

A SUMMARY OF MERCURY EMISSIONS
AND APPLICABLE CONTROL TECHNOLOGIES
FOR MUNICIPAL WASTE COMBUSTORS

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1.0 INTRODUCTION

This report provides information on mercury emission rates and control technologies applicable to municipal waste combustors (MWC's). Section 2.0 presents emissions data for MWC's located in North America. Discussions on apparent relationships between mercury removal and various parameters such as particulate matter (PM) control device inlet temperature and levels of carbon in the fly ash are included.

Section 3.0 discusses mercury control technologies currently being used in Europe and Canada, and includes a review of MWC's that use sodium sulfide (Na_2S) injection, activated carbon injection, and wet scrubbing to limit mercury emissions. Section 4.0 provides a listing of the references used.

2.0 EXISTING MERCURY DATA EMISSIONS

2.1 REVIEW OF EXISTING DATA

Table 2-1 lists mercury emissions data for MWC's in North America that are not equipped with specific mercury control technologies. The data cover 47 MWC units at 32 different plants. For those facilities reporting both inlet and outlet mercury concentrations (in micrograms/dry standard cubic meter [$\mu\text{g}/\text{dscm}$] at 7 percent O_2), mercury removal efficiencies are calculated. Table 2-1 also lists the type of combustor, type of air pollution control device (APCD), PM control device inlet temperature, and inlet dioxin/furan (CDD/CDF) concentrations.

Uncontrolled (i.e., APCD inlet) mercury concentrations are reviewed in Section 2.2. Section 2.3 reviews the controlled (i.e., APCD outlet) concentrations for different APCD types and discusses the apparent relationship between controlled mercury levels versus APCD type and PM control device temperature. The temperature entering the PM control device is important because mercury exists in a vaporous form at temperatures greater than 300 °F and does not effectively condense onto PM. The relationship with inlet CDD/CDF concentrations is also examined in this section. Inlet CDD/CDF levels serve as a surrogate for estimating residual carbon in the fly ash, which may enhance mercury removal due to the adsorption of mercury onto carbon. A summary of the results and conclusions drawn from these relationships is presented in Section 2.4.

2.2 UNCONTROLLED MERCURY LEVELS

As listed in Table 2-1, mercury levels prior to APCD's range from roughly 200 to 1400 $\mu\text{g}/\text{dscm}$. Most of the concentrations range from 400 to 1000 $\mu\text{g}/\text{dscm}$ and average roughly 650 $\mu\text{g}/\text{dscm}$. Based on the data, there is no clear distinction in inlet mercury levels at mass burn plants and refuse-derived fuel (RDF) plants.

TABLE 2-1. EXISTING MERCURY EMISSIONS DATA

MWC NAME	RUN NUMBERS	COMBUSTOR TYPE	APCD TYPE	APCD TEMP. (F)	INLET COD/CDF _a (ng/dscm)	INLET Hg AVERAGE _a (ug/dscm)	OUTLET Hg AVERAGE _a (ug/dscm)	REMOVAL EFFICIENCY (%)	REFERENCE
Detroit (7/89)	9 Runs	RDF	ESP	600	--	--	653	--	1a
Detroit (11/89)*	3 Runs	RDF	ESP	600	--	--	96	--	1a
Detroit (11/89)**	14 Runs	RDF	ESP	600	--	--	193	--	1a
Detroit (12/89-1/90)***	13 Runs	RDF	ESP	600	--	--	172	--	1a
Detroit (3/90)	9 Runs	RDF	ESP	600	--	--	194	--	1b
Hillsborough	3 Runs	MB/WW	ESP	--	--	--	823	--	1c
Oneida County	1-3	M/S	ESP	NM	--	--	2060	--	2
Pigeon Point	1-3	M/E	ESP	410	--	--	363	--	2
Pinellas County	1-3	MB/WW	ESP	543	54	--	847	--	2
Pope/Douglas	1-3	M/E	ESP	482	--	--	133	--	2
Quebec City	2,10,11	MB/WW	ESP	406	--	--	918	--	2
Quebec City	5,6,12	MB/WW	ESP	417	--	--	685	--	2
Tulsa	1-3	MB/WW	ESP	375	--	--	418	--	2
Tulsa	3 Runs	MB/WW	ESP	--	--	--	1000	--	1c
Tulsa	3 Runs	MB/WW	ESP	--	--	--	746	--	1c
Tulsa	3 Runs	MB/WW	ESP	--	--	--	600	--	1c
Tulsa	3 Runs	MB/WW	ESP	--	--	--	711	--	1c
Tulsa	3 Runs	MB/WW	ESP	--	--	--	97	--	1c
Tulsa	2 Runs	MB/WW	ESP	--	--	--	466	--	1c
Dayton	1-3	MB/R	ESP	560	252	962	1016	-5.6	2
Dayton	4-6	MB/R	ESP	401	328	1055	1150	-9.0	2
Dayton	10-12	MB/R	FSI/ESP	394	38	973	757	22.2	2
Dayton	13-15	MB/R	FSI/ESP	298	14	907	709	21.8	2
Dayton	16-18	MB/R	OSI/ESP	308	5	716	491	31.4	2
Alexandria, Unit 1 (12/88)	1-3	MB/WW	FSI/ESP	--	--	--	517	--	1c
Burnaby, Unit 3 (11/88)	1-3	MB/WW	OSI/FF	313	78	527	485	8.0	3
Burnaby, Unit 1 (4/89)	1-3	MB/WW	OSI/FF	307	--	1360 b	--	--	3
Burnaby, Unit 1 (9/89)	1-3	MB/WW	OSI/FF	324	--	--	470	--	3
Burnaby, Unit 2 (9/89)	1-3	MB/WW	OSI/FF	325	--	--	368	--	3
Burnaby, Unit 3 (9/89)	1-3	MB/WW	OSI/FF	319	--	--	1086	--	3
Dutchess County, Unit 1	1-3	MB/WW	OSI/FF	430	--	--	1080	--	2
Dutchess County, Unit 2	1-3	MB/WW	OSI/FF	365	--	--	85	--	2
Quebec City - Pilot	5-6	MB/WW	OSI/FF	400	1597	451	614	-36.1	2
Quebec City - Pilot	1,2,11	MB/WW	OSI/FF	285	2277	320	16	95.0	2
Quebec City - Pilot	3-4	MB/WW	OSI/FF	250	2361	480	13	97.3	2
Quebec City - Pilot	12-13	MB/WW	OSI/FF	231	887	445	40	91.0	2

