

# **Controlling Multiple Emissions from Coal-fired Power Plants**

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Reynaldo Forte, U.S. Environmental Protection Agency, Clean Air Markets Division, Washington, DC 20460

Ravi K. Srivastava, U.S. Environmental Protection Agency, National Risk Management Research Laboratory, Research Triangle Park, NC 27711

E. Stratos Tavoulares, Energy Technologies Enterprises Corp., 1112 Towlston Rd., McLean, VA 22102

Rui Afonso, Energy and Environmental Strategies, 50 Old Faith Road, Shrewsbury, MA 01545

Wojciech Jozewicz and Michiel Doorn, ARCADIS Geraghty & Miller, P.O. Box 13109, Research Triangle Park, NC 27709

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## **ABSTRACT**

Technologies capable of simultaneously controlling multiple pollutants of emissions from electric utility sources can be quite beneficial. Such technologies can provide options for meeting numerous regulatory requirements and, in some cases, represent the only practical method of providing the necessary environmental benefits. For example, in a constrained plant layout, application of a particular multipollutant control technology may be the only viable option. In addition, a multipollutant control system may be capable of operating with a lower energy requirement than a traditional one using a series of controls in succession, each targeting a different pollutant.

This paper presents and analyzes nine existing and novel control technologies designed to achieve multipollutant emissions reductions. It provides an evaluation of multipollutant emission control technologies that are potentially available for coal-fired power plants of 25 megawatts (MW) capacity or larger in the United States. Some of these technologies are combinations of commercial technologies that are being used to control at least one pollutant while others are under development with the specific goal of controlling multiple pollutants. Issues related to cost, byproduct management, residue or waste disposal, and scaleup are currently being addressed to make these technologies more cost-effective and broadly applicable.

The paper primarily addresses technologies that are capable of simultaneously controlling nitrogen oxides (NO<sub>x</sub>), sulfur dioxide (SO<sub>2</sub>), and mercury emissions from electric utility sources. Technologies that are capable of simultaneously controlling SO<sub>2</sub> and mercury are also addressed because of high interest in controlling mercury emissions. The information provided for each

technology includes: a brief technology description, the level of commercial readiness and industrial experience, and emission control performance. Three of the evaluated control technologies are capable of achieving simultaneous reductions of SO<sub>2</sub>, NO<sub>x</sub>, and mercury and show potential to achieve above 80 % reductions of all three pollutants.

## **INTRODUCTION**

Recent changes in the structure of the electric utility industry -- including the shift towards restructuring, the growing demand for electricity generation, and environmental needs -- are driving additional reductions of multiple pollutants. Historically, industry has developed and implemented control technologies in incremental steps to mitigate emissions of sulfur dioxide (SO<sub>2</sub>), nitrogen oxides (NO<sub>x</sub>), particulate matter, and other pollutants, as driven by air pollution requirements. Control technologies that are capable of simultaneously reducing emissions of multiple pollutants may offer the potential to achieve this at lower cost and reduced footprint when compared to conventional controls.

This paper presents and analyzes various control technologies designed to achieve multi-pollutant emissions reductions. Having up-front knowledge of environmental performance, cost, and limitations of multipollutant control technologies can help power companies select effective and less expensive compliance strategies at individual plants, compared with compliance choices made when the requirements are addressed individually.

## **BACKGROUND**

Electricity is critical to the functioning of residential, commercial, and industrial sectors in the U.S. More than 3,170 traditional electric utility plants and 2,110 non-utility power plants are responsible for ensuring an adequate and reliable source of electricity to consumers in their service territories<sup>1</sup>. While electricity plays a critical role in sustaining the Nation's economic growth, the unintended byproducts of electricity generation can have an undesirable effect on the environment and public health. Most of these health impacts result from emissions produced through the combustion of fossil fuels (coal, oil, and natural gas) which supply about 70 % of the Nation's requirements for electricity generation.

As a result, power plants are currently required to reduce emissions of NO<sub>x</sub> and SO<sub>2</sub>. The revision of the National Ambient Air Quality Standards (NAAQS) for particulate matter (PM) and ozone may also affect power plant emissions. These revisions may require electric utility sources to adopt control measures designed to reduce concentrations of fine (less than 10 μm in diameter) PM in the atmosphere. In addition, the U.S. Environmental Protection Agency (EPA) has recently determined that regulation of mercury emissions from these sources is appropriate and necessary. Concurrently, legislation has been proposed in both the previous and current Congresses that would require simultaneous reductions of multiple emissions, and the Administration's National Energy Policy<sup>2</sup> recommends the establishment of "mandatory reduction targets for emissions of three main pollutants: sulfur dioxide, nitrogen oxides and mercury." On February 14, 2002, President Bush proposed a far-reaching effort to decrease power plant emissions, the Clear Skies Initiative. This proposal is intended to aggressively reduce air pollution from electricity generators and improve air quality throughout the Country. The Clear Skies Initiative<sup>3</sup> is designed to decrease air pollution by 70 %, using a proven, market-

based approach that could save consumers millions of dollars. The Clear Skies Initiative calls for:

- Decreasing SO<sub>2</sub> emissions by 73 %, from current emissions of 11 million tons to a cap of 4.5 million tons in 2010, and 3 million tons in 2018,
- Decreasing NO<sub>x</sub> emissions by 67 %, from current emissions of 5 million tons to a cap of 2.1 million tons in 2008, and to 1.7 million tons in 2018, and
- Decreasing mercury emissions by 69 % by implementing the first-ever national cap on mercury emissions. Emissions will be cut from current emissions of 48 tons to a cap of 26 tons in 2010, and 15 tons in 2018.

