and surface area (for sulfur dioxide and oxidized mercury capture) have been shown to be most effective (Ref 2, 23).

Multi-pollutant calcium-based sorbents have been developed that can remove both elemental and oxidized mercury as effectively as the commercially available activated carbon in fixed-bed tests (at 80°C) (Ref. 26). In these tests, oxidant-enriched, calcium based sorbents[49] have proved far superior to activated carbon in SO_2 uptake. The performance of these materials was also better than the baseline lime hydrates for NO_x and SO_2 adsorption in fixed- and fluidized-bed tests.

The superiority of these sorbents has been confirmed at coal-fired boiler gas conditions typical of gas-cooled, semi-dry adsorption (SDA) processes. These sorbents need to be evaluated for higher-temperature conditions of duct sorbent injection, i.e., for application in boiler systems that are equipped only with ESP and/or FF.

Full-scale tests of calcium-based sorbents (in September 2000) on two boilers burning eastern bituminous coals and equipped with a SDA-FF (180 MWe) and a CFBA-FF (55 MWe) control system have indicated over 97 percent Hg removal in these control systems on the average (based on the inlet/outlet gas measurements). Further pilot- and field-scale testing has been planned for evaluation of mercury control (using calcium-based multi-pollutant sorbents) in systems equipped with SDA and CFBA controls (DOE-EPRI-EPA programs) (Ref. 2, 27).

Recently, a technology for the efficient capture of mercury through in-furnace injection of a calcium-based sorbent has been developed, and tested at full-scale. As part of a study conducted by McDermott Technologies, Inc. titled "Combustion 2000 Project/Low emission Boiler system Program," limestone was injected into the upper furnace of a boiler firing bituminous coal and an 80% efficient cyclone was used to collect the fly ash and calcined lime. The mercury concentration in the gas was significantly lower when the limestone was injected compared to the baseline case (without sorbent injection), with an overall average mercury reduction of 82%. As the researchers noted, using the more efficient ESP or FF particulate control devices (with collection efficiencies of greater than 99%) in place of a cyclone would result in an additional increase in the Hg removal. Additional investigations with different lime injection levels have demonstrated that limestone injection substantially reduces gaseous oxidized mercury. However, limestone injection had no apparent effect on Hg^0 emissions. The data indicated that injection of limestone sorbent at a rate of about 15 times that of the activated carbon (200 lbs/hr vs. 14 lbs/hr) achieved the same level of total Hg removal (53% reduction).[50] It was concluded that activated carbon injection is more efficient on a mass basis. However, the cost of limestone is typically an order of magnitude lower than the cost for activated carbon, therefore use of lime would be more cost-effective (Ref. 2, 12).

[49] Lime- and silicate- based sorbents, enriched with proprietary oxidants.

[50] Test data indicated a total mercury reduction of 41% using a lime sorbent with a Ca:S mass ratio of 0.04 and an injection rate of 25 lbs/hr. The lime sorbent with a Ca:S mass ratio of 0.35 and an injection rate of 200 lbs/hr achieved a total mercury reduction of 53%. This indicates that, with a change in the Ca:S mass ratio, an eight-fold decrease in the injection rate of the sorbent resulted in about 23 percent decrease in the total mercury reduction. Consequently, it may be possible to reduce significantly the lime sorbent injection rate under certain circumstances (i.e., depending on the desired level of mercury control and Ca:S requirements).

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Co-injection of Activated Carbon with Alkaline Materials

There have been two studies, in two different coal-fired utility plants using two different types of coal, in which alkaline materials have been co-injected with activated carbon[51] to investigate combined effects of sorbent injection for control of mercury and SO_2. The results of these two studies were not in agreement regarding the effect of the co-injection of alkaline materials (for SO_2 control) on mercury adsorption of activated carbon.

In one study (Ref. 28), activated carbon was co-injected with either sodium carbonate or lime for SO_2 control. With either of these sorbents, an improvement in the adsorption of gaseous Hg by the activated carbon was reported.

In a second study, co-injection of a sodium-based sorbent (sodium sesquicarbonate) with activated carbon impeded the removal of gaseous Hg by the native fly ash and the activated carbon. Negative mercury capture efficiencies were reported for co-injection of the sorbents. It is speculated that the impediment of the Hg capture was either due to inhibition of the sorbent mechanism by or increased levels of NO_2 in the gas due to the sodium sorbent impacts. NO_2 is a strong oxidizer and, if its level is increased, it can strip Hg from the internal surfaces of the system, thereby, increasing the Hg emissions.

A low-sulfur eastern bituminous coal and a PRB coal were used in the two studies respectively. Sufficient data is not available to reach definite conclusions regarding co-injection of alkaline materials with activated carbon.

3.2.2.a.ii. Nobel-Metal-Based Sorbents

Mercury can form amalgamates (alloys) with noble metals such as gold and silver. Mercury can be collected using noble metal sorbents and removed from the sorbent by a simple thermal desorption process. Under the trade name of Mercu-RE, ADA technologies Inc (ADA) has patented a process in which adsorption of mercury occurs in a fixed-bed of noble-metal sorbents (Ref. 29, 30). The sorbent is thermally regenerated, and the desorbed Hg is recovered for commercial recycle or disposal. Laboratory tests indicated that virtually all Hg (elemental and oxidized) was adsorbed by the sorbents. However, the slipstream tests performed at a coal-fired plant station during a six-month period indicated that acid gases in flue gas can negatively impact the adsorption capacity of the noble-metal sorbents. Laboratory testing indicated that prior scrubbing of the acid gases can eliminate this problem. Additional field tests are under evaluation.

3.2.2.b. Capture of Mercury in WFGD Scrubbers

Wet SO_2 scrubber performance in capturing mercury can be improved primarily by increasing the oxidation of elemental mercury in the flue gas, and reducing/preventing conversion of adsorbed Hg^{2+} to Hg^0 in the scrubber. Several scrubbing and flue gas additives are currently under development for: a) oxidization of the Hg^0, and b) preventing the conversion of adsorbed Hg^{2+} to gaseous Hg^0 in WFGD systems. Promoting oxidization of elemental mercury to oxidized mercury may be accomplished by the injection of appropriate oxidizing agents or installation of fixed oxidizing catalysts (i.e., in fixed-bed configuration).