TABLE 2-1. EXISTING MERCURY EMISSIONS DATA

MVC NAME	RUN NUMBERS	COMBUSTOR TYPE	APCD TYPE	APCD TEMP. (F)	INLET COD/CDFa (ng/dscm)	INLET Hg AVERAGEa (ug/dscm)	OUTLET Hg AVERAGEa (ug/dscm)	REMOVAL EFFICIENCY (%)	REFERENCE
Charleston, Units A & B	1-3	MB/WW	SD/ESP	--	-- c	--	723	--	4
Haverill, Unit A (6/89)	1-3	MB/WW	SD/ESP	285	--	--	247	--	1c
Haverill, Unit B (6/89)	1-3	MB/WW	SD/ESP	285	--	--	208	--	1c
Haverill, Unit B (3/90)	1-3	MB/WW	SD/ESP	--	--	--	567	--	1c
Honolulu, Unit 1	1-3	RDF	SD/ESP	300	-- d	--	5	--	5
Honolulu, Unit 2	1-3	RDF	SD/ESP	293	-- d	--	7	--	5
Millbury, Unit 1	1-6	MB/WW	SD/ESP	249	--	--	565	--	2
Millbury, Unit 2	1-3	MB/WW	SD/ESP	240	170 e	--	954	--	2
Portland, Unit 1 (12/89)	4-6	MB/WW	SD/ESP	308	-- f	--	550	--	6
Portland, Unit 2 (12/89)	1-3	MB/WW	SD/ESP	285	-- f	--	382	--	6
SEMASS, Unit 1	1-3	RDF	SD/ESP	287	-- g	--	59	--	7
SEMASS, Unit 2	2-4	RDF	SD/ESP	293	-- g	--	105	--	7
West Palm Beach, Unit 1	3 Runs	RDF	SD/ESP	275	--	--	56	--	8
West Palm Beach, Unit 2	3 Runs	RDF	SD/ESP	278	--	--	23	--	8
Babylon, Unit 2	1-3	MB/WW	SD/FF	331	--	--	451	--	9
Babylon	3 Runs	MB/WW	SD/FF	--	--	--	323	--	1c
Biddeford	1-3	RDF	SD/FF	278	903	389	ND	>99	2
Bristol	3 Runs	MB/WW	SD/FF	--	--	--	99	--	1c
Bristol	3 Runs	MB/WW	SD/FF	--	--	--	105	--	1c
Bristol	3 Runs	MB/WW	SD/FF	--	--	--	64	--	1c
Bristol	3 Runs	MB/WW	SD/FF	--	--	--	399	--	1c
Commerce (1987)	11,13,14	MB/WW	SD/FF	270 h	28	450	570	-26.7	2
Commerce (1988)	3,5,9	MB/WW	SD/FF	290 h	446 e	453	39	91.4	2
Commerce (1988)	13,16,18,29	MB/WW	SD/FF	290 h	783 e	261	68	74.0	2
Fairfax	3 Runs	MB/WW	SD/FF	--	--	--	406	--	1c
Fairfax	3 Runs	MB/WW	SD/FF	--	--	--	466	--	1c
Fairfax	3 Runs	MB/WW	SD/FF	--	--	--	331	--	1c
Fairfax	3 Runs	MB/WW	SD/FF	--	--	--	514	--	1c
Hempstead, Unit 1 (9/89)	1-3	MB/WW	SD/FF	310 h	--	--	9	--	10
Hempstead, Unit 2 (9/89)	1-3	MB/WW	SD/FF	310 h	--	--	25	--	10
Hempstead, Unit 3 (10/89)	1-3	MB/WW	SD/FF	310 h	--	--	25	--	10
Huntsville	3 Runs	MB/WW	SD/FF	--	--	--	1275	--	1c
Huntsville	3 Runs	MB/WW	SD/FF	--	--	--	463	--	1c

TABLE 2-1. EXISTING MERCURY EMISSIONS DATA

MWC NAME	RUN NUMBERS	COMBUSTOR TYPE	APCD TYPE	APCD TEMP. (F)	INLET CDD/CDF _a (ng/dscm)	INLET Hg AVERAGE _a (ug/dscm)	OUTLET Hg AVERAGE _a (ug/dscm)	REMOVAL EFFICIENCY (%)	REFERENCE
Indianapolis, Unit 1	1-3	MB/WW	SD/FF	307	--	--	283	--	11
Indianapolis	3 Runs	MB/WW	SD/FF	--	--	--	200	--	1c
Indianapolis	3 Runs	MB/WW	SD/FF	--	--	--	277	--	1c
Long Beach	1-3	MB/WW	SD/FF	298	305	--	180	--	2
Marion County	4-6	MB/WW	SD/FF	272	43 e	--	239	--	2
Mid-Connecticut (7/88)	1-3	RDF	SD/FF	276	1019	1008	--	--	2
Mid-Connecticut (7/88)	1-3 (Hg) ⁱ	RDF	SD/FF	284	--	884	50	94.3	2
Mid-Connecticut (2/89)	12-14	RDF	SD/FF	--	436	668	9	98.7	2
Quebec City - Pilot	7-8	MB/WW	SD/FF	282	1764	187	10	94.7	2
Quebec City - Pilot	9-10	MB/WW	SD/FF	284	2157	360	19	94.7	2
Stanislaus County, Unit 1	14,16,19	MB/WW	SD/FF	295	--	--	499	--	2
Stanislaus County, Unit 2	38,40,42	MB/WW	SD/FF	290	--	--	462	--	2
Stanislaus County	3 Runs	MB/WW	SD/FF	--	--	--	508	--	1c
Stanislaus County	3 Runs	MB/WW	SD/FF	--	--	--	481	--	1c
Stanislaus County	3 Runs	MB/WW	SD/FF	--	--	--	427	--	1c
Kent	3 Runs	MB/WW	SD/FF	--	--	--	166	--	1c
Kent	3 Runs	MB/WW	SD/FF	--	--	--	248	--	1c

M/E - Modular/Excess Air
 M/S - Modular Starved Air
 MB/R - Mass Burn/Refractory
 MB/WW - Mass Burn/Waterwall
 ND - Not detected.
 RDF - Refuse Derived Fuel

* Secondary trommel bypass.