This paper focuses on control technologies that promise to simultaneously control NO<sub>x</sub>, SO<sub>2</sub>, and mercury emissions from coal-fired power plants since these plants generate slightly over 50 % of the electricity generated in the United States. The coal-burning electric power industry is a major source of various air pollutant emissions including SO<sub>2</sub>, NO<sub>x</sub>, and mercury. During 1998, fuel-combustion electric utilities contributed 67 % of the total SO<sub>2</sub>, 25 % of the NO<sub>x</sub>, and 35 % of the mercury emitted. <sup>4</sup>

## **DEFINITION OF MULTIPOLLUTANT CONTROL TECHNOLOGIES**

This paper describes the technologies identified as multipollutant control technologies and which have reached a stage of development beyond pilot scale. Multipollutant control technologies are defined as options which integrate *in-situ* and/or post-combustion controls of at least two of the SO<sub>2</sub>, NO<sub>x</sub>, and mercury pollutants, either in one process or a combination of coordinated and complementary (synergistic) processes. In addition to the above definition, two other criteria are applied in selecting the technologies described in this paper. These are: (1) there should be at least one installation in operation in a power plant worldwide as of July 1, 2001, and (2) while it is acceptable for the technology to be used even in a slipstream (not the entire power plant), the size of the technology installation should be at least 5 MW or equivalent.

Using the above definition and criteria, a literature search was performed (using technical papers from conferences, the internet, technical reports by organizations such as Department of Energy (DOE), EPA, Electric Power Research Institute (EPRI), and contacting vendors and utilities) and the technologies were identified. The gathered information was analyzed based on the review criteria and findings summarized in this paper. The paper describes post-combustion controls (environmental control options) with a focus on technologies capable of simultaneously reducing SO<sub>2</sub>, NO<sub>x</sub>, and mercury emissions. A limited discussion of processes for the control of SO<sub>2</sub> and mercury emissions is also included because of the significant role they may play in controlling mercury from existing power plants. Wherever possible, for each SO<sub>2</sub>-NO<sub>x</sub>-mercury technology presented in the paper, the following information is provided: a brief technology description, commercial readiness and industry experience, the emission control performance, and issues and barriers associated with the technology.

## **SIMULTANEOUS SO<sub>2</sub>, NO<sub>x</sub>, AND MERCURY CONTROL**

The results of the literature search and assessment revealed three technologies capable of simultaneously reducing SO<sub>2</sub>, NO<sub>x</sub>, and mercury emissions: 1) Activated Coke, 2) Electro-Catalytic Oxidation, and 3) SCR and Wet FGD. These technologies are discussed in the ensuing section of the paper.

### **Activated Coke**

The activated coke process<sup>5</sup> involves three steps: 1) adsorption, 2) desorption, and 3) (optional) by-product recovery. In the first step (adsorption), flue gas passes through a bed of activated coke moving downwards in a two-stage adsorber at a constant flow rate. The porous activated coke consists of carbon with large surface area. In the first stage, SO<sub>2</sub> is removed by adsorption into the activated coke where it forms sulfuric acid (H<sub>2</sub>SO<sub>4</sub>) and is maintained in the coke inner surface at temperatures of 100 to 200 °C (212 to 392 °F). The adsorber acts also as a particulate control device, reducing particulates below 0.012 grain/scf when the inlet is kept below 0.207 grain/scf. In the second stage of the adsorption process, the activated coke acts as a catalyst in the decomposition of NO<sub>x</sub> to nitrogen and water with injection of ammonia (NH<sub>3</sub>) in the activated coke bed. The chemical reaction occurs in the 100 to 200 °C (212 to 392 °F) temperature range.

As the activated coke is loaded with H<sub>2</sub>SO<sub>4</sub>, its adsorption capacity declines. Further, unreacted NH<sub>3</sub> reacts with H<sub>2</sub>SO<sub>4</sub> to form ammonium sulfate [(NH<sub>4</sub>)<sub>2</sub>SO<sub>4</sub>]. To regenerate the activated coke, it is conveyed by a bucket elevator to a desorber where the (NH<sub>4</sub>)<sub>2</sub>SO<sub>4</sub> is heated up and decomposed to nitrogen, SO<sub>2</sub>, and water. The reactions take place in the 300 to 500 °C (572 to 932 °F) temperature range. After cooling, the activated coke passes through a vibrating screen to eliminate smaller particles (fines) and then is recycled back into the adsorber. Fines are returned the boiler as fuel for combustion. SO<sub>2</sub>-rich gas can be reduced to hydrogen sulfide (H<sub>2</sub>S) in a reduction column and then to elemental sulfur in a Claus unit. Alternatively, the process can produce H<sub>2</sub>SO<sub>4</sub>.

Mercury can be removed also by adsorption. Once adsorbed on the coke, mercury must be collected in a form suitable for disposal. One method proposed is the use of a selenium filter, which absorbs the mercury from the flue gas and forms mercuric selenide (HgSe), a chemically stable compound. The selenium filter is considered commercial and is expected to have 98 % Hg collection efficiency during the filter life (usually 4-5 years). Once spent, the selenium filter has to be disposed of in a hazardous waste facility. Other methods of mercury removal/disposal are also considered, but none has been tested yet.

Activated coke is a carbonaceous material produced by steam activation at approximately 900 °C (1,650 °F). It has high mechanical strength against abrasion and crushing. Its surface area is 150-250 m<sup>2</sup>/g, less than conventional activated carbon but much higher than metallurgical coal.

