where emissions were unavailable for certain control devices. Since emissions data on anthracite coal-fired emissions from utility boilers were unavailable in the literature, emission factors estimated for bituminous coals were assumed to apply for anthracite coals too. The type of oil used, residual or distillate, was not generally specified for industrial boilers, and hence estimated emission factors could not be delineated for the two oil types for this category.

For the utility category, flue gas emissions of arsenic, chromium, lead, manganese, nickel, and vanadium from bituminous coal-fired boilers are relatively high. Due to high emissions of arsenic, cadmium, nickel, and vanadium from residual oil-fired utility boilers, these pollutants warrant special concern. POM and BaP emissions are considerably lower for both coal- and oil-fired utility boilers; formaldehyde emissions are somewhat high for coal-fired utility boilers. Although dioxin emissions appear to be insignificant from combustion sources, additional emissions data on dioxins would be required to confirm the reported emission factor.

In the industrial category, trace metals comprising arsenic, chromium, lead, nickel, selenium, and vanadium are emitted at the highest concentrations in flue-gas streams from coal -fired boilers. For oil-fired boilers, arsenic, cadmium, chromium, nickel, and vanadium have high emission factors. POM emissions are generally low for both coal- and oil-fired industrial sources.

Emissions of all the selected trace metals and organic compounds, with the exception of beryllium, cadmium, and mercury, appear to be considerably high from stoker-fired commercial boilers. Significant quantities of POM, BaP, and formaldehyde are also emitted from these sources. For oil-fired combustion, arsenic, cadmium, chromium, nickel, and vanadium are emitted in substantial quantities.

The seven trace metals with a high level of emissions from commercial coal-fired boilers also have the highest emission factors for residential coal-fired boilers. POM and BaP emissions are very high due to the poor combustion efficiency of such units. For residential oil-fired units, nickel and formaldehyde are the only trace pollutants which are emitted in high concentrations.

FUEL CONSUMPTION FOR COMBUSTION SOURCE CATEGORIES

In order to quantify emissions of trace pollutants on a national basis, fuel (coal and oil) consumptions for the various combustion-source categories were estimated based on existing boiler population and fuel use data. The most reliable and current available information was used.

Fuel consumption estimates for utility, industrial, commercial/institutional, and residential boilers are presented in Tables 6 and 7. Utility boilers account for about 90% of the total coal consumption for the four categories. Combustion of bituminous coal represents 88% of the utility coal combustion, pulverized dry bottom units being the predominant furnace type. The utility category is responsible for about 66% of total residual-oil consumption, the remainder being shared almost equally between the industrial and commercial categories. The residential boiler category is the largest consumer of distillate oil (64%), followed by the commercial/institutional category (27%).

CONTROL-DEVICE POPULATION FOR EXISTING BOILERS

The national trace emissions from coal and oil combustion depend on the extent and type of particulate control employed in existing boilers, since control devices influence pollutant emission factors considerably. Comprehensive data on control-device population are, however, not readily available for the various categories.

Utility Boilers

Electrostatic precipitators (ESP) constitute the most popular type of control device employed for utility boilers firing pulverized coal [*11*]. ESP's also control over 83% of the capacity of cyclone-fired boilers using bituminous coal [*12*]. Wet scrubbers and baghouses are employed to a much lesser extent. Multicyclones are extensively employed on stoker units and on lignite-fired cyclone units. Utility oil-fired boilers typically do not utilize particulate controls [*13*], and it has been estimated the only 20% of such units are equipped with particulate control devices [*14*].

For the present study, the following simplifying assumptions were made regarding the control-device population for utility boilers (1978):

- All pulverized coal units are equipped with ESP's
- All stoker units are equipped with multicyclones
- All cyclone units firing bituminous coal are equipped with ESP's; lignite-fired cyclone units are equipped with multicyclones for 80% of their capacity, and with ESP's for the remaining 20%
- Oil-fired units are uncontrolled for 80% of their capacity, and equipped with ESP's for the remaining 20%.