** Lime fed at 1200 lb/hr.

*** Both "*" and "***" apply.

a Results reported at 7% O₂.

b Inlet values reported for comparison purposes; outlet values influenced by Na₂S injection.

c Outlet CDD/CDF values: Unit 8 - 44.2 ng/dscm (average of three runs conducted during same test campaign).

d Outlet CDD/CDF values: Unit 1 - 6.3 ng/dscm; Unit 2 - 3.8 ng/dscm.

e Inlet CDD/CDF samples collected during separate runs from Hg, but during same test campaign and at similar operating conditions.

f Outlet CDD/CDF values: Unit 1 - 36.5 ng/dscm; Unit 2 - 43.6 ng/dscm.

g Outlet CDD/CDF values: Unit 1 - 9.3 ng/dscm; Unit 2 - 12.3 ng/dscm.

h Temperatures not reported for Hg runs; temperatures estimated based on other runs during same test campaign.

i Additional inlet and outlet mercury samples were collected by Method 101A. Not measured simultaneously with other metals.

2.3 CONTROLLED MERCURY LEVELS

2.3.1 Electrostatic Precipitators (ESP's)

Nine of the facilities reviewed are equipped with ESP's. With the exception of the data from the Pope/Douglas and the Oneida County MWC's, and one set of runs from the Detroit and Tulsa MWC's, mercury outlet levels range from approximately 200 to 1200 $\mu\text{g/dscm}$. The Dayton MWC was the only ESP-equipped plant that measured inlet mercury concentrations, and the corresponding removal efficiencies for the ESP-only averages at Dayton were both negative (-9.0 and -5.6 percent).

Based on typical uncontrolled levels, the measured outlet mercury levels at ESP-equipped MWC's suggest little or no removal of mercury by this control device type. Flue gas temperatures reported for these tests range from 375 °F to 600 °F. At these temperatures no mercury condensation will have occurred; therefore, no relationship between flue gas temperature and mercury outlet levels were observed.

2.3.2 Sorbent Injection/ESP

Two facilities equipped with sorbent injection for acid gas control followed by an ESP have been tested for mercury emissions. One set of data was collected from the stack of the Alexandria MWC, which is equipped with a furnace sorbent injection (FSI) system. The system generally operates at an ESP inlet temperature of 360 to 370 °F. The average emission concentration from three runs was 517 $\mu\text{g/dscm}$. Inlet CDD/CDF levels were not measured, but were probably low based on information from other Martin grate systems.² This suggests that levels of carbon in the fly ash at Alexandria were probably low.

Three sets of data were collected at the Dayton MWC. Two of the data sets were with FSI, and the third data set was with duct sorbent injection (DSI). Inlet and outlet mercury levels were measured during all three test sets. The mercury removal efficiencies for Runs 10-12 (FSI at an average ESP inlet temperature of 394 °F) and Runs 13-15 (FSI at an average ESP inlet temperature of 298 °F) are both 22 percent, which

correspond to average mercury outlet levels of 757 $\mu\text{g/dscm}$ and 709 $\mu\text{g/dscm}$, respectively. Mercury reductions during Runs 16-18 (DSI at an average ESP inlet temperature of 306 $^{\circ}\text{F}$) average 31 percent, corresponding to a mercury outlet level of 491 $\mu\text{g/dscm}$. Inlet CDD/CDF levels reported for all of these tests average less than 40 ng/dscm.

The data from Alexandria and Dayton indicate that sorbent injection/ESP systems may have a small impact on controlling mercury emissions, and that little or no additional benefits are achieved by lowering flue gas temperature. The limited mercury control achieved by these sorbent injection/ESP systems may have been influenced by the lack of carbon in the fly ash.

2.3.3 Sorbent Injection/Fabric Filter

Test data are available for six MWC units at three sites with DSI/fabric filter (FF) systems. Operating conditions and outlet mercury emissions varied considerably during these tests.

During testing of a pilot-scale DSI/FF system at Quebec City, reported outlet mercury emissions varied from 13 to 614 $\mu\text{g/dscm}$. At the lower readings (13 to 40 $\mu\text{g/dscm}$), the flue gas temperature at the FF inlet was less than 300 $^{\circ}\text{F}$, and the inlet CDD/CDF levels averaged between 900 and 2400 ng/dscm. The high mercury reading (614 $\mu\text{g/dscm}$) was at a FF inlet flue gas temperature of 400 $^{\circ}\text{F}$, and the inlet CDD/CDF concentration averaged 1600 ng/dscm. Based on measured inlet mercury concentrations, mercury removal efficiencies range from essentially zero at FF inlet temperatures of 400 $^{\circ}\text{F}$ or more, to over 90 percent at FF temperatures less than 300 $^{\circ}\text{F}$.

At Dutchess County, average stack mercury emissions reported from Unit 1 (operating at 430 $^{\circ}\text{F}$) and Unit 2 (operating at 365 $^{\circ}\text{F}$) are 1080 $\mu\text{g/dscm}$ and 85 $\mu\text{g/dscm}$, respectively. No inlet mercury or CDD/CDF measurements were made.

At Burnaby, outlet mercury emissions range from 368 to 1086 $\mu\text{g/dscm}$. Inlet mercury levels were measured during two sets of runs and suggest little or no mercury reductions. Flue gas inlet temperatures at the FF reported for these tests are between

307-325 °F. Inlet CDD/CDF levels were measured during the first set of tests only, and were relatively low at 78 ng/dscm.

These data suggest that mercury removal may be a function of flue gas temperature and inlet fly ash carbon content. At high flue gas temperatures (greater than 400 °F) or low CDD/CDF levels (less than 200-300 ng/dscm), mercury control is low. At lower temperatures and higher CDD/CDF levels, however, the level of mercury control increases. At Quebec City, mercury reductions exceed 90 percent at flue gas temperatures of less than 300 °F and inlet CDD/CDF levels exceeding 800 ng/dscm.

2.3.4 Spray Dryer/ESP

Outlet mercury emissions data for SD/ESP systems are available for 14 units at seven MWC facilities. Four of the MWC's, Charleston, Haverill, Millbury, and Portland, are mass burn combustors. The other three, Honolulu, SEMASS, and West Palm Beach, are RDF units. Outlet mercury levels at the mass burn MWC's range from approximately 210 to 950 µg/dscm. Reported ESP inlet temperatures are approximately 300 °F or less. The RDF units operated at similar temperatures. Outlet mercury levels for these units, however, range from 5 to 105 µg/dscm. Due to the suspension firing of fuel in the combustor, RDF units generally have higher PM loadings and higher carbon contents at the combustor exit than do mass burn units. The results from the RDF units support the theory that increased levels of carbon in the fly ash enhance mercury removal.