The process is commercially available in Japan and Germany. It was originally developed by Deutsche Montan Technologie and demonstrated at a 93,000 SCFM plant, the Kellerman generating station of STEAG GmbH. Mitsui Mining Co., Ltd. of Japan (Mitsui) obtained a license from Deutsche Montan Technologie and tested it in a pilot facility from 1981 to 1983<sup>6</sup>. Installations of the Mitsui activated coke process in Japan<sup>7,8</sup> and Germany include (designed for both SO<sub>2</sub> and NO<sub>x</sub> control unless otherwise indicated):

- 18,700 scfm at Mitsui's power generating station (1984).
- 124,500 scfm at Idemitsu Kosan's refinery on a residual fluidized-bed catalytic cracking process (1987).
- 280,000 and 404,600 scfm boilers at EVO GmbH's Arzberg power station in Germany (1987).
- 404,600 scfm at Hoechst AG's power station in Frankfurt, Germany (1989).
- 10,000 scfm at Electric Power Development Corp.'s Wakamatsu power station (1990).
- 1,163,000 scfm (350 MW) Atmospheric Fluidized-Bed Combustion (AFBC) boiler at Electric Power Development Corp.'s Takehara power station (1995). This facility, designed only for NO<sub>x</sub> reduction, achieved above 80 % NO<sub>x</sub> reduction.
- 2,000,000 scfm (600 MW) power plant (Electric Power Development Corp.'s Isogo station) burning low-sulfur Australian coal. The Activated Coke (AC) process is designed for 95 % SO<sub>2</sub> removal; no NO<sub>x</sub> reduction was sought.

SO<sub>2</sub> control efficiency has ranged from 90 to 98 %, and NO<sub>x</sub> control efficiency 60 to 80 %<sup>7, 8</sup>. NO<sub>x</sub> reduction is higher for lower SO<sub>2</sub> concentrations at the inlet of the adsorber; for example, 1000 ppm SO<sub>2</sub> concentration may result in NO<sub>x</sub> reduction in the 35-40 % range, while 200 ppm SO<sub>2</sub> concentration will raise NO<sub>x</sub> reduction to above 70 %. NO<sub>x</sub> reduction is also affected by the amount of ammonia (NH<sub>3</sub>) injected (a NH<sub>3</sub>/NO<sub>x</sub> ratio typically in the 0.5-1.0 range results in above 70 % NO<sub>x</sub> reduction), the oxygen (O<sub>2</sub>) concentration of the flue gas (lower excess O<sub>2</sub> results in lower NO<sub>x</sub> reduction), and the inlet gas temperature. Based on pilot-scale tests carried out by Mitsui, 90-99 % mercury removal is projected. These tests resulted in 99+ % mercury reduction at operating temperatures of 150 to 180 °C (302 to 356 °F).

The main issue associated with this technology is the high cost of activated coke. Also, during start-up, it takes longer to bring up the temperature in the DeNO<sub>x</sub> system. Therefore, NO<sub>x</sub> reduction in cycling units may suffer during start-up unless they are designed to utilize an external heat source to prepare the DeNO<sub>x</sub> reactor.

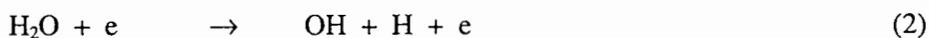
### **Electro-Catalytic Oxidation<sup>TM</sup>**

The Electro-Catalytic Oxidation (ECO) process<sup>9</sup> treats flue gas in three steps to achieve multi-pollutant removal. First, a majority of the ash in the flue gas stream is removed in a conventional dry ESP. Following the ESP, a barrier discharge reactor oxidizes the gaseous pollutants to higher oxides. For example, nitric oxide (NO) is reacted to form nitric acid (HNO<sub>3</sub>), SO<sub>2</sub> is converted to H<sub>2</sub>SO<sub>4</sub>, and mercury is oxidized to mercuric oxide (HgO). Products of the oxidation process are then captured in a wet electrostatic precipitator (WESP) that also collects fine particulate matter. Liquid effluent from the WESP may be treated to remove collected ash then delivered to a system to produce concentrated H<sub>2</sub>SO<sub>4</sub> and HNO<sub>3</sub> for sale. The ECO system is designed to be retrofitted into the last fields of an existing ESP. If the ESP does not have adequate space to fit

the ECO system, some or all components could be built downstream of the ESP. In the latter case, the downtime of the plant is reduced, but additional space (footprint) is needed. The H<sub>2</sub>SO<sub>4</sub> and HNO<sub>3</sub> produced and captured in the WESP effluent can be made into salable byproducts such as concentrated acids, gypsum, or fertilizer.

Oxidation of gaseous pollutants in the barrier discharge reactor is the key component of the ECO process. Oxidation is accomplished through generation of a non-thermal discharge or plasma. In a dielectric barrier discharge, energetic electrons are produced throughout the reactor without heating the gas stream to high temperatures, requiring less energy (about 5 % of the gross electricity output) than plasma discharges. Dielectric barrier discharges can be operated over a wide range of temperatures and pressures and have been widely used for commercial ozone (O<sub>3</sub>) generation<sup>10-13</sup>.