Mercury capture in WFGD systems can also be enhanced by injection of sorbents (such as activated carbon) upstream of the PM control device because this increases the oxidized mercury fraction of the

[51] Both studies used the same commercially available activated carbon (Darco FGD activated carbon).

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flue gas. A greater level of mercury reduction can be achieved when the PM control device is a fabric filter because, as discussed previously, the filter cake of the baghouse causes oxidization of mercury when the flue gas passes through the cake. When ESP is the PM control device preceding the WFGD system, the reduction improvements are limited by sorbent injection and mercury adsorption rates.

3.2.2.b.i. Oxidation Additives

The use of oxidizing agents that could potentially convert gaseous Hg^0 into more soluble species has been under investigation by Argonne National Laboratory (Ref. 2, 31). The oxidizing agent currently employed is NOXSORBJ (a commercial product containing hydrochloric acid and sodium chlorate). Introduction of a dilute solution of this agent into simulated flue gas upstream of a WFGD scrubber resulted in a 100 percent removal of the gaseous Hg^0 from the flue gas and its recovery in the WFGD process liquids. Approximately 80 percent of the NO was removed at the same time, indicating that the potential exists for a process that combines removal of SO_2, NO, Hg^0, and perhaps, PM. Research into the effects of process parameters such as reagent concentration, SO_2 concentration, NO concentration, and reaction time is in progress. Preliminary cost estimates have projected the chemical cost for NO oxidation to be less than $5,000 per ton of NO removed, and about $20,000 per lb of Hg^0 removed.

McDermott Technologies has investigated the use of additives to prevent conversion of adsorbed Hg^{2+} to gaseous Hg^0 (Ref. 2, 32). Two potential chemical additives, Hydrogen Sulfide (H_2S) and ethylene-diamine-tetra-acetic-acid (EDTA), for controlling the conversion of Hg^{2+} to Hg^0 and enhancing the control of Hg in a WFGD system were investigated in pilot-scale tests[52] (Ref. 12). Injection of H_2S[53] gas into the flue gas entering the scrubber resulted in an increase (from 46% to 71%) in gaseous mercury removal by the WFGD. A decrease in the conversion of Hg^{2+} to Hg^0 is believed to be the main reason for this increase in the mercury removal. Addition of EDTA[54] to the scrubbing slurry also resulted in an increase in total mercury removal by the WFGD (from 46 to 73 percent). These tests were performed firing Ohio bituminous coals.

A full-scale test program of using scrubber additives to achieve increased mercury removal is being conducted by McDermott Technologies, Inc., under a new agreement with DOE/NERL[55] (Ref. 33). These full-scale tests involve units that burn high sulfur bituminous coals.

3.2.2.b.ii. Oxidation Catalysts

Laboratory and field test studies have been conducted to investigate catalytic oxidation of gaseous Hg^0 in coal-fired boiler flue gas (Under a DOE/NETL cooperative agreement) (Ref. 2, 34). Various fly ash and catalyst materials (carbon, palladium, and iron) were tested.[56] The actual rates to convert gaseous Hg^0 to a soluble Hg^{2+} were measured in both simulated and actual coal combustion flue gas, and the most-active catalysts were further investigated in field tests. The field tests indicated that there is agreement between

[52] As part of a program titled the Advanced Emissions Control Development Program (AECDP), and jointly funded by the DOE Federal Energy Technology Center, the Ohio Coal Development Office (OCDO), and McDermott Technology Inc.
[53] Selection of H_2S was based on the possibility that a sulfide donating species has the potential to promote capture of oxidized mercury.
[54] EDTA was selected because it is a strong chelating agent. A chelating agent can bond with metallic ions and thus can potentially prevent the action of the transition metals in converting Hg^{2+} to Hg^0.
[55] These two facilities are: Michigan South Central Power Agency's (MSCPA) 55-MWe Endicott Station located in Litchfield, MI; and Cinergy's 1300-MWe Zimmer Station located near Cincinnati, OH.
[56] The subbituminous and bituminous coal fly ashes generally showed higher oxidation rates than the lignite coal.

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the lab and the field tests in oxidation percentages achieved. However, the metal-based and some carbon-based catalysts were deactivated in the field tests after relatively short time exposures to the combustion gases. Sulfur trioxide (SO_3) and selenium compounds have been identified as possible flue gas constituents for this deactivation. Additional bench-scale laboratory tests indicate that it should be possible to regenerate the spent catalysts (Ref. 2, 34, 35, 36).

The potential commercial application of mercury oxidation catalysts to enhance mercury capture in a WFGD system downstream of a high-efficiency ESP is being investigated in a pilot-scale field test under a DOE/NETL cooperative agreement (Ref. 2, 37). These catalysts have been identified through previous DOE-sponsored research as being effective and are being evaluated in a commercial form in larger pilot-scale units for longer periods (over one year at each testing site). The DOE/NETL is working with URS Group, Inc. (formerly Radian International), EPRI, and two electric utility companies.[57]

3.2.2.b.iii. Wet FGD Scrubber Design and Operating Modifications

Pilot-scale WFGD test studies suggest that modifying the operation and design of the scrubber and the upstream ESP system may improve the capture of gaseous Hg^{2+} and reduce the conversion of the adsorbed Hg^{2+} to Hg^0. These studies indicate that the operating voltage of the ESP and the oxidation air of the WFGD influence the Hg^{2+} to Hg^0 conversion in the WFGD.[58] Liquid-to-gas ratios and the tower design of the WFGD unit affect adsorption of Hg^{2+} (Ref. 2).