2.3.5 Spray Dryer/Fabric Filter (SD/FF)

Mercury data were obtained from 14 MWC's (17 units) that use SD/FF's. With the exception of one test average from the Huntsville MWC, outlet mercury levels from these plants vary from below detection to 570 µg/dscm. The high test average from the Huntsville MWC (1275 µg/dscm) was due to one high run of over 2700 µg/dscm.

Flue gas temperatures entering the FF's were less than 300 °F at all of the SD/FF-equipped facilities. As with the

SD/ESP data, the lowest mercury outlet levels and highest removal efficiencies occurred at the two RDF plants, Biddeford and Mid-Connecticut. The average inlet CDD/CDF levels at these two plants were 903 $\mu\text{g/dscm}$ and 436 $\mu\text{g/dscm}$, respectively. The Quebec City mass burn/waterwall (MB/WW) pilot-scale SD/FF test achieved 94.7 percent removal and had an inlet CDD/CDF level of 2157 ng/dscm.

The lowest reported mercury removal efficiency (-27 percent) was during the 1987 tests at the Commerce MWC. During this testing, inlet CDD/CDF levels were low, averaging 28 ng/dscm. During subsequent testing the following year, average mercury outlet levels were approximately 40 $\mu\text{g/dscm}$ (91 percent removal) and 70 $\mu\text{g/dscm}$ (74 percent removal). During the 1988 testing the mercury inlet levels were similar to those during the 1987 test, but the CDD/CDF levels were much higher, averaging 450 ng/dscm and 780 ng/dscm. These data further support the theory that increased levels of carbon in the fly ash enhance mercury removal.

It should be noted that the Hempstead MWC, which is a mass burn MWC, also had low mercury emissions -- below 25 $\mu\text{g/dscm}$. Inlet CDD/CDF levels were not reported.

2.4 SUMMARY

The test data indicate that mercury emission levels from municipal solid waste combustion vary significantly from site to site. Factors such as waste composition, combustion efficiency (carbon burnout), and APCD type and operation may affect mercury removal. Their exact effects are unclear. However, it appears that good PM control, low temperatures in the APCD system, and significant carbon in the fly ash are necessary to achieve mercury control. As discussed previously, the combination of a low PM control device operating temperature and a high level of carbon in the fly ash (as indicated by the level of CDD/CDF at the combustor exit) enhance mercury adsorption onto particles which are removed by the PM control device.

Based on compliance test data, the PM operating temperature that is critical for mercury capture is not clear, but appears to be in the range of 300 to 400 °F. Based on published literature citing theoretical calculations, however, a temperature of around 300 °F appears to be necessary.¹² The data indicate that RDF units (which generally have higher uncontrolled PM and CDD/CDF at the combustor exit, and thus, higher expected fly ash carbon levels) can achieve mercury emissions less than 110 µg/dscm when equipped with a good PM control system operating at less than 300 °F. The mercury emissions data for mass burn units range from 10 to over 1000 µg/dscm, even when equipped with the best acid gas/PM control systems. These units are generally characterized as having low organic emissions, low fly ash carbon content, and low PM loadings relative to RDF units.

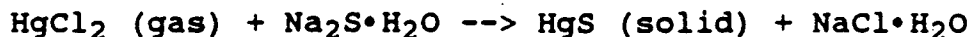
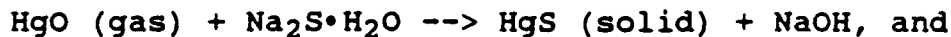
3.0 MERCURY EMISSION CONTROL TECHNOLOGIES

Mercury control technologies include the injection of Na_2S , activated carbon or modified activated carbon into the flue gas prior to the DSI or SD-based acid gas control system. Alternatively, wet scrubbing can be used for mercury control. These technologies have not been used on U.S. MWC's, but have been applied to MWC's in Europe, Canada, and Japan. Brief discussions of these technologies are presented in this section.

3.1 SODIUM SULFIDE

3.1.1 Chemistry

Sodium sulfide is a crystalline solid that dissolves in water to form a solution of up to 10 weight percent Na_2S in 34 °F water and 15 weight percent Na_2S at 60 °F. The resulting Na_2S solution is sprayed into the flue gas prior to the acid gas control device. Aqueous Na_2S is caustic and will off-gas toxic hydrogen sulfide (H_2S). The reaction of Na_2S and Hg precipitates solid HgS that can be collected in the PM control device. The specific reactions of Na_2S and Hg are not totally understood, but appear to be:



While (1) flue gas temperature, or (2) lime or ammonia injection for acid gas or NO_x control may affect these mercury reactions, their effects are uncertain. Testing is currently being conducted that should provide insight on some of these relationships.

3.1.2 Existing Use of Na_2S By MWC's

Sodium sulfide is or has been used for mercury control by MWC's in Avesta, Koping, and Hogdalen, Sweden; Kempton, and Munich (South), Germany; and Burnaby, British Columbia. Injection of Na_2S has been used at the Hogdalen MWC since 1986. The Avesta, Koping, and Kempton plants began Na_2S injection in 1989. The Munich plant began operation with Na_2S injection in 1990. The Burnaby MWC began testing of Na_2S in 1989 and began

continuous operation with a temporary system in December 1989. In October 1991, however, the Burnaby plant is intending to switch to activated carbon injection for mercury control.

All of these facilities use DSI/FF systems supplied by Fläkt for acid gas and PM control. Injection of Na_2S occurs prior to the DSI system at flue gas temperatures of 265-480 °F. Hogdalen reduces flue gas temperatures prior to Na_2S injection with a heat exchanger that provides hot water for district space heating. The Burnaby and Munich MWC's use water quench towers for flue gas cooling. Flue gas temperatures at the stack at Burnaby normally range from 260-300°F. Additional information on the Munich plant was not available.

Fläkt reports that Na_2S feed rates vary from 0.05 to 0.5 kg/Mg (0.1 to 1 lb/ton) of MSW, depending on site-specific conditions such as the amount of mercury in the flue gas, the level of control required, and the level of carbon present in fly ash.¹³ As discussed in Section 2.0, residual carbon in the fly ash is believed to promote mercury removal through adsorption onto the carbon. As a result, if a plant has little carbon in its fly ash, it may be necessary to increase the amount of Na_2S injected.