TABLE 2. EMISSION FACTORS FOR TRACE POLLUTANTS FROM COAL- AND OIL-FIRED COMBUSTION: UTILITY BOILERS (>264 GJ/hr INPUT)

Fuel type	Furnace type	Control device	As	Be	Cd	Cr	Hg	Mn	Ni	Pb	Se	V	Di-oxins	HCHO	POM	BaP
			Emission factor, pg/J													
Bituminous coal	Pulverized dry bottom	ESP	15.3	2.1	0.8	60:2	7.7	41.3	30.1	39.1	13.0	39.4	0.01	59.3	1.0	0.03
		Multicyclones		6.9			7.7							59.3	1.2	0.03
		Scrubber	5.3	0.3	1.7	170	1.5	48.2	22.1	10.4	16.3	62.8				
		None	133	23.7	8.9	1505	7.7	98.0	130	537	161	110				
	Pulverized wet bottom	ESP	12.4	1.7	0.6	49.0	7.7	33.5	24.3	31.0	10.5	32.3	0.01	35.3	1.0	0.08
		Multicyclones		5.6			7.7							35.3	1.0	0.08
		Scrubber		0.2			1.5									
		None		18.9			7.7									
	Cyclone	ESP	3.0	0.6	0.3	8.0	7.7	26.1	2.0	5.0	1.4	30.1	0.01	56.8	1.0	0.08
		Multicyclones		1.2			7.7									
		Scrubber		0.7		46.0	2.1	54.2			33.0	30.0			ND[a]	
		None		4.0			7.7	98.0	130							
	Stoker	Multicyclones	206	5.6	5.5	16.3	6.0	47.3	29.2	610	36.1	24.9	0.01	37.4	0.9	0.09
		None		18.1			6.0							60.2		
Anthracite coal	Pulverized	ESP	15.3	2.1	0.8	60.2	7.7	41.3	30.1	39.1	13.0	39.8	0.01	59.3	1.0	0.06
	Stoker	Multicyclones	206	5.6	5.5	16.3	6.0	47.3	29.2	610	36.1	24.9	0.01	37.4	1.2	0.10
Lignite coal	Pulverized dry bottom	ESP	6.8	0.6	0.3	26.5	10.3	18.1	13.2	2.5	5.7	17.5	0.01	56.8	1.1	0.07
		Multicyclones		15.1	3.2		10.3			18.1						
		Scrubber		0.3			2.1									
		None		64.5			10.3									
	Pulverized wet bottom	ESP	5.5	0.5	0.3	21.6	10.3	14.7	10.7	2.0	4.6	14.2	0.01	35.3	1.2	0.09
		Multicyclones					10.3									
		Scrubber					2.1									
		None					10.3									
	Cyclone	ESP	6.7	0.3	0.7	17.8	10.3	57.2	4.5	11.2	3.1	233	0.01	56.8	1.1	0.09
		Multicyclones	120	3.0	9.8	430	10.3	711	320	154	3.4	291	0.01	78.3	1.1	0.09
		Scrubber		0.2			2.1									
		None		55.9			10.3									
	Stoker	Multicyclones	206	6.0	5.5	16.3	2.4	47.3	29.2	121	36.1	24.9	0.01	37.3	1.1	0.09
		None		24.1			2.4									
Residual oil	Tangential	ESP	9.5	0.6	14.4	5.7	0.9	2.2	57.2	4.0	2.0	3-3		10.8	0.04	
		Scrubber		0.02			0.2									
		None	47.3	2.3	71.8	28.6	0.9	11.0	287	20.0	10.1	1516		10.8	0.09	0.02
	Wall	ESP	9.5	0.6	14.4	5.7	0.9	2.2	57.2	4.0	2.0	303		10.8	0.04	
		Scrubber		0.02			0.2									
		None	47.3	2.3	71.8	28.6	0.9	11.0	287	20.0	10.1	1516		10.8	0.09	

[a]Not detected

TABLE 3. EMISSION FACTORS FOR TRACE POLLUTANTS FROM COAL- AND OIL-FIRED COMBUSTION: INDUSTRIAL BOILERS (>26 GJ/hr INPUT)

Fuel type	Furnace type	Control device	As	Be	Cd	Cr	Hg	Mn	Ni	Pb	Se	V	Di-oxins	HCHO	POM	BaP
			Emission factor, pg/J													
Coal	Pulverized	ESP		1.9			7.7									
		Multicyclones	280	6.5	2.7	71.8	7.7	29.4	39.0	161	48.6	33.0		38.7	9.5	0.03
		Scrubber	92.0	1.0	0.4	54.2	1.6	6.3	26.0	8.8	41.0	24.0		24.1	ND[a]	ND[a]
		None		21.5	8.9		7.7									
	Stoker	Multicyclones	206	5.6	5.5	16.3	22.4	47.3	29.2	121	36.1	24.9		60.2	13.2	0.03
		None	482	18.1	12.9	38.3	6.0	11.0	68.4	282	84.3	58.1		94.6	31.0	0.06
Oil	Tangential	Scrubber	9.4	0.3	21.0	5.7	0.2	1.3	62.8	4.1	2.0	260		63.6	ND[a]	ND[a]
		None	47.3	1.9	71.8	28.6	0.9	6.5	314	20.4	10.1	1300		86.0	0.5	0.13
	Wall	Scrubber	9.4	0.3	21.0	5.7	0.2	1.3	62.8	4.1	2.0	26-		63.6	ND[a]	ND[a]
		None	47.3	1.9	71.8	28.6	0.9	6.5	314	20.4	10.1	1300		86.0	0.8	0.2

[a]Not detected.