3.2.3. Multi-Pollutant Control Technologies[59]

The control systems being commercially offered or developed for multi-pollutant emissions control are summarized in this section. Many of these technologies were initially developed for control of one or two pollutants and the explanation of their current status is based on reports with such a focus. An integrated approach in evaluating any control system should be adopted for a successful multi-pollutant control, i.e., in implementing a control device, the impact of that device on all pollutants as well as its interactions with and effects on all other pollution control devices and the system as a whole should be considered. Some control strategies can be effective in reducing multiple pollutants, and as a result can offer some cost savings and operational benefits. However, there is not as much research on multiple pollutant effects and performance as there is for single pollutant performance.[60]

Corona Discharge

An intense corona discharge[61] in the flue gas upstream of an ESP-WFGD system is under investigation for improving PM control. In this process, SO_2 and NO are converted to SO_3 and NO_2 (and subsequently to H_2SO_4 and HNO_3). Elemental mercury is oxidized by oxygen-carrying reactive species that are

[57] The first test site is the Great River Energy Coal Creek Station, which fires North Dakota lignite. The second site is the City Public Service of San Antonio's J.K. Spruce Plant, which fires a Powder River Basin (PRB) subbituminous coal.
[58] Lowering the ESP operating voltage and lowering the oxidation air of the WFGD reduces the conversion of Hg^{2+} to Hg^0.
[59] This section is based on materials in the EPA Report (Ref. 2).
[60] Some of the available multipollutant preliminary data have been quoted in this report under the relevant sections that discuss these technologies in detail (such as the subsection 2.2.b.i.on Oxidation Additives").
[61] Corona discharge is generated by application of high voltage to a pair of electrodes in a gas and ionization of the gas.

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generated by the corona discharge. The increased SO_3 helps oxidization of Hg^0 and improves the PM collection in the ESP.

Two companies have been developing corona discharge pollution control systems. In the system developed by Environmental Elements Corporation, the oxidized sulfur and nitrogen compounds are recovered as marketable sulfuric and nitric acids in wet ESP sections and/or adsorbers. The initial slipstream pilot plant tests[62] have indicated results of 80 percent mercury removal and a complete oxidation of elemental mercury (under two different control settings).

Power Span Corporation is developing a single, integrated pollution control device that uses a proprietary technology called Electro-Catalytic Oxidation™ or ECO™ to control SO_2, NO_x, Hg, and fine PM. A dielectric barrier discharge is used to convert NO_x and SO_2 to acids and oxidize Hg^0. Acid mists, fine PM, and Hg are collected in a condensing wet ESP and are processed to generate saleable products (e.g., commercial grade acids, gypsum, and ammonia). A conventional ESP is placed upstream of the ECO™ unit to capture the majority of the fly ash particles. Slipstream pilot tests[63] of flue gas from a 150-MW boiler unit burning high-sulfur eastern bituminous coal have shown mercury emission reduction of 68 percent (Ref. 38).

Under a new DOE cooperative agreement, a research project is being conducted using the ECO™ pilot test facility to optimize the technology's Hg removal capability while maintaining the performance of the ECO™ unit for removal of nitrogen oxides, sulfur dioxide, and fine PM (Ref. 39). In addition, an $11.9 million ECO commercial demonstration unit is currently under construction[64] (with a $3.5 million co-funding from the Ohio Coal Development Office).

Electron Beam Irradiation

The chemical reactions in electron beam (E-beam) radiation are identical to corona discharge, however, the oxidation occurs by the electron bombardment. The oxidation products (H_2SO_4, and HNO_3) then enter a semi-dry absorption system and react with ammonia reagent to produce ammonium sulfate and nitrate salts suitable for use as a fertilizer. Elemental mercury is oxidized and would be present in the fertilizer as a contaminant. The E-Beam Process has been offered commercially since the 1980s and is now used in Japan and China (Ref. 40).

Oxidant Injection in Flue Gas

Injection of an oxidant such as chlorine, peroxide, or ozone into the flue gas upstream of an absorber has been proposed for multi-pollutant control (Ref. 2). The reaction products would be similar to corona or electron beam. The process wastes are saleable products such as weak acids, sulfate/nitrate fertilizers, or lower-value soil amendments. These products would contain trace mercury salts.

Lo-Tox is an example of this technology (Ref. 41). The ISCA is a chlorine-based system producing byproduct acids. Hydrogen peroxide and other chlorine-based oxidation schemes have been investigated but have not been proposed for commercial use (Ref. 42).

[62] At Alabama Power Miller (Unit 3)
[63] At FirstEnergy's R.E. Burger Plant near Shadyside, OH
[64] At FirstEnergy's Eastlake Plant near Cleveland, OH

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Catalytic Oxidation

Lower temperature catalysts (those applied in temperatures less than 500°F) would likely directly oxidize Hg^0 to Hg^{2+}. High temperature catalysts that oxidize SO_2 and NO_x [65]can increase oxidation of Hg^0 indirectly by increasing SO_3 and $NO_2/N_2O_4/N_2O_5$ concentrations. Hg^0 oxidation occurs in the downstream acid gas and PM control devices due to the increased acid gas concentrations. Any catalytic oxidation scheme that produces byproduct acids would likely remove a substantial portion of the total Hg with the acids as mercury salts (chloride, sulfate, or nitrate). A number of catalytic technologies are currently under commercial development. SNO_x technology has been evaluated under DOE's Clean Coal Technology Program. The effectiveness of an oxidation catalyst upstream of WFGD scrubber to decrease total Hg emissions is under investigation (under DOE sponsorship) (Ref. 43)

Oxidant Addition to Scrubber[66]

Several DOE and EPA projects focus on addition of an oxidant to a FGD scrubber. The effectiveness of adding a mercury oxidant to the liquor of commercial wet scrubbers is being investigated in a current DOE test program. Another research, sponsored by the EPA, will culminate in a pilot-scale slipstream evaluation of oxidant addition to the FGD scrubber (Ref. 44).

One DOE-sponsored project is investigating the use of lime and lime-silica sorbents in a semi-dry circulating bed absorber for combined SO_2, NO_x, and Hg control (Ref. 45). An efficient PM collector such as the EPRI Toxecon™ process may be used in conjunction with combinations of sorbents injected upstream of the PM device for a multiple pollutant control strategy.

Catalytic Fabric Filters

Based on field pilot-scale observations that substantial mercury oxidation has occurred within a fabric filter (Ref. 46), presumably by catalytic action of certain fibers or residual fly ash imbedded within the fabric, development of woven carbon fibers or other catalytic materials that can be integrated into the bag filters for a combined Hg/PM control device have received attention. Currently, such options are being investigated.