To form a barrier discharge, a dielectric insulating material is placed between two discharge electrodes. Typically, the material has a high dielectric strength and high dielectric constant (e.g., glass or ceramic) and covers one of the two electrodes. High voltage applied to the electrodes causes the gas in the gap to break down. Presence of the dielectric barrier prevents this breakdown from forming an arc with its resulting energy consumption. Instead, breakdown is in an array of thin filament current pulses or “microdischarges.” They are well distributed spatially over the discharge gap. Typical duration of a microdischarge is of the order of a few nanoseconds, and electron energies range from 1 to 10 electron volts. The electron energies formed in the microdischarge are ideal for generating gas-phase radicals, such as hydroxyl (OH) and atomic oxygen (O), through collision of electrons with water and oxygen molecules present in the flue gas stream, as shown in Equations (1) through (3):



In a flue gas stream, these radicals simultaneously oxidize NO<sub>x</sub>, SO<sub>2</sub>, and Hg to form HNO<sub>3</sub> and NO<sub>2</sub>, H<sub>2</sub>SO<sub>4</sub>, and HgO, respectively. The above reactions leading to radical formation and the subsequent oxidation reactions can be made to occur at low temperatures, 65 to 150 °C (150 to 300 °F).

Presence of a dielectric barrier allows for several possible electrode configurations, including coaxial cylinders, cylindrical electrodes with plates, and parallel plate electrodes. Different reactor designs have little effect on overall conversion efficiency. This allows for spacing that reduces the potential for plugging of the reactor and results in a minimal pressure drop across the reactor. Aerosols formed by the oxidation reactions, including HgO, HNO<sub>3</sub>, and H<sub>2</sub>SO<sub>4</sub>, exit the barrier discharge reactor in the flue gas stream. At this point, the gas enters a condensing WESP where aerosols, fine particulate matter, and other air toxic compounds are collected.

The byproducts of the ECO process are raw sulfur,  $\text{HNO}_3$ , and  $\text{H}_2\text{SO}_4$ , which can be used to produce fertilizer and gypsum. Of course, the extent to which these by-products would be actually used depends on economics (supply and demand of competing products) in the local market (around the power plant).

The technology is in the demonstration stage. It was originally tested at laboratory scale (1 and 100 scfm). Then, it was tested at pilot scale at First Energy's R.E. Burger #5 unit<sup>14, 15</sup> (a 156-MW unit), where a slipstream of 2000-4000 scfm (equivalent to approximately 2 MW) was used to assess the performance of the ECO process. The pilot-scale tests were carried out in early 2000. Presently, a demonstration project is planned at First Energy's R.E. Burger plant. The technology will be tested at a slipstream (110,000 scfm or 7.4 % of the total flue gas) of equivalent 50 MW scale. The first results from this demonstration project are expected in late 2002.

At First Energy's R.E. Burger station (2 MW pilot scale), the technology achieved 76, 44, and 68-82 % of  $\text{NO}_x$ ,  $\text{SO}_2$ , and mercury emission reduction, respectively<sup>16</sup>. Also measured were 88 % hydrochloric acid (HCl) reduction and 96-97 % removal of PM with aerodynamic diameters of less than  $2.5 \mu\text{m}$  ( $\text{PM}_{2.5}$ ). These results were achieved with 337 ppm  $\text{NO}_x$  in the inlet of the ECO system, approximately 40% higher than in a similar installation with low  $\text{NO}_x$  burners. The demonstration at Eastlake 5 (50 MW) is projected (by Powerspan Corp.) to achieve 70, 40-50, and 70+ %  $\text{NO}_x$ ,  $\text{SO}_2$ , and mercury emission reduction, respectively, in addition to 90 %  $\text{PM}_{2.5}$  removal.

As the process is scaled up, the main uncertainty is whether it can achieve the performance (emission reduction), which was achieved at smaller scale. Additionally, the estimated energy consumption of the ECO system is expected to be 5 % of the gross energy production at the plant. Finally, some uncertainty exists with regard to the salability of the byproducts in terms of both their suitability (meeting market specifications) and price.

## **SCR + Wet FGD**

The contribution of selective catalytic reduction (SCR) technology to mercury reduction originates from the fact that SCRs have been shown to oxidize elemental mercury. Hence, the synergism with wet scrubbers, which are effective in capturing oxidized mercury. Both SCR and wet scrubber [wet flue gas desulfurization (FGD)] technologies are discussed below.

**SCR –  $\text{NO}_x$  Control.** SCR technology<sup>17</sup> reduces  $\text{NO}_x$  through a catalytically enhanced reaction of  $\text{NO}_x$  with ammonia, reducing  $\text{NO}_x$  to water and nitrogen. This reaction takes place on the surface of a catalyst, which is "housed" in a "reactor" vessel. The reactor ensures that the flue gas is uniformly distributed over the catalyst as well as determining the flue gas velocity. Typical catalyst materials are titanium/vanadium on a "coated" substrate structure that may take various forms (e.g., plate, honeycomb). SCR system configurations are generally referred to by the location of the SCR relative to the power plant:

- "high-dust" – SCR located between the economizer and air preheater, upstream of the ESP.
- "low-dust" – SCR located between a hot-side ESP and the air preheater.

- “tail-end” – SCR located after the air preheater, ESP, and FGD. This approach requires the flue gas to be reheated prior to entering the SCR.

Ammonia (anhydrous or aqueous) is injected into the flue gas upstream of the SCR reactor through a nozzle grid designed to ensure its uniform distribution in the flue gas and then through the catalyst.

**Wet FGD.** Wet FGD refers to the most widely used SO<sub>2</sub> control technology worldwide (approximately 200 GW of installed capacity)<sup>18</sup>. The most commonly used FGD technology uses a wet limestone scrubber with *in-situ* forced oxidation to remove SO<sub>2</sub> from the flue gas while producing a gypsum-grade byproduct. This is accomplished typically in a vertical vessel, with flue gas contacting and reacting with limestone slurry to produce calcium sulfite/sulfate. Through controlled oxidation of the reaction products, a salable byproduct in the form of commercial grade gypsum may be produced. The intimate contact between gas and liquid is ensured through different design approaches, usually involving several counterflow spray levels and mass transfer “trays” to optimize gas/liquid interactions. The technology has evolved over the years through “mechanical” improvements, which have included better gas and liquid distribution within the scrubber, droplet size and size distribution, as well as “chemistry” improvements such as the addition of organic acids (e.g., adipic acid, a dibasic organic acid, DBA), which not only improve overall SO<sub>2</sub> capture but also help the settling characteristics of the waste products. Several commercial variations of the technology exist based on reagent type, vessel design, etc.