Industrial Boilers

The extent of particulate control employed in industrial boilers depends, to a great extent, on the size of the boiler. Large pulverized coal industrial boilers are often equipped with fine particulate control devices, while multicyclones are the only form of control devices employed in smaller units [15]. Stoker-fired units also employ multicyclones in some cases, but are usually uncontrolled. In the case of oil-firing, control is rarely employed, except possibly for the larger residual oil-fired boilers.

The control-device population postulated in the current study for different size ranges of industrial boilers is shown in Table 8. Estimates of fuel consumption for the various size ranges are available in Reference 10.

Commercial/Institutional Boilers

Air pollution-control equipment is generally not installed on smaller commercial/institutional units [16]. It was assumed for this study that such sources are totally uncontrolled.

TABLE 4. EMISSION FACTORS FOR TRACE POLLUTANTS FROM COAL- AND OIL-FIRED COMBUSTION: COMMERCIAL BOILERS (<26 GJ/hr INPUT)

Fuel type	Furnace type	Control device	As	Be	Cd	Cr	Hg	Mn	Ni	Pb	Se	V	Dioxins	HCHO	POM	BaP
			Emission factor, pg/J													
Coal	Pulverized	None		9.1			7.8								19.1	
	Stoker	None	482	18.1	12.9	38.3	6.2	111	68.4	282	84.3	58.1		163	45.2	4.7
Residual oil	Tangential	None	47.3	0.1	71.8	50.0	0.9	6.5	804	20.4	10.1	3660		86.0	44.0	0.4
	Wall	None	47.3	0.1	71.8	50.0	0.9	6.5	804	20.4	10.1	3660		86.0	44.0	0.4
Distillate oil	Tangential	None	47.3	0.1	71.8	36.0	0.9	6.5	112	20.4	10.1	30.0		86.0	20.0	0.4
	Wall	None	47.3	0.1	71.8	36.0	0.9	6.5	112	20.4	10.1	30.0		86.0	20.0	0.4

TABLE 5. EMISSION FACTORS FOR TRACE POLLUTANTS FROM COAL- AND OIL-FIRED COMBUSTION: RESIDENTIAL BOILERS (<422 MJ/hr INPUT)

Fuel type	Furnace type	Control device	As	Be	Cd	Cr	Hg	Mn	Ni	Pb	Se	V	Dioxins	HCHO	POM	BaP
			Emission factor, pg/J													
Bituminous coal	All	None	717	7.2	17.9	71.8	7.2	2150	71.8	359	143	71.8		43.0	1737	108
Anthracite coal	All	None	166	6.6	6.6	66.2	6.6	66.2	66.2	265	99.3	66.2		43.0	1032	108
Lignite coal	All	None	430	1.7	1.7	17.2	172	430	17.2	172	51.6	34.4		43.0	8600	108
Distillate oil	All	None	1.5	1.9	11.0	1.1	1.2	0.6	103	9.5	2.9	10.1		262	10.3	0.1

TABLE 6. FUEL CONSUMPTION IN UTILITY BOILERS, U.S., 1978[a]

Fuel consumption, PJ																	
Coal																	
Bituminous					Anthracite			Lignite					All coal	Residual oil		
Pulverized dry bottom	Pulverized wet bottom	Cyclone	Stoker	Total	Pulverized	Stoker	Total	Pulverized dry bottom	Pulverized wet bottom	Cyclone	Stoker	Total	Total	Tangential	Wall	Total
7558	1242	711	19	9530	6	6	12	1100	140	19	13	1272	10814	1738	1904	3642

[a]Based on data in Reference [9].

TABLE 7. FUEL CONSUMPTION, U.S.

Category	Coal: Pulverized	Coal: Stoker	Coal: Total	Oil: Residual	Oil: Distillate	Oil: Total
	Fuel consumption, PJ					
Industrial[a]	343	612	955	967	288	1255
Commercial/institutional[a]		207	207	891	897	1788
Residential[b]			113		2097	2097

[a]Based on data in Reference [10], 1977.
[b]Based on data in Reference [9], 1978.