Carbon-fiber FFs and ESPs

Combined Hg/PM control would be improved by using carbon-fiber fabric filters and ESP plates. Carbon-fiber fabric filters are commercially available. Carbon-fiber ESP plates are being investigated under a study sponsored by the Ohio Coal Development Office. The limited capacity of carbon to adsorb mercury does not allow continued operation of the FF or ESP after a short time. Therefore, a process for regeneration of the carbon active sites without replacing the fabric filter bags or ESP plates should be developed.

4. Summary of Post-Combustion Mercury Controls

The following summarizes the post-combustion mercury control approaches discussed above in detail.

4.1. Post-combustion Mercury Control Retrofit

Retrofitting existing air pollution control systems to add control of Hg has the potential advantage of reducing the costs of implementing Hg controls by enhancing the capability of Hg capture of the air

[65] Oxidation of Hg^0 does not occur by the high temperature catalysts.
[66] These technologies were briefly mentioned in the previous sections.

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pollution control system(s) already in place. Retrofit control options have been a focus of the current research and development in coal-fired boiler flue gas mercury control. For the existing electric utility boilers that are only equipped with ESPs or FFs, retrofit technologies that are currently under development are based on injecting sorbents into the flue gas upstream of the FF or ESP. Retrofit technologies for improving Hg capture in the WFGD scrubbers are based on promoting oxidization of Hg^0 to soluble species by addition of oxidizing agents or installation of fixed oxidizing catalysts upstream of the scrubber. Co-injection of a second sorbent can enhance mercury adsorption in boilers using SDA for SO_2 control. Specific retrofit mercury removal options that can be used with specific air control pollution control equipment are discussed below.

4.1.a. Cold-side ESP Retrofit Options

Flue Gas Cooling

Lowering the temperature of the gas entering the ESP assists natural fly ash sorption of Hg and improves the performance of any sorbents injected upstream for Hg control. A limitation is the potential for HCl or SO_3 mist formation in certain cases when the gas temperature approaches the acid dew point temperature.

Sorbent Injection

Injection of sorbents into the flue gas upstream of the ESP increases the Hg_p fraction of the total Hg in the flue gas (by adsorption of the gaseous Hg onto the sorbent particles) and enhances mercury removal in the PM control device. For marginally performing ESPs that have difficulty meeting opacity requirements, addition of a FF downstream of the ESP, or possibly modifying the ESP, can address the needed additional particulate collection requirements.

Sorbent Injection in conjunction with Installing A Polishing FF

Installing a FF downstream of the existing ESP improves PM collection efficiency significantly, leading to a significant improvement in mercury removal. A polishing FF requires a smaller collecting surface due to lower particulate loading, and can operate with longer cleaning cycles (good for sorbent performance and bag life). Consequently a smaller FF (compared to the case when FF is the main PM collection system) is required.

ESP Modifications

The last field of the ESP can be converted to a wet ESP[67] or a very compact pulsejet FF. Such modifications may arise from a need for increased PM collection efficiency due to reduced opacity requirements, and will reduce mercury emissions.

4.1.b. Fabric Filter Retrofit Options

Flue Gas Cooling

This option poses the same opportunities and potential limitations as the case for lowering the flue gas temperatures entering ESPs, which is discussed above.

Sorbent Injection

Some internal FF modifications may be required[68] when injecting sorbents upstream of a FF. There may be a need for more frequent cleaning with the additional sorbent loading.

[67] It is also possible to install a separate tubular wet ESP to improve the PM collection. Such systems do not have the same footprint requirements as the dry ESPs.

[68] Removing baffles, changing the point of gas entry, increasing gas velocity, or using smaller sorbent particles are possible options for optimizing the FF performance for sorbent injection.

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FF Modifications

Fabric bags can be potentially replaced with catalytic bags that oxidize Hg^0 to Hg++ and Hg_p, or electrostatic augmentation can be added to the FF to increase the bag cleaning cycle interval time (this increases mercury capture by increasing sorbent/gas contact time). Electrostatic augmentation would be especially beneficial in conjunction with higher-cost, high-capacity sorbent injection.

4.1.c. HS-ESP and PS System Retrofit Options

These options have not been discussed in this document because currently no Massachusetts coal-fired electric utility boiler affected by mercury requirements of the 310 CMR 7.29 regulations has an existing HS-ESP or PS PM control system. Due to the fact that these PM control systems are less effective compared to other PM control systems, deployment of these systems in future is not expected.

4.1.d. Spray Dryer Absorber Retrofit Options

Oxidation Additives

Possible performance improvements include direct addition of activated carbon to the absorber with lime, use of calcium-based sorbents (for multi-pollutant control), and addition of oxidants to the absorber. Boiler modifications (such as use of low-NO_x burners) that result in production of a fly ash with higher unburned carbon content can also improve the performance of the SDA.[69]

Improving PM Collection Downstream of the SDA System

In control systems that use an ESP downstream of the SDA, replacement of the ESP unit with a FF is likely to improve Hg removal as a result of enhanced PM control efficiency as well as greater conversion of Hg^{2+} to Hg_p (on the filter cake). Use of a polishing FF in addition to the ESP can improve the PM collection as well.

4.1.e. Wet FGD Scrubber Retrofit Options

Oxidation Additives

As discussed earlier, in general, improving mercury oxidation increases the total Hg removal by the wet scrubber. Several flue gas and scrubbing additives for enhancing mercury oxidation in the flue gas upstream of WFGD or in the WFGD scrubber itself, as well as flue gas and scrubber additives that prevent conversion of Hg^{2+} to Hg^0 in wet FGD systems, are being developed. Increasing oxidation potential of mercury upstream or within the scrubber may also increase the potential to oxidize other species such as SO_2 and NO/NO_2 to acid aerosols. This potential increase in formation of acid aerosols needs to be addressed in the operational requirements of the system when this retrofit is selected.

Fixed Oxidizing Catalysts Upstream of Scrubber

The performance of Wet FGD scrubber in mercury capture can be enhanced by installing fixed oxidizing catalysts upstream of the scrubber to promote oxidization of Hg^0 to soluble mercury salts. Several potentially suitable catalysts are currently being tested.