Both technologies, SCR and wet FGD, are widely used commercially worldwide. In Germany, for example, essentially all coal-fired boilers are equipped with SCR technology combined with wet scrubbers. Over 50,000 MW of capacity is deployed worldwide. In the U.S., the technology is being deployed at a rapid pace.<sup>19</sup> Therefore, both SCR (for NO<sub>x</sub> control) and wet scrubbers (for SO<sub>2</sub> control) are readily commercially available.

As indicated before, the contribution of SCR technology to mercury reduction comes from the fact that SCRs have been shown to oxidize elemental mercury. With respect to SCR performance on mercury oxidation, testing is on-going at pilot- and full-scale sites<sup>20-23</sup>. Efforts by B&W<sup>20, 22</sup> and EPRI<sup>21</sup> are examples of pilot-scale activities. Full-scale testing is taking place at various sites as well<sup>23, 24</sup>. The intense gas/liquid mass transfer, combined with the fact that oxidized vapor-phase mercury is water-soluble (elemental mercury is not), is what allows wet scrubbers to be, potentially, an excellent means of mercury control.

SCR systems are widely used in conjunction with wet FGD technology, and the combination has yielded total mercury capture exceeding 80 %<sup>22, 24</sup>. In tests conducted at Grosskraftwerk Mannheim AG in Germany, mercury oxidation across the SCR increased HgCl<sub>2</sub> content in the flue gas from 77 to 95 %<sup>23</sup>. Results from tests at B&W indicated that oxidized mercury increased from 50.9 to 93.4 % in the presence of the SCR catalyst at typical SCR temperatures while, at lower (air preheater outlet) temperatures, oxidized mercury levels rose from 81.9 to 94.1 %<sup>20</sup>.

EPRI-sponsored pilot- and full-scale tests<sup>21</sup> showed a significant variation in results, suggesting that the fundamental mechanisms of mercury oxidation across the SCR catalyst may not be fully understood. Table 1 summarizes some of the results.

Studying mercury oxidation has become a focus in efforts to enhance SCR and, in turn, wet FGD technology. Further testing on the speciation of mercury must be conducted to gain a better understanding of oxidation potential, oxidation vs. catalyst age, as well as fundamental mechanisms. As SCR and wet FGD technologies are increasingly combined for NO<sub>x</sub>/SO<sub>2</sub> reduction, efforts to increase our knowledge and improve the ability of the SCR to oxidize elemental mercury will result in a significant and inexpensive way to also control mercury emissions.

Table 1. Selected SCR Test Results.

Control Unit	Control Unit-Status	Inlet Mercury Oxidation (% of total)	Outlet Mercury Oxidation (% of total)
Pilot SCR	No ammonia	8-12	2-10
Full-scale SCR	Normal	10-18	4-7
Full-scale SCR	No ammonia	10-18	50
NH <sub>3</sub> injection system	Normal	50-87	67-85
NH <sub>3</sub> injection system	No ammonia	50-87	70-90

## SIMULTANEOUS SO<sub>2</sub> AND MERCURY CONTROL

Dry scrubbers, advanced dry FGD systems, sorbent injection, modified wet FGD, and a wet FGD/WESP combination can control SO<sub>2</sub> and mercury simultaneously. These technologies are discussed below.

### Dry Scrubbers

Dry scrubbers (spray dryers) are capable of reducing multiple pollutants (specifically SO<sub>2</sub> and mercury) and are typically used in low- to medium-sulfur coal-fired power plants. "Dry" refers to the fact that the flue gas leaving the scrubber is *not* saturated as in wet FGD (wet scrubbers). The technology is suitable for new and retrofit applications. Spray dryers have been installed on utility and industrial boilers, as well as hazardous and municipal waste incinerators.

In addition to SO<sub>2</sub>, spray dryers have been shown to reduce mercury in the flue gas<sup>25-27</sup>. In this case, the more complex chemistry and speciation forms of the mercury make it more difficult to fully understand the processes and reactions that take place. However, flyash, lime, and activated-carbon-based sorbents all provide varying degrees of affinity to adsorb vapor-phase mercury present in the flue gas.

This technology, while predominantly used on low- and medium-sulfur coals, can be applied to plants burning higher-sulfur coal as well, although this may be limited by the capacity of the existing particulate control device (in retrofit situations) to accommodate the increase in particulate loading (the quantity of sorbent is proportional to the SO<sub>2</sub> concentration and the desired reduction sought, therefore increases with higher sulfur and reductions required). The quantity of sorbent for a given application is typically referred to in terms of calcium-to-sulfur ratio or stoichiometry and ranges from about 1.0 to 2.0 for SO<sub>2</sub> removals of 75 to 90+ %. Spray dryers are a commercial and well-established technology in the U.S. and abroad, with over 11,000 and 7,000 MW of installed capacity, respectively<sup>18</sup>. The technology was first used in the early 1980s, and has been deployed in bituminous, subbituminous, and lignite applications. Significant experience was gained in the U.S. through extensive testing programs<sup>28</sup>.