Mercury control performance data with Na_2S injection are shown in Tables 3-1 and 3-2. The data have been compiled from information provided by Fläkt, the Burnaby MWC facility owner (the Greater Vancouver Regional District (GVRD)), and from trip reports to the Hogdalen and Burnaby MWC's.^{3,13,14,15,16,17}

Mercury levels prior to Na_2S injection at the Burnaby MWC (400-1400 µg/dscm) are higher than general inlet values reported at European MWC's (55-560 µg/dscm). The objective of the testing conducted at the Burnaby MWC was to evaluate key system parameters. During the initial tests, 1 to 3 kg/hr (2 to 7 lb/hr) of Na_2S was fed as 10-15 percent concentration solutions and achieved mercury reductions of 50-65 percent. Subsequent tests conducted at a feed rate of 2 to 6 kg/hr (4 to 13 lb/hr) of

TABLE 3-1. MERCURY EMISSIONS DATA FROM THE BURNABY MWC

MWC PLANT	WASTE TPD	APCD TYPE	Na ₂ S FEED RATE (kg/hr)	TESTED Hg INLET (ug/dscm)	EMISSIONS ^a OUTLET (ug/dscm)	REDUCTION EFFICIENCY (%)
Burnaby 3/89b (10% Na ₂ S)	265	DSI/FF	Run 1 = 1.0 Run 2 = 2.0 Run 3 = 2.0 AVG	1465 993 1151 1203	570 407 393 457	AVG 62
Unit 1, 4/89 (15% Na ₂ S)			All runs = 3.0 AVG	1423 1443 1205 1357	670 750 473 632	AVG 53
8/89b (2-4% Na ₂ S)			Run 1 = 2.5 Run 2 = 6.0 Run 3 = 2.0 Run 4 = 3.0 Run 5 = 6.0 AVG	406 775 670 793 661 661	98 91 84 101 103 95	AVG 86
Unit 1, 12/89 (2% Na ₂ S)			All runs = 4.0 NR	NR NR NR	138 67 146 117	NA
Unit 2, 12/89 (2% Na ₂ S)			All runs = 4.0 NR	NR NR NR	149 115 118 127	NA
Unit 3, 12/89 (2% Na ₂ S)			All runs = 4.0 NR	NR NR	152 159 155	NA

NR - Not reported; NA - Not applicable

^a Results reported at 12% CO₂ (assumed to be equal to 7% O₂).^b Unit not specified.

TABLE 3-2. MERCURY EMISSIONS DATA FROM THE HOGDALEN AND KEMPTEN MWC's

MWC PLANT DATE	WASTE TPO	APCD TYPE	APCD INLET TEMP (F)	Na2S FEED RATE (kg/hr)	TESTED Hg INLET (ug/dscm)	EMISSIONS ^a OUTLET (ug/dscm)	REDUCTION EFFICIENCY (%)
Hogdalen, Unit 3	265	DSI/FF					
(02/86)			343	--	--	96	
(05/86)			316	--	181	168	7
(08/86)			304	1.2	--	65	
(08/86)			343	1.2	344	37	89
(08/86)			345	1.2	463	57	88
(09/86)			304	0.9	--	51	
(12/86)			334	1.2	--	28	
(02/87)			253	1.2	310	3	99
(03/87)			334	--	124	105	15
(04/87)			334	1.2	207	54	74
(09/87)			336	1.2	366	30	92
(12/87)			336	--	--	139	
(04/88)			336	--	266	136	49
(05/88)			325	1.2	369	22	94
(08/88)			311	1.2	121	18	85
(08/88)			311	1.2	--	8	
(08/88)			311	--	--	22	
(10/88)			291	1.8	102	13	87
(10/89)			270	1.2	158	142	10
(11/89)			280	2.4	192	4	98
(02/90)			280	1.2	--	9	
(02/90)			262	1.2	--	8	
(02/90)			261	2.4	--	6	
(06/90)			266	2.4	--	26	
Kempton (Germany)	210	DSI/FF	--	--	--	<56	

^a Results reported at 12% CO2 (assumed to be equal to 7% O2).

Na₂S and a solution concentration of 2-4 percent achieved average mercury reductions of 86 percent and outlet mercury concentrations between 84 and 103 µg/dscm. Testing conducted at a Na₂S feed rate of 4 kg/hr (9 lb/hr) and a solution concentration of 2 percent achieved average outlet mercury concentrations between 117 and 155 µg/dscm; inlet mercury concentrations were not measured during these tests, therefore percent reductions could not be calculated. The improved mercury reduction at lower Na₂S concentrations is believed to be the result of improved atomization and mixing when feeding higher volumes of low concentration solution versus lower volumes of high concentration solutions.

Mercury performance data for the Hogdalen (Unit 3) and Kempton MWC's are presented in Table 3-2.^{14,15,16,17} Mercury testing with Na₂S injection at the Hogdalen facility began in the summer of 1986. Testing prior to the installation of the Na₂S injection system indicated mercury levels as high as 165 µg/dscm. Testing in 1986 with a Na₂S feedrate of 1.2 kg/hr (2.6 lb/hr) and 0.9 kg/hr (2 lb/hr) decreased mercury emissions to between 37 and 65 µg/dscm. When inlet levels were measured, emission reductions were 88 and 89 percent. Subsequent testing with Na₂S injection in 1987 resulted in similar emission levels, with emission reductions between 74 and 99 percent. For those tests conducted without Na₂S injection, minimal mercury control was achieved.

In the summer of 1988, a heat exchanger was installed, replacing a precooler, which resulted in improved performance of the Na₂S system. Other changes to the system have been made over the course of operation (see discussion in Section 3.1.3) which also improved performance. Test results from 1989 and 1990, excluding the October 1989 testing, show mercury levels between approximately 5 and 25 µg/dscm. The poor performance during the October 1989 testing may be due to the operating conditions during the test--the boiler load was constantly increased from low load to full load, which increased the boiler wall temperatures and potentially volatilized mercury adsorbed on

collected soot. Also note that the high level of performance during the August 1988 testing without Na_2S injection was measured immediately after a measurement with Na_2S injection. Therefore, the results are uncertain.¹⁷

Injection of Na_2S on the two older units at the Hogdalen plant was also investigated, but was discontinued since these units were able to achieve low mercury levels ($< 4 \mu\text{g/dscm}$) without using the Na_2S system. The high collection of mercury has been attributed to the high content of unburned carbon in the flue gases from these two older units.^{14,17}

Limited information is available on the Kempten, Germany MWC, but outlet mercury levels at Kempten when using Na_2S injection averaged less than $56 \mu\text{g/dscm}$.