Wet FGD Scrubber Modifications

Pilot-scale studies of wet FGD systems suggest that the design and operation of a wet FGD and its upstream ESP affect the capture of Hg^{2+} and the conversion of absorbed Hg^{2+} to Hg^0 in the scrubber. Factors affecting mercury emissions are the liquid-to-gas ratio and tower design of the wet FGD, as well as the operating voltage of the ESP.

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[69] As discussed earlier, use of low NOx burners increases the unburned carbon content of the fly ash. This can improve adsorption of mercury onto the native fly ash and improve mercury adsorption in the PM control device.

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4.2. Integrating Mercury Control into a Multi-pollutant Control Strategy

Implementation of new SO_2, NO_x, and fine particulate control systems can reduce mercury emissions from coal-fired electric utility boilers, hence reducing or eliminating the need for mercury specific control devices. For example, installation of a wet or semi-dry FGD unit can significantly reduce oxidized Hg emissions (by 90 to 95 percent over previous levels); and adding a SCR NO_x control system upstream of the FGD would further reduce total Hg emissions (by increasing the oxidized Hg). Installation of new particulate control systems (such as EPRI COHPAC, advanced hybrid particulate collectors, electrostatic augmentation of pulsed fabric filters, and wet ESPs optimized for use in coal-fired plants), as well as taking advantage of new developments in improving the collection efficiency of the existing PM systems (such as new conditioning additives for improving ESP performance) can result in high-efficiency control of particulate matter[70] and lead to additional mercury reductions. The efficacy of these PM control systems in mercury capture further increases when they are used in combination with sorbent injection.

A number of new multi-pollutant control systems are under development and at least one technology (electron beam irradiation) is currently commercially available and in use in Japan and China. Some of these technologies were initially developed to address a single specific pollutant, and have been undergoing further development for multi-pollutant control (e.g., calcium-based sorbents).

In conclusion, although every control option cannot be implemented in every coal-fired electric utility plant, several mercury control options are available for each plant configuration to achieve further reductions in mercury emissions. Some of these mercury control options are based on commercially available technology/equipment. A number of these control technologies are in the field-demonstration stage and are approaching commercialization. Others are in earlier stages of development and have proved promising. Due to the highly interactive nature of SO_2, NO_x, Hg, and PM control, the interaction of control equipment used for control of single pollutants should be considered in a multi-pollutant context. A multi-pollutant emission control strategy may be the most cost-effective Hg control approach in the long-term perspective.

[70] In many cases collection efficiency of fine particulate mater is improved in addition to the total PM collection efficiency.

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APPENDIX B: MERCURY CONTROL COSTS

In general, the air pollution control methods appropriate for a given coal-fired electric utility boiler depend on many factors including the age and size of the unit, unit location and plant space limitations, and the type of coal burned. The costs of controls, for mercury and other pollutants, are highly variable based on these and other factors. This section does not attempt to assess the costs of any specific control measure for any given coal-fired facility. Rather, it presents some preliminary cost evaluations of mercury controls that have been performed as part of the development of mercury control technologies.

Various mercury control methods and their general availability and feasibility have been discussed above. Technologies based on injection of powdered activated carbon (PAC) have been investigated most and are likely to reach commercialization for mercury removal from coal-fired utility boiler flue gas before other technologies. Non-PAC-based mercury control technologies, such as enhanced mercury oxidation using oxidants or catalysts followed by wet scrubbing, are expected to become available in the future. The commercially available SCR-FGD control combinations already achieve significant mercury reductions and may become more cost effective (Ref. 1).

Some preliminary cost evaluations of the PAC injection-based and other technologies are available. A brief discussion of these cost estimates and a few related issues are presented below.

EPA-Estimated Costs for PAC Injection-Based Mercury Control Technologies

As part of the EPA's coal-fired utility boiler MACT development process, EPA has developed a preliminary estimate of costs[71] for a retrofit of PAC injection-based technology to a series of model plant scenarios representative of coal-fired electric utility power plants operating in the United States. The PAC injection-based technologies were selected by EPA because sufficient pilot-scale data were available to make reasonable cost estimates. EPA deemed mercury-capture performance data for other potential control technologies insufficient to develop equivalent cost estimates for those technologies.

EPA cost estimates for PAC injection-based control technology were calculated using the PAC injection technology pilot-scale test and ICR data, and a computer cost model[72] developed by DOE/NETL for estimating the costs of Hg control options for coal-fired electric utility boilers.[73,74] The information developed in this cost analysis has been used in EPA's coal-fired utility boiler MACT development process regarding mercury and other air toxics.

The total annual costs of controlling Hg emissions were examined. These costs include annualized capital costs, annual fixed operation and maintenance (O&M) costs, and annual variable O&M costs.[75] In general, the major fraction of the annual costs for mercury control associated with PAC injection-based

[71] EPA notes that this calculation is based on pilot-scale data (and hence few data-points) and is considered preliminary. Some performance aspects of the technology in a full-scale application (e.g., the degree of mixing between the flue gas and activated carbon in large ducts, and potential system impacts such as formation of deposits arising from continuous long term operation) are not identical to pilot-scale operation and their effects may not be completely accounted for in preliminary cost projections (Ref. 1).
[72] This model is called Integrated Environmental Control Model (IECM) and has been expanded to include performance and cost models for a variety of mercury control options. This model is used to obtain quantitative estimates of the cost and emissions impacts of interactions among technologies for multi-pollutant controls. This model currently incorporates a powdered activated carbon injection module (Ref. 2).
[73] For more information, please refer to the Appendix D of the document in Reference (1) of this section.
[74] The DOE/NETL cost model has also been used in other pollution control cost study evaluations. Please refer to the document in Reference (1) of the Reference list for this section, and references therein for more information.
[75] An examination of these costs including the cost of PAC is provided in the document in Reference (3).

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control technologies is the cost related to the use of PAC; the capital costs comprise a relatively minor portion of the total annual costs.