Spray dryers are capable of very high SO<sub>2</sub> reductions (up to 95 %). Data from the International Energy Agency's (IEA's) coal research indicates SO<sub>2</sub> reductions from 70 to 96 % with a median value of 90 %, comparable to that of wet FGD technology. This performance reflects applications with coals of less than 2 % sulfur<sup>18</sup>. Information and experience with mercury is less available than for SO<sub>2</sub>. However, a number of test programs as well as the recent EPA's Mercury Information Collection Request (ICR) program have yielded some insight into the potential mercury reductions in spray dryers<sup>25-27</sup>. It is important to recognize that the performance of the spray dryers is typically reported together with the associated particulate control device [ESP or fabric filter (FF)]. In other words, mercury reductions are reported from the inlet to the spray dryer to the outlet of the ESP or FF. In a 1994 study<sup>29</sup>, spray dryers captured mercury in a wide but not fully understood range (6-96 %), based on data for seven installations on coal-fired power plants. Although at that time, mercury speciation was not measured, the amount of mercury removal increased with coal chlorine content, suggesting that spray dryers preferentially remove oxidized mercury. The wide range in the reduction values indicates a lack of understanding of basic physical and chemical processes taking place in the control devices.

The efficiency of mercury removal by dry scrubbers is related to mercury speciation, as well as a number of other factors. Additional information on mercury speciation and operating parameters in spray dryer power plants is necessary to better understand and predict mercury reduction performance. "Dedicated" mercury sorbents such as activated carbon should increase mercury capture potential.

### **Advanced Dry FGD**

Advances in dry scrubbing technology have focused on the general concept of increasing gas/solids mixing, hence reducing residence times in the absorber and allowing for more rapid evaporative cooling (1-2 vs. about 10 seconds in the conventional spray dryer). From a configuration perspective, these designs for the most part, represent variations of Circulating Fluid Bed (CFB) technology with differentiating design features specific to each vendor. As in conventional spray dryers, lime slurry or hydrated lime is the typical sorbent used. A generic description is presented below, followed by brief descriptions of specific technologies offered by the major vendors. They include Circulating Dry Scrubbing (CDS) offered by LURGI, Gas Suspension Absorbers (GSAs) by FLS Miljo, Reflux Circulating Fluidized-Bed absorbers

(RCFBs) by WULFF GmbH, and the Rapid Absorption Process (RAP) by Beaumont Environmental.

The CFB absorber is a vertical reactor where a dense material bed of recycle products (ash and sorbent) ensures high gas/solids contact and more rapid cooling. The flue gas flows up through the bed, with sorbent typically being sprayed in a slurry into the gas upstream of the bed. CDS-LURGI technology uses a circulating fluid bed to establish a zone of high particle density. The technology is used with hydrated lime injection for control of acid gases, and the bed is enhanced with activated carbon for mercury adsorption<sup>30-32</sup>. GSA uses a cyclone to recycle products into a dense bed, which allows for rapid evaporative cooling as with the other technologies<sup>33,34</sup>. Flue gas from the boiler flows directly into the bottom of the GSA vessel. Simultaneously, a lime-slaked slurry is atomized into the reactor, flowing upward with the flue gas. The RCFB introduces an internal reflux within the circulating fluidized-bed designed to increase the gas/solid mixing and sorbent residence time<sup>35,36</sup>. As with the other technologies, gas temperature is controlled via internal water injection and SO<sub>2</sub> reduction via the amount of sorbent supply. The RAP uses a flash-drying reactor technology combined with an external mixing chamber<sup>37,38</sup>. Differently from circulating fluid beds, lime slurry is introduced into a recycle transfer bin where it is mixed with recycle products, and then introduced into the reactor. Rapid cooling occurs as the products are introduced into the reactor.

While not widely used in the U.S. at present, the four CFB-based technologies are commercial, with installations in the U.S. and abroad. The first commercial CFB installation in the U.S. was deployed on an 80-MW, coal-fired unit. Next, a 55-MW unit was installed, followed by pilot-scale multipollutant control tests on a 321-MW coal-fired boiler. FLS Miljo offers GSA commercially, with over 35 installations worldwide in operation since 1986. WULFF GmbH commercially offers the RCFB. The technology is in full commercial use in plants ranging from 3 to 300 MW for the simultaneous removal of SO<sub>2</sub> and mercury. RAP technology is currently being demonstrated at the Southern Research Institute's (SRI's) combustion test facility. In addition, a full-scale demonstration program at the Medical College of Ohio is currently proceeding.

In general, the advanced scrubbers are capable of 90+ % SO<sub>2</sub> reduction<sup>39,40</sup>. With respect to mercury control, less information is available, but high removal rates have been reported. CFB without activated carbon injection achieved 50% capture of the mercury vapor. Mercury was reduced by 80 % when the CFB was injected with iodine-impregnated activated carbon. For GSA, the results of mercury removal tests ranged from about 41.5 to 89.5 %, without the use of activated carbon. Mercury reduction by RCFB using activated coke is in the 90 % range.

In summary, similar to spray dryers, SO<sub>2</sub> performance is well documented for the CFB-based absorbers. Mercury capture can potentially be up to 90+ %, but is not well understood at present. Opportunity to add "dedicated" mercury sorbent (e.g., activated carbon) will increase overall mercury removal potential.

### **Sorbent Injection Processes**

Sorbent Injection Processes refer to the use of sorbent materials, typically in a powder or slurry form, which are injected into the flue gas upstream of a particulate control device. Inherently,

sorbent injection is directly related to the type of particulate control used with it, as these devices offer additional contact time for the reactions to take place. Sorbent injection technologies received significant “attention” in the U.S. in the 1980s. More recently, the technology has seen renewed interest driven by the need to control emissions of mercury from power plants. Two types of sorbent hold promise for mercury removal: activated carbon and combined SO<sub>2</sub>/mercury sorbents.