As indicated by the data, typical inlet mercury levels at the European facilities are lower than those in the U.S. and Canada. This may be the reason for Hogdalen's lower Na_2S feedrates and the resulting Hg outlet levels at Hogdalen and Kempten. The reduction efficiencies, however, are generally similar for all facilities currently using Na_2S injection for mercury control.

3.1.3 Potential Technical Limitations with Na_2S Injection

All of the existing MWC's using Na_2S injection are equipped with DSI/FF systems. As a result, some uncertainty exists regarding the applicability of Na_2S injection to other APCD configurations, such as SD/FF's and SD/ESP's. Potential problems related to application of Na_2S to spray drying systems include the existence of adequate time for reaction between mercury and aqueous Na_2S and possible reactions between Na_2S and acid gas control sorbent. If Na_2S is injected into hot flue gas (e.g., 450°F), the associated water may evaporate rapidly, leaving a dry Na_2S particle, which may be less reactive with mercury. If Na_2S and calcium in the sorbent react to form calcium sulfide (CaS), the availability of S for reaction with mercury would be diminished and reduce the mercury collection efficiency. Fläkt stated that they do not believe this was a problem, but do not

have any actual operating experience with application of Na_2S to spray drying systems. Fläkt did indicate, however, that it would probably be necessary to have separate Na_2S and calcium sorbent feed and injection systems to avoid CaS scaling of the sorbent feed line. A concern related to the use of ESP's is the collection capability of an ESP if the HgS precipitates as a very fine particulate.^{3,13}

The only operating problem reported by Fläkt was gas-side corrosion of cool surfaces (such as the Na_2S piping and nozzles) by condensation of HCl from the humid flue gas. To prevent this, hastalloy steel has been used on these surfaces. An initial concern raised by the Burnaby MWC operator was an apparent increase of roughly 50 percent in lime consumption rates following installation of the Na_2S system. However, due to limited operating experience at that time, the plant operator was not certain whether this increase was due to Na_2S use or was caused by other changes in plant operations. The plant operator had carefully inspected the DSI/FF system during the plant's last outage prior to beginning continuous injection of Na_2S . The plant had not been out of service since restarting operation, therefore, the operator had not been able to re-examine the unit for corrosion or other problems.^{3,13} Recent information from the plant did not indicate the occurrence of any such problems.¹⁸ Further, recent discussions with plant personnel indicated that the lime consumption increase was not related to the use of Na_2S injection.¹⁹

The Hogdalen plant encountered a problem due to moisture buildup which resulted in the clogging and plugging in the screw conveyor that was used to transport the sodium sulfide to the mix tank. Additionally, the sodium sulfide caked up and solidified due to pressurization of the storage silo when transferring the sodium sulfide. To overcome these problems, Hogdalen eliminated the storage silo and developed a system in which 500 kg bags of sodium sulfide are emptied directly into the mix tank.^{14,17}

Another problem encountered at Hogdalen was sludge buildup occurring in the mix tank as a result of the presence of inorganic salts in the mixing water. To remedy this, treated boiler feed water is now used for mixing. Other operational modifications at the Hogdalen plant include the use of piston-type pumps rather than impeller pumps in order to maintain a more consistent feed rate, and the injection of the sodium sulfide downstream of the heat exchanger to prevent clogging of the nozzle.^{14,17}

None of the problems discussed above appear to be of a magnitude to raise concerns about the ability of Na₂S injection to control mercury on a continuous basis.

3.1.4 Cost Estimates for Na₂S Injection

Available cost data are based on estimates from Fläkt, information provided for the Burnaby plant, and supporting chemical costs from PPG. The Burnaby MWC operator estimated capital costs for a Na₂S system for the Burnaby plant, which has a MSW combustion capacity of 800 TPD, at \$150,000-250,000 (1990 dollars).³ The chemical costs for the sodium sulfide, as quoted by Fläkt, range from \$0.10-0.50/ton of MSW.¹³ This cost is dependent upon the uncontrolled mercury level and the level of reduction required. The chemical cost reported for the Burnaby MWC is \$0.30/ton of MSW, and the chemical cost (without shipping) reported by PPG is \$0.30/ton of MSW, both of which are consistent with Fläkt's estimate. Based on this information, annualized costs (based on a capital recovery factor of 0.1315 and 8,000 hours of operation per year) for Burnaby are estimated at \$0.20-0.60/ton of MSW.

3.2 ACTIVATED CARBON INJECTION

Another mercury control technology used in Europe is the injection of powdered activated carbon prior to the APCD. It is believed that the activated carbon is a catalyst for the oxidation of elemental mercury to mercuric oxide, which can be captured in the APCD.²⁰ This technology has been used commercially on an MWC located in Zurich, Switzerland, and during

test programs at MWC's in Amager, Denmark; Kassel, Germany; and Burnaby, British Columbia.

The Zurich MWC is equipped with an SD/ESP system. Powdered activated carbon is injected into the flue gas ahead of the SD, and the temperature entering the SD is between 430 and 540 °F. Test results from the Zurich plant are shown in Table 3-3. Testing was conducted with and without activated carbon injection and at SD outlet temperatures between 230-284 °F. For tests run without activated carbon injection, the lowering of temperature did not result in a substantial increase in mercury capture. The addition of activated carbon, however, increased the average percent removal efficiencies from the mid-40's to over 87 percent. It was observed that fluctuating mercury inlet levels did not affect performance when activated carbon was used. The affect of increasing additive was investigated during the testing at a SD outlet temperature of 248 °F. The increase from 9 mg/dscm to 20 mg/dscm to 39 mg/dscm did not have a significant impact on mercury outlet levels or removal efficiency. In all cases, the average removal efficiencies were greater than 85 percent, and average outlet levels were between roughly 30 and 90 µg/dscm.²¹

The Amager MWC is equipped with a SD/FF system and operates similarly to the Zurich plant. Testing was conducted with temperatures at the SD exit of 284 °F and at 260 °F. As shown in Table 3-4, results from the testing with activated carbon injection at the higher temperature indicate outlet mercury levels between 23 and 77 µg/dscm, corresponding to removal efficiencies between 82 and 95 percent. Without activated carbon injection, outlet mercury emissions were between 67 and 195 µg/dscm, with removal efficiencies between 15 and 65 percent. The highest removal efficiencies when using activated carbon occurred with increased additive levels (70 mg/dscm vs. 7 mg/dscm).²¹