The Model Plant Scenarios and Assumptions

The model scenarios that EPA developed for this cost evaluation incorporate retrofit PAC injection-based technologies on various existing coal-fired utility boiler plant pollution control systems. These retrofit PAC configurations include plants with an existing HS-ESP, CS-ESP, FF, SDA + FF, and SDA + CS-ESP for control of PM. Several variations on the retrofit options were considered including retrofit systems with and without spray cooling and retrofit systems with and without added polishing fabric filter (PFF). The retrofit options also included a case in which lime was co-injected with PAC because pilot-scale tests have indicated that lime co-injection can significantly reduce the rate of PAC injection. The model plant scenarios included plants that burn bituminous coals (both low- and high-sulfur cases were modeled) as well as plants that fire subbituminous coal. For both coal types, both larger (975 MWe) and smaller (100 MWe) plants were modeled with appropriate[76] applicable existing pollution control devices.

In these cost estimates, a plant capacity factor of 65 percent, a PAC cost of $1.00/per kilogram, and a flue gas mercury concentration of 10 microgram/Nm^3 were assumed.[77] An approach to acid dew point (ADP) of 10°C (18°F) was used for the retrofit system with spray cooling (SC) to operate above the ADP and avoid problems associated with acid mist (SO_3) formation. No PAC recycling was considered in this analysis. Because PAC injection rate requirements increase nonlinearly with increases in Hg removal efficiency, model plant costs were estimated for Hg removal efficiencies of 60, 70, 80, and 90 percent.

Sensitivity Analysis

EPA also performed sensitivity analysis on a selected group of variables in this cost evaluation to assess the impact of factors such as the acid dew point approach, PAC recycling, increased flue gas residence time (by adding ductwork to the plant), and use of composite PAC-lime sorbents.[78] The sensitivity analysis indicates that neither PAC recycling at a rate of 20 percent, nor increased flue gas residence time has any significant impact on the control costs.[79] However, use of composite PAC-lime sorbent (with a PAC-to-lime injection ratio of 2:19) lowers the total annual costs by 34.7 to 38 percent (based on a 90% Hg removal in a 500 MWe plant). The sensitivity analysis shows that an increase in the ADP (from ADP+18°F to ADP+ 40°F) would increase the Hg control costs for a plant firing bituminous coal, while it would decrease the costs for a plant firing subbituminous coal (because the water injection requirements significantly decreases, while the PAC injection rate for mercury removal does not increase much).[80]

Projection of Mercury Control Costs

EPA estimated the mercury control costs for various boiler and control device combinations with the following assumptions:[81]

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[76] For example, larger plants that use high sulfur bituminous coal tend to use a WFGD for SO_2 control; while in smaller plants that use high sulfur bituminous coal, use of both SDA + ESP/FF or WFGD for SO_2 control is common.

[77] This Hg concentration is in the range of mean concentrations (1.7-50.1 microgram/Nm^3) determined from ICR for pulverized-coal-fired electric utility boilers equipped with different air pollution controls.

[78] The sensitivity analysis was performed on a model scenario with a 500 MWe plant.

[79] For the recycling to impact the control costs, a much higher rate of recycling is necessary.

[80] Generally an approach of ADP+18°F is considered. When a higher temperature is required, use of SC + PAC injection + PFF may be less expensive.

[81] Please refer to the document in Reference (1) for a full discussion.

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- A mercury capture efficiency of 80% is obtained using ESPs and 90% using FFs (due to the fact that FFs are more efficient than ESPs in control of PM).

- The projected costs for PAC injection technology were arrived at by applying a 40 percent reduction to the total annual costs of the current cost estimates. A 40 percent reduction reflects the potential cost savings that may be possible with the use of more effective sorbents. It was based on the results of the sensitivity analysis, which indicated that using composite PAC-lime sorbent injection would reduce the costs by nearly 40 percent, and the expectation that injection of composite sorbents would not pose any significant technical constraints.[82]

The results of this study show that, because FFs provide better sorbent utilization than ESPs, reducing Hg emissions between 60 and 90 percent using FFs instead of ESPs would significantly reduce the total annual costs on the average (about 70% for the 975 MWe plants, and 45 % for the 100 MWe plants, i.e., an average of 58% across all plants). Hg control costs may be negligible (essentially equal to the cost of monitoring) for plants with SCR and WFGD firing bituminous coal where the percentage of Hg^{2+} content in the flue gas is at least 95 % of the total Hg, as a result of fuel, combustion conditions, and Hg oxidation due to SCR.

The cost estimates obtained in this EPA study are comparable to the mercury control cost estimates obtained in an earlier EPA study[83] of lime and PAC injection in which EPA used the Integrated Planning Model (IPM) for boilers ranging in size from 100 to 1000 MWe (Ref. 3, 4). The current EPA cost estimates range from 0.305 to 3.783 mills/kWh. The costs in the earlier EPA study ranged from 0.7 to 1.76 mills/kWh.

Comparison with NO_x Control Costs

In order to provide a context for the impact of the Hg control costs to the utility plants that burn coal in their electric power generation, these costs have been compared to the costs of another currently controlled air pollutant, namely NO_x. Table B-1 presents the ranges of total annual costs in year 2000 constant dollars for the mercury controls examined in the EPA cost-estimate study and the costs for two currently used NO_x technologies, i.e., low NO_x burners (LNB) and SCR.[84,85] In this comparison, the costs associated with the LNB and SCR control technologies were selected for NO_x because, in general, the costs of currently used NO_x controls are expected to fall within the range of costs associated with LNB and SCR.

[82] Some data are available for PAC-lime sorbent with PFF.
[83] Published March 1999.
[84] EPA has derived the NOx cost information from the document in Reference (5).
[85] The NO_x costs are for boilers ranging in size from 100 to 1000 MWe and operated at a plant capacity factor of 65 percent. The Hg control costs were estimated for boilers ranging in size from 100 to 975 MWe and operated at a plant capacity factor of 65 percent.

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Table B-1. Comparison of mercury control costs using powdered activated carbon injection technology to the costs of NO_x control.[86]

Air Pollutant Controlled	Control Technology	Total Annual Control Cost Range (mills/kWh)	
		Current Costs	Projected Costs
Hg	PAC Injection	0.305 - 3.783 (a) 0.035 - 1.915 (b)	0.183 - 2.270 (a) 0.183 - 1.149 (b)
NO_x	LNB	0.210 - 0.827 (c)	
	SCR	1.846 - 3.619 (c)	

Key: (a) All modeled plants; (b) All modeled plants except those with HS-ESP; (c) Actual costs

These estimates indicate that, based on the currently available information, the cost of mercury control, using PAC technology, ranges from 0.305 to 3.783 mills/kWh.[87] If the plants with an existing HS-ESP system for PM control are excluded,[88] these costs would range from 0.305 to 1.915 mills/kWh. Future cost projections based on a composite lime-PAC sorbent injection for Hg removal, range from 0.183 to 2.270 mills/kWh for all modeled plants and from 0.183 to 1.149 mills/kWh excluding plants with a HS-ESP.