TABLE 8. POSTULATED CONTROL DEVICE POPULATION FOR INDUSTRIAL BOILERS

Size range, GJ/h	Pulverized coal	Stoker coal	Residual oil	Distillate oil
26-53	100^{a}_{M}	$50_M 50_U$	100_U	100_U
53-106	$80_M 20_S$	$70_M 30_U$	100_U	100_U
106-264	$60_M 40_S$	$80_M 20_U$	$80_M 20_S$	100_U
>264	100_S	100_M	$60_M 40_S$	100_U

[a]Numbers represent the percentage of the total capacity and suffix denotes the type of control employed: M - Multicyclones, U - Uncontrolled, S - Scrubbers, e.g., 100_M means that 100% of the capacity is controlled by multicyclones.

Residential Boilers

Residential coal- and oil-fired units were assumed to be uncontrolled.

NATIONAL EMISSIONS

From a knowledge of fuel consumption and particulate control-device population for the various boiler categories, national emissions of the trace pollutants were estimated for coal and oil combustion sources, based on emission factors presented earlier. Results are summarized in Table 9.

Trace Metals

As would be expected, national emissions of trace metals are highest for the utility sector. Arsenic, chromium, lead, manganese, nickel, selenium, and vanadium are emitted at rates greater than 100 metric tons/yr from utility coal-fired boilers. Only arsenic and lead are emitted at such rates from industrial coal-fired boilers. These two metals are also emitted in significant quantities from commercial and residential coal-fired boilers. In addition, national emissions of manganese are considerably high for residential coal-fired units.

TABLE 9. NATIONAL EMISSIONS OF TRACE POLLUTANTS FROM COAL AND OIL COMBUSTION (metric tons/yr)

Trace pollutant	Utility boilers[a] (>264 GJ/hr input)		Industrial boilers[b] (>26 GJ/hr input)		Commercial boilers[b] (<26 GJ/hr input)		Residential boilers[a] (<422 MJ/hr input)	
	Coal	Oil	Coal	Oil	Coal	Oil	Coal	Oil
Arsenic (As)	149.1	144.7	214.8	54.7	99.3	84.6	60.3	3.2
Beryllium (Be)	19.2	7.0	6.2	2.2	3.7	0.1	0.8	4.1
Cadmium (Cd)	7.7	219.7	4.9	83.9	2.7	128.4	1.6	23.1
Chromium (Cr)	561.3	87.5	33.3	33.1	7.9	76.8	7.8	2.3
Lead (Pb)	360.0	61.1	113.3	23.6	58.2	36.5	36.8	19.9
Maganese (Mn)	407.2	33.7	31.5	7.5	22.8	11.6	163.9	1.2
Mercury (Hg)	86.9	3.1	4.6	1.0	1.3	1.5	1.0	2.5
Nickel (Ni)	281.1	877.3	34.0	363.1	14.1	818.0	7.8	216.4
Selenium (Se)	120.9	30.9	44.4	11.7	17.4	18.1	14.5	21.2
Vanadium (V)	390.0	4637	29.4	1505	12.0	3293	7.8	6.1
Benzo-a-pyrene (BaP)	0.5	0.1	0.1	0.2	1.0	0.8	12.2	0.2
Dioxins	0.1	ND	ND	ND	ND	ND	ND	ND
Formaldehyde (HCHO)	603.2	39.1	51.6	105.2	33.7	153.8	4.9	550.1
POM	11.2	0.3	11.6	0.8	9.3	57.4	171.6	21.6

a-1978. b-1977. ND-Not determined.

For oil-firing, trace-metal emissions of arsenic, cadmium, nickel, and vanadium are substantial from utility, industrial, and commercial boilers. Vanadium emissions exceed 1000 metric tons/yr from each of the three categories. For residential oil-fired boilers, nickel is the only trace metal emitted at a significant rate.

Organic Emissions

POM and BaP emissions are only significant from residential coal-fired units. Formaldehyde emissions exceed 100 metric tons/yr for utility coal-fired boilers and industrial and commercial oil-fired boilers. Owing to lack of data, national emissions of dioxins could not be projected for most of the boiler categories.

SUMMARY

In summary, coal combustion emits significant quantities of a greater number of trace pollutants than does oil combustion. Ongoing risk assessment studies will provide a greater insight into the hazards posed by such pollutants. Meanwhile, emissions data on toxic pollutants, such as dioxins, is required for the various boiler sectors to fill gaps in the existing emissions data base.

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