Testing at the lower APCD inlet temperatures shows greater control of mercury, especially when activated carbon injection

TABLE 3-3. MERCURY EMISSIONS DATA FROM THE ZURICH MWC

ADDITIVE (mg/dscm)	SD OUTLET TEMPERATURE (F)	INLET MERCURY (ug/dscm)	OUTLET MERCURY (ug/dscm)	REMOVAL EFFICIENCY (%)
0	284	703	510	27
		449	310	31
		890	546	39
		730	542	26
		531	438	17
		1403	1003	28
		----	----	--
	AVERAGE	784	559	29
9	248	656	122	81
		574	62	89
		----	----	--
	AVERAGE	615	92	85
20	248	300	43	86
		230	14	94
		313	29	91
		----	----	--
	AVERAGE	281	29	90
39	248	705	51	93
		771	41	94
		202	26	87
		148	30	80
		----	----	--
	AVERAGE	457	37	92
0	239	648	304	53
		841	271	68
		306	153	50
		1242	877	29
		963	623	35
		525	327	38
		----	----	--
	AVERAGE	754	426	44
39	239	461	58	88
		462	58	88
		368	38	90
		----	----	--
	AVERAGE	430	51	88

TABLE 3-3. MERCURY EMISSIONS DATA FROM THE ZURICH MWC

ADDITIVE (mg/dscm)	SO OUTLET TEMPERATURE (F)	INLET MERCURY (ug/dscm)	OUTLET MERCURY (ug/dscm)	REMOVAL EFFICIENCY (%)
0	230	326	162	50
		293	173	41
		453	277	39
		---	---	--
	AVERAGE	357	204	43
	230	636	89	86
		851	59	93
		171	58	66
		546	52	90
		352	67	81
		---	--	--
		511	65	87

*All concentrations are at 7 percent O₂.

TABLE 3-4. MERCURY EMISSIONS DATA FROM THE AMAGER MWC

=====				
	SO OUTLET	INLET	OUTLET	REMOVAL
ADDITIVE	TEMPERATURE	MERCURY	MERCURY	EFFICIENCY
-(mg/dscm)	(F)	(ug/dscm)	(ug/dscm)	(%)
=====				
0	284	203	154	24
		229	195	15
		219	86	61
		202	74	63
		165	67	59
		---	---	--
		AVERAGE	204	115
7	284	378	58	85
		227	40	82
		---	--	--
		AVERAGE	303	49
20	284	214	31	86
		248	35	86
		336	36	89
		---	--	--
		AVERAGE	266	34
70	284	1516	77	95
		318	23	93
		---	--	--
		AVERAGE	917	50

0	260	421	32	92
		196	48	76
		163	30	82
		189	54	71
		---	--	--
		AVERAGE	242	41
23	260	201	24	88
83	260	198	6	97
		220	7	97
		---	--	--
		AVERAGE	209	6.5
=====				

*All concentrations are at 7 percent O₂.

was not used. With activated carbon, outlet mercury levels ranged from 6 to 24 $\mu\text{g/dscm}$ (88 to 97 percent removal), and without activated carbon the outlet levels were between 30 and 53 $\mu\text{g/dscm}$ (72 to 92 percent removal).²¹

The MWC in Kassel is equipped with an ESP followed by a SD/FF, and the system has the capability of operating in either the single-pass or partial-product recycle mode. (Zurich and Amager are single-pass systems.) The recycle design of the Kassel system results in an increased chloride content of the lime slurry, therefore, the temperature exiting the SD must, at a minimum, be kept at 275 °F. Recent test results at a temperature of 279 °F and carbon additive feedrates of between 0 and 84 mg/dscm are shown in Table 3-5. Without activated carbon injection average mercury outlet levels exceeded 750 $\mu\text{g/dscm}$ (35 percent removal). By using carbon injection at levels of 25 mg/dscm and higher, mercury levels less than 75 $\mu\text{g/dscm}$ were achieved, with removal efficiencies exceeding 80 percent.

Recently available information on the use of carbon injection at the Burnaby MWC indicate significant mercury reductions. Results of testing from June 1990 through January 1991 show mercury removal efficiencies averaging 84 percent. It has been determined that the final installation at the Burnaby plant will be a carbon based injection system. The annual operating costs with such a system will be less than an Na_2S injection system, and the health risk to employees (caused by the offgassing of Na_2S) will be reduced. It is expected that the final mercury control system will be operational in October 1991.¹⁸

List prices for activated carbon range from \$0.50-1.00 per pound depending on the raw material used to produce the carbon and the available surface area.²² Based on a carbon feed rate of 1 to 2 kg/hr, these costs correspond to \$0.15-0.35/ton of MSW. Estimates of capital costs for the construction of an activated carbon injection system at the Burnaby MWC are on the order of \$200,000 (1990 dollars).¹⁸ With this information, the annualized

TABLE 3-5. MERCURY EMISSIONS DATA FROM THE KASSEL MWC

ADDITIVE (mg/dscm)	SO OUTLET TEMPERATURE (F)	INLET MERCURY (ug/dscm)	OUTLET MERCURY (ug/dscm)	REMOVAL EFFICIENCY (%)
0	279	1175	762	35
12	279	440	229	48
26	279	424	75	82
62	279	234	25	89
84	279	389	68	82

*All concentrations are at 7 percent O₂.

costs (based on a capital recovery factor of 0.1315 and 8000 hours of operation per year) for Burnaby are estimated at \$0.30 - 0.50/ton of MSW. One of the criteria for selecting the additive used at the Zurich MWC was its low cost.²³

3.3 ACTIVATED CARBON/LIME INJECTION

Another mercury control technique in use in Europe is the injection of an activated carbon scrubber additive consisting of approximately 95-97 percent lime and 3-5 percent activated carbon. One of the first tests using this additive was on the MWC in Geiselbullach, Germany, in January 1989. The plant is equipped with a DSI/FF system and has two lines, each capable of combusting 158 tpd of MSW. Despite high operating temperatures during the initial testing (sometimes as high as 465 °F exiting the combustor), mercury emissions were reduced from inlet levels of 250 to 330 µg/dscm, to outlet levels under 110 µg/dscm. Subsequent testing with inlet levels between 140 and 640 µg/dscm resulted in outlet levels between 12 and 46 µg/dscm.^{24,25}

Along with the Geiselbullach MWC, activated carbon/lime injection has been used on other MWC's in Germany including the Berlin-Ruhleben, Würzburg, and Siemens-KWU MWC's. During full-scale testing using this additive at the Berlin-Ruhleben MWC, which is equipped with a SD/FF system, inlet mercury levels averaged 444 µg/dscm for Boiler 2 and 402 µg/dscm for Boiler 3. Outlet levels were reduced to average levels of 99 µg/dscm and 83 µg/dscm for Boilers 2 and 3, respectively.^{25,26}

At the Würzburg MWC (DSI/FF), mercury emissions were reduced by over 80 percent to levels under 65 µg/dscm when using activated carbon/lime injection. At the Siemens-KWU MWC, which is equipped with a wet scrubber followed by a FF, injection of this additive is used as a final purification stage. Outlet levels of mercury during testing were less than 25 µg/dscm.²⁵

Sorbalit (Manufactured by Marker Zementwerk GmbH) was the commercial product used. All test results discussed in this section are based on the use of this product.