The data show that the current cost of mercury control using PAC injection-based control technologies is comparable to the current cost of NO_x control. For facilities that do not have an existing HS-ESP, Hg control costs lie within the range of the NO_x control costs. A mercury control cost reduction of about 40% is expected by application of more efficient sorbents (such as PAC-lime composite sorbents).

An important point to note is that for technology applications on bituminous-coal-fired boilers using ESPs, the current estimates were based on the PAC injection rates derived from the mercury fly ash capture in the pilot-scale test data. The EPA ICR data reflects higher levels of Hg capture by the native fly ash than those seen in pilot-scale tests (leading to lower PAC injection rates for achieving the same level of Hg control). Therefore, these cost estimates for technology applications on bituminous-coal-fired boilers using ESPs may be conservatively high (i.e., if the PAC injection rates are estimated using the EPA ICR data instead of the pilot-scale data, the estimated control costs would be lower than the figures presented here[89]).

It should be noted that these preliminary cost estimates were developed based on short-term pilot-scale tests and may not account for factors such as mass transfer effects in full-scale applications (i.e., the impact of flue gas and sorbent mixing in larger ducts). However, on-going research is expected to address these issues and to improve the cost-effectiveness of PAC injection technologies.

In addition to using sorbents with higher mercury adsorption capacity and/or lower costs (such as composite PAC-lime sorbents or impregnated activated carbons), improvements in the PM control device, such as use of an EPRI COHPAC (a pulsed high-ratio fabric filter known as Compact Hybrid Particulate Collector or COHPAC) could improve the cost-effectiveness of PAC injection-based technologies.

[86] Adapted from the document in Reference (1).
[87] 1.00 mill/kWh is equivalent to $0.01/MWh.
[88] The coal-fired utility boilers in Massachusetts, subject to provisions of mercury standards in 310 CMR 7.29, do not have any hot-side ESP. All ESP units in these facilities are cold-side.
[89] EPA performed two sets of cost analysis. The required PAC injection rate for mercury control was derived in the first set from ICR data, and in the second set from the pilot-scale test data for PAC injection-based technology.

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Availability of A Methodology for Assessing Sorbents for Mercury Control in Coal-Combustion Flue Gas

Current studies indicate that use of sorbents with ultra fine mean particle size can significantly affect the efficacy of sorbent use and the costs associated with sorbent injection-based mercury control technology. Additionally, because the sorbent injection rate (for achieving the same mercury control efficiency) is reduced when ultra fine sorbents are used, issues related to excess carbon content of fly ash (as a result of AC sorbent injection) can potentially be addressed. The following section provides some detail regarding use of ultra fine sorbents.

A sorbent evaluation methodology (model) has been developed by EPRI and its contractors (URS, Apogee and Meserole Consulting) that provides an effective and low-cost method to compare potential sorbents for mercury control prior to testing at full-scale (Ref. 6). The results obtained during sorbent evaluations at several sites have indicated that laboratory tests (in conjunction with the evaluation methodology developed by EPRI) can be used effectively to identify sorbents with the greatest potential for success in field test applications. Fixed-bed[90] test results in conjunction with model predictions can be used to project the estimated removal (in an ESP or in a baghouse). Consequently, availability of this tool can facilitate evaluation and comparison of sorbents and help expedite development of cost-effective sorbent injection technologies.

Impacts of Particle Size on Predicted Costs of Mercury Control Using Sorbent Injection

Under an EPRI contract,[91] a theoretical model has been developed that combines sorbent adsorption characteristics with mass transfer considerations to predict mercury removal by duct-injection in full-scale applications (Ref. 7). The model predicts the effects of various sorbent properties on mercury removal and associated costs when the sorbent is injected upstream of an ESP or FF.

The estimated costs are affected by the sorbent characteristics, price, and the nature of the downstream pollution devices. The calculations suggest that the economics of the injection of a dry sorbent upstream of an ESP may depend largely on the average particle size of the sorbent if the price and sorption capacity are reasonable (Ref. 8).

It has been shown that the particle size of the sorbent is a major determining factor in the required sorbent injection rate for achieving a certain degree of mercury removal. This especially affects the injection upstream of an ESP. Reducing the particle size of the sorbent has a positive impact on mercury removal. Finer particles of a given sorbent can be produced by grinding the commercially available material prior to injection.

The effects of mercury adsorption capacity for ultra fine sorbents is predicted to be more pronounced at higher removal efficiencies (i.e., the smaller the particle size, the greater the impact of sorbent capacity on the higher removal efficiencies). Another advantage of having smaller particle sizes at a given sorbent capacity is that high removal efficiencies can be achieved at low sorbent residence times.

These investigations have indicated that the use of high capacity fine-sized sorbents injected upstream of an ESP have the potential to achieve mercury removals that is competitive with a fabric filter if the

[90] In this configuration the sorbent materials is not injected into the flue gas, rather the flue gas passes through a fixed bed of sorbent material in a container (such as a tube). Such tests are generally performed prior to injection tests.
[91] The contractors were Meserole Consulting and URS Corporation.

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sorbent price is less than about $1.00 per pound.[92] Thus, the use of fine sorbents has the potential to lower the cost of mercury control for sorbent injection upstream of an ESP below that predicted for fabric filter.

Ultra fine sorbents with high capacity have the potential to substantially control the cost of achieving high mercury removal efficiencies compared to using commercially available activated carbons. The overall costs could be decreased by a factor of 2 or 3 depending on the price of these small diameter sorbents[93] (assumed to be $1.00/lb and $0.50/lb respectively for this study). Development of cost-effective sorbents with high mercury sorption capacities and small diameters, and injection technology for materials with average diameters less than 5 microns, would result in significant cost reductions.