*Activated Carbon for Mercury Control.* The most commonly studied sorbent for mercury control has been activated carbon. Commercially, activated carbons are available in a range of particle sizes, as well as other performance characteristics<sup>41</sup> such as capacity and reactivity. Furthermore, special activated carbon products, such as iodine- and sulfur-impregnated, are also available and have been studied<sup>42,43</sup>. DOE is currently sponsoring a full-scale demonstration of activated carbon injection, which is scheduled for completion in 2003. The overall performance of the technology is a function of many factors, including sorbent characteristics, as well as plant configuration and operating conditions. Reduction levels from 50 to 90 % are possible and anticipated for the range of technology configurations and activated carbons available. One potential issue associated with activated carbon injection may be the deployment of new kilns and furnaces that would be necessary to increase the production of activated carbon to meet the potential market for coal-fired boilers. The current market for activated carbon is 250,000 tons/yr. Once mercury regulations are fully implemented, this could increase the demand to 2-3 million tons/yr.

*Combined Mercury and SO<sub>2</sub> Sorbents.* The technologies for combined mercury/SO<sub>2</sub> and/or multi-pollutant sorbent injection involve the same approaches described in the previous sections, while using a combination of sorbents (e.g., activated carbon plus hydrated lime) or single, multi-pollutant-capability sorbents. Pilot test programs have<sup>44-45</sup> documented the performance of combined sorbents (activated carbon plus hydrated lime). Combining activated carbon with hydrated lime can reduce the amount of carbon required (for an equivalent mercury removal) by 35 to 50%. Pilot tests of limestone furnace injection, followed by a cyclone separator, also showed good removal of mercury from flue gas in a pilot-scale unit burning eastern bituminous coals<sup>46</sup>. Much laboratory activity has focused on the development of novel and enhanced sorbents<sup>47,48</sup>. Based on this experience, sorbent injection technology for combined SO<sub>2</sub>-mercury reduction represents a viable, although not fully quantified, approach for multipollutant control.

Laboratory investigations of calcium-based sorbents for mercury control<sup>47,49</sup> have shed light on the mechanisms involved, offering the potential for more efficient use of such sorbents across a range of applications. Fly ash, hydrated lime, ADVACATE™, and all calcium-based sorbents captured mercuric chloride (HgCl<sub>2</sub>) from simulated flue gas at 100 °C (212 °F) (although less than commercial activated carbon). Addition of SO<sub>2</sub> to the gas mixture decreased the sorption of HgCl<sub>2</sub>, suggesting that there is competition for the same alkaline sites between the two species. In contrast, the calcium-based sorbents showed little or no removal of elemental mercury (Hg<sup>0</sup>) in the absence of SO<sub>2</sub>. Addition of SO<sub>2</sub> to the gas greatly enhanced the uptake of Hg<sup>0</sup>, suggesting the possibility of some chemical reaction on the surface. More recently, hydrated lime and silicates have been evaluated for mercury, NO<sub>x</sub>, and SO<sub>2</sub> capture in bench-scale tests. Oxidant-enhanced silicate sorbents indicated enhanced mercury capture. The practical significance of these results is that it is possibly more effective to separate the injection of sorbents dedicated to

bulk acid gas removal (lower cost alkaline sorbents), from the higher porosity, oxidant-enhanced sorbents for mercury control<sup>47,48</sup>. Unfortunately, while these studies offer a great deal of new understanding about the chemical and physical interactions between the flue gas, mercury, and sorbent, the results cannot yet be directly translated to full-scale performance.

Pilot scale testing<sup>44,47</sup> with activated carbon, sodium, and calcium sorbents in a COHPAC/TOXECON configuration has shown the ability to inject activated carbon simultaneously with other sorbents. Activated carbon performance was enhanced when tested with hydrated lime. Similar mercury capture of 80+ % was obtained with much lower levels of activated carbon when combined with hydrated lime.

### **Wet FGD Processes**

As discussed earlier, wet FGD is the most widely used SO<sub>2</sub> control technology in the World. Therefore, the fact that wet-FGD has been shown to be efficient in capturing oxidized mercury in the flue gas<sup>50-54</sup> is significant. This fact has triggered a number of developments geared towards understanding and promoting the oxidation of elemental mercury in the flue gas of wet-FGD-equipped plants. These efforts have focused mostly on the catalyst-enhanced oxidation and reagent injection approach for mercury oxidation. In addition, and as a result of developments in WESP and the compatibility of WESPs with wet FGD, the wet scrubber/WESP combination represents another system approach to combined SO<sub>2</sub> and mercury capture, as will be discussed later. Because these various processes are predicated on well-known, conventional, and widely used FGD technology, only the “add-on” technology components are discussed here.

The two major areas of development underway in the area of mercury oxidation in the flue gas, upstream of wet scrubbers, involve catalytic oxidation<sup>52,54</sup> and oxidation resulting from reagent injection<sup>53,55</sup>. The catalytic oxidation approach involves the deployment of a catalyst in the flue gas to oxidize elemental mercury. While catalyst development and testing is at the laboratory scale, full-scale application would likely involve a conventional support structure (e.g., honeycomb) placed between the particulate control device and the wet scrubber. A number of catalyst materials have been investigated at several test sites including carbon, palladium, iron, and high carbon flyash<sup>55</sup> with varying degrees of success.