Activated carbon/lime injection has also been used on special waste incinerators in Germany (Schöneiche and Schwel-Brenn-Anlage), where substantial reductions in mercury were observed.^{24,25}

Details on costs associated with the use of this additive were not available, but similar to activated carbon, low investment costs and easy management are cited as two of the advantages of the product.²⁴

3.4 WET SCRUBBING

Wet scrubbing is a form of acid gas and metals control that has been used primarily at MWC's in Europe and Japan. Wet scrubbing of MWC flue gases typically involves passing the flue gas through an ESP to reduce PM, followed by a two-stage absorber where flue gas is contacted with water to remove HCl in the first stage and an alkaline solution in the second stage to remove SO₂. The absorber also saturates the gas stream and reduces flue gas temperatures to as low as 130 °F. Several wet scrubber designs include a fine PM collection system following the second absorber to reduce aerosol and fine particulate emissions. The alkaline solution, typically containing calcium hydroxide [Ca(OH)₂], reacts with the acid gas to form salts, which are generally insoluble and may be removed by sequential clarifying, thickening, and vacuum filtering. The dewatered salts or sludges are then landfilled.

Due to the low absorber operating temperature that promotes mercury condensation, wet scrubbing technology achieves high mercury reduction. Mercury emissions can be reduced by up to 90 percent. The use of liquid chelating agents enhances the coagulating sedimentation and the fixation of the mercury compound in the sludge.²⁷ Disadvantages of wet scrubbing, however, include the quantity of water required and potential difficulties with waste handling. To stabilize condensed mercury compounds, use of additives, such as TMT (trimercapto-s-triazine) is required in some wet scrubber designs. Failure to stabilize and remove collected mercury compounds from the scrubber solution

can result in revolatilization of mercury from the scrubber solution and, thus, reduced collection efficiency. Further, while mercury control may be higher for wet systems, control of organic emissions may be lower than that achieved with dry acid gas controls.

Test results from three wet scrubber-equipped MWC plants located in France and Switzerland are available. The two French plants, Lyon-Nord and Lyon-Sud, began commercial operation in 1989 and 1990, respectively, and they are equipped with ESP's followed by wet scrubbers. Mercury emissions results from these plants are shown in Table 3-6. Average mercury outlet emissions at Lyon-Nord were under 50 $\mu\text{g/dscm}$ for Unit 1 and 62 $\mu\text{g/dscm}$ for Unit 2. Average removal efficiencies were greater than 82 percent for Unit 1 and 62 percent for Unit 2. At Lyon-Sud, average mercury outlet emissions were less than approximately 60 $\mu\text{g/dscm}$ for both units, and average removal efficiencies were greater than 86 percent.²⁸

The Basel, Switzerland MWC, which was originally equipped with only ESP's, was retrofitted with wet scrubbing in 1989. Mercury outlet emissions, listed in Table 3-6, ranged from 16 $\mu\text{g/dscm}$ to 20 $\mu\text{g/dscm}$ at Unit 1, and from less than 13 $\mu\text{g/dscm}$ to 34 $\mu\text{g/dscm}$ at Unit 2. This corresponds to average removal efficiencies between 90 and 96 percent for Unit 1, and between 82 and 96 percent for Unit 2.²⁸ The higher mercury control efficiency at the Basel MWC may reflect higher unburned carbon levels in the fly ash from the older Basel unit as compared to the new combustors in Lyon.

3.5 OTHER TECHNOLOGIES

In addition to the mercury control technologies discussed in the previous sections, final stage activated carbon beds are being investigated as an applicable mercury control technique. Activated carbon beds are "back end" controls, positioned after all other APCD's in the system. As the flue gases pass through the bed, pollutants adsorb onto the porous surface.²⁶

TABLE 3-6. MERCURY EMISSIONS DATA FROM WET SCRUBBING SYSTEMS

MWC NAME	UNIT	RUN NUMBER	INLET MERCURY (ug/dscm)	OUTLET MERCURY (ug/dscm)	REMOVAL EFFICIENCY (%)	
LYON-NORD, FRANCE	1	1	168	<49	>71	
		2	289	<50	>83	
		3	578	<49	>91	
		AVERAGE	345	<49	>82	
	2	4	177	49	72	
		5	177	76	57	
		6	140	60	57	
		AVERAGE	165	62	62	
	LYON-SUD, FRANCE	1	3	457	72	84
			4	568	<49	>91
AVERAGE			513	<61	>88	
2			1	438	69	84
		2	373	<49	>87	
AVERAGE		406	<59	>86		
		BASEL, SWITZERLAND	1	1	252	16
2				168	17	90
4				401	17	96
7				513	20	96
8	187			19	90	
2	1			186	<13	>93
	2		224	<14	>94	
	3		261	32	88	
	4		224	<13	>94	
	5		168	<13	>92	
	6	168	21	88		
	7	140	<13	>91		
	20	363	13	96		
21	270	33	88			
23	75	<13	>82			
24	196	<13	>93			

*All concentrations are at 7 percent O₂.

A potential disadvantage to the carbon bed technology includes the possibility of fires, since activated carbons are naturally flammable and may self-ignite at temperatures as low as 175 °F.²⁶ Also, if the bed is regenerated, special precautions must be taken to ensure the capture of any resulting mercury emissions.

Another emerging mercury control technology includes the use of selenium filters. Such filters are used in metallurgical smelting operations, and consist of a cylindrical shell which contains graded porous material impregnated with selenium. Selenium has a strong affinity of mercury. Flue gas exiting an ESP would pass through the filter prior to the stack. The filters would need to be replaced once they are spent.²⁹

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