Estimated Mercury Control Costs for Oxidation Catalyst-Based Technology

Preliminary cost estimates were developed for a catalytic oxidation-based mercury control technology following field tests that indicated high elemental mercury oxidation of flue gas (Ref. 9). This technology can be used for mercury control in coal-fired power plants that are equipped with WFGD. The catalyst materials[94] were applied to conventional (commercially available) honeycomb structures.[95] The costs for this control technology were compared to the PAC control technology cost estimates presented in an EPRI paper (Ref. 10).

The plant modeled for the cost evaluation of this catalyst-based control technology is a 400 MWe coal-fired utility plant that has a conventional ESP for particulate control followed by a wet FGD system. The flue gas was assumed to have a total mercury content of 10 microgram/Nm^3, of which 75% is in elemental and 25% in oxidized form.[96] It was assumed that the WFGD system will remove 95% of the oxidized mercury in the flue gas but no elemental mercury. Mercury control costs were estimated for both the 80% and 90% mercury reduction levels. The same economic factors and plant descriptions were used in these calculations as those in the above-mentioned EPRI paper calculations for consistency. Costs estimated for PAC injection application were based on a system retrofitted with a COHPAC system as the PM control device because such a system is more cost effective than a CS-ESP.[97] PAC injection in plants with only a CS-ESP would require much higher rates of PAC injection.

The preliminary cost estimates for mercury control using oxidation catalyst technology indicate significant cost reductions compared to PAC injection-based control technology using an EPRI COHPAC retrofit. For plants firing subbituminous PRB coal, 44% and 17% cost reductions were achieved at the

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[92] For example, a high adsorption capacity (2000 microgram/g) fine particle (5 micron mean diameter) sorbent (which costs $0.05/lb) injected upstream of ESP would be more cost effective compared to a sorbent with the same mercury adsorption capacity but with larger particle size (15 micron, and with a cost of $0.25/lb) injected upstream of an FF. It should be noted that the mercury adsorption capacity assumed for these cost calculations is within the adsorption capacity range of commercially available activated carbon. For reference, the capacities of sorbents such as commercially available activated carbon typically range from 500 to 2000 microgram/g.

[93] The base-case cost for the commercially available activated carbon was set to be $0.25/lb, based on an anticipated reduction of the cost currently used in pilot-scale applications (i.e., $0.50/lb).

[94] Several materials warrant further development at larger scale, i.e., for periods of two to three years to better establish catalyst life.

[95] This technology has been tested at three facilities at the slipstream test level. For the full-scale tests, the catalysts would be placed downstream of the PM control device and upstream of WFGD.

[96] This mercury content is same as that in the PAC cost study.

[97] The EPA study of the cost estimates for PAC injection-based technology models the commonly used PM control configurations in US coal-fired plants and does not include the more efficient COHPAC particulate matter control system.

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80% and 90% mercury removal levels respectively. The corresponding cost reductions for plants firing bituminous coal are 62% and 9%.

This technology appears to be cost-effective relative to competing processes for plants that have existing FGD systems. Lower-cost catalyst materials and extending catalyst life through regeneration could further improve the economics.

Estimated Control Costs for Oxidation-Enhanced Sorbent Technology

Multi-pollutant oxidant-rich calcium-based hydrated lime and silicate sorbents that can be used in flue gas desulfurization systems[98] have been under investigation. Preliminary economic analysis suggests that the oxidant-rich calcium-based silicate sorbents reduce the mercury control costs by 80% compared to PAC injection-based technology[99] (Ref. 11). Although the oxidant-rich calcium-based lime sorbents offer somewhat lower cost reductions, they still offer significant cost savings compared to PAC injection. The same methodology used by EPA[100] for PAC cost calculations was used in the cost calculations for these sorbents.

The investigations indicated that injection of the oxidant-rich calcium-based silicate sorbent for mercury control, in the presence of a relative abundance of SO_2, can result in significant SO_2 removal (above the baseline reductions achieved with the currently used FGD calcium-based sorbents without optimizing the sorbent for SO_2 or NO_x control. The reductions for both SO_2 and NO_x were above the baseline for both oxidant-enriched calcium-based lime and silicate sorbents.

Impact of Multi-Pollutant Controls on Costs

Coal-fired electric utility power plants are currently required to limit their emissions of NO_x, SO_2, and PM under federal requirements.[101] Under 310 CMR 7.29, these facilities are required to address their emissions of mercury and CO_2, as well as reduce the emissions of NO_x and SO_2. Multi-pollutant interactions affect the emissions of each pollutant and the cost of environmental compliance. Therefore, an evaluation of the emissions and compliance costs would need to be performed in the context of a multi-pollutant approach.

To address this multi-pollutant evaluation need, the Integrated Environmental Control Model (IECM) was developed for DOE/NETL by Carnegie Mellon University (Ref. 12, 13, 14). IECM provides plant-level performance, emissions, and cost estimates for a variety of environmental control options for coal-fired power plants (Ref. 15). The IECM modeling framework accounts for emissions of criteria air pollutants (SO_2, NO_x, and particulates), major air toxics (especially mercury), CO_2 and other greenhouse gases, and all system solid wastes or byproducts. In particular, the interactions among technologies designed to control individual pollutants are addressed. The effects of such interactions are illustrated in a few examples below.

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[98] These sorbents have been tested with superior results compared to PAC for flue gas conditions in semi-dry adsorber systems (80°C). Their application in high temperature duct injection conditions has not yet been tested.
[99] At mercury control costs of 1.79 mills/kWh for the oxidant-enriched silicate sorbent and 0.36 mills/kWh for the oxidant-enriched lime sorbent.
[100] A 100-MWe boiler firing low-sulfur bituminous coal that has a capacity factor of 65% was used in the modeling. The costs were calculated for a mercury removal of 80%. The sorbent costs for PAC, oxidant-enriched silicate sorbents, and oxidant-enriched lime sorbents were assumed to be $1.00/kg, $0.20/kg, and $0.13/kg respectively.
[101] These are the requirements under Acid Rain (CAA Title IV, for SO2), Ozone (CAA Title I for ozone precursors including NOx) and requirements for PM to meet federal opacity requirements. There are also state requirements for opacity.

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