Reagent-based oxidation involves the introduction of dedicated reagents into the flue gas or the scrubber itself. In both cases, the objective is to promote the conversion of elemental mercury to an oxidized form. The flue gas injection approach is expected to promote the conversion of HCl to Cl<sub>2</sub> in the flue gas, thereby providing a pathway for the formation of HgCl<sub>2</sub>. The direct scrubber injection approach involves the addition of small amounts of a proprietary reagent into the scrubber recirculation system<sup>53</sup>.

At present, catalytic oxidation is at laboratory and pilot-scale development stages. Tests have identified several catalyst materials successful in oxidizing elemental mercury. Further testing of these catalysts has focused on two issues associated with the catalytic oxidation process: 1) catalyst life, and 2) the applicability of the process for the U.S. electric utility industry<sup>52,54</sup>. Results to date suggest that larger-scale testing is warranted at this time.

In the course of several reagent-based oxidation tests conducted for wet scrubber enhancement, a reagent was found which significantly improved mercury removal while having no negative effects on scrubber operation. The technology is currently being demonstrated on a 55-MW scale and further scale-up of the technology is planned <sup>53</sup>.

In laboratory and pilot-scale catalytic oxidation tests, Hg<sup>0</sup> oxidation was measured in the 70 to 95 % range. In particular, palladium, carbon, and high-carbon flyash-based catalysts, exhibited high levels of performance. Further, tests to address catalyst longevity, while preliminary, indicate that the palladium catalyst (little deactivation at close to 4000 hours), and three of the five tested retained better than 70 % oxidation of the inlet elemental mercury at the end of the 5-month test period <sup>52</sup>. Results from two series of reagent-based oxidation testing indicated that high levels of mercury removal (up to 86 %) were repeatedly achieved with small amounts of proprietary reagents with no adverse effects on scrubber operation or SO<sub>2</sub> removal. This is in comparison to baseline (no reagent) removal of mercury across the scrubber of about 72 % <sup>53</sup>.

### **Wet FGD with WESP**

In the WESP, the collecting surface is cleaned with a liquid, as opposed to mechanical cleaning for ESP. As a result, the two technologies differ in the nature of particles that can be removed, the overall efficiency of removal, and the design and maintenance parameters <sup>56,57</sup>. While dry ESPs are typically limited to power levels of 100-500 W per 1,000 cfm, WESPs can handle power levels as high as 2,000 W per 1,000 cfm. As a result, WESPs can handle a wide variety of pollutants and flue gas conditions and are highly efficient on submicron particles and acid mist. WESPs have also been found to be most efficient in treating flue gases with high moisture content and/or sticky particulate matter. WESPs are compatible with and easily integrated into a system design with a wet FGD. In fact, integration of the WESP *within* the wet scrubber is a design option with many synergisms and attractive features <sup>22</sup> such as: 1) compact footprint, 2) ability to integrate the handling of the wash water and solids from the WESP with scrubber slurry, and 3) ability to collect the fine sulfuric acid mist that typically escapes the scrubber due to its very small droplet size.

Wet ESPs have been used for almost a century as standard technology in abating the submicron particle SO<sub>3</sub> mist in H<sub>2</sub>SO<sub>4</sub> plants. It was until recently, however, a relative unknown technology to the electric power industry. WESP has been retrofitted on Northern States Power Company's Sherco Station in a wet FGD/WESP configuration. In addition, a WESP system was recently installed at Potomac Electric Power Company's Dickerson Generating Station, converting an existing dry ESP to hybrid operation, by replacing the third field of the existing ESP to wet operation <sup>56</sup>. Two more power plant applications are underway: 1) a 5,000 cfm slipstream at Bruce Mansfield Station; and 2) a plate-type WESP for integration with Powerspan's ECO technology to be demonstrated at First Energy's Eastlake Station.

When integrated with upstream technology, including wet scrubbers, multiple pollutants can be removed by WESPs. At a hazardous waste facility, a two-stage WESP following a scrubber achieved 99.9 % removal of all acid gases, dioxins/furans, PM<sub>2.5</sub>, and metals. It achieved 78 % removal of mercury <sup>56,57</sup>. At a mining operation, a combined scrubber and WESP system

achieved an SO<sub>2</sub> removal of 99 %<sup>56,57</sup>. In pilot-scale tests at SRI<sup>58</sup>, a plate-type WESP yielded the following emission reductions: SO<sub>2</sub>, 10-25 %; SO<sub>3</sub>, ~65 %; PM, 90-99 %; and Hg, ~30 %.

Several conditions determine the efficiency of a WESP system and should be considered in each specific design. These include air distribution, sparking, and corona current suppression. Integration with wet scrubbers can offer significant advantages to wet scrubber operations, specifically in H<sub>2</sub>SO<sub>4</sub> mist control. Material performance will be key to overall cost of the technology as expensive alloys may reduce market appeal.

## CONCLUSIONS

This paper presented various existing and novel control technologies designed to achieve multi-pollutant emissions reductions. It provided an evaluation of multipollutant emission control technologies that are available for coal-fired power plants of 25-megawatt (MW) capacity or larger in the United States. The paper primarily addressed technologies that are capable of simultaneously controlling NO<sub>x</sub>, SO<sub>2</sub>, and mercury emissions from electric utility sources. Technologies that are capable of simultaneously controlling SO<sub>2</sub> and mercury were also addressed because of high interest in controlling mercury emissions.

The technology reviews are based on several sources of information including technology vendors, technical papers, expert consultations, reports published by the DOE, and trade publications. The results of this review reveal that:

- The number of technologies under development, demonstration, or already commercially available is significant.
- A number of technologies have been widely used in power plants and/or industrial applications.
- A couple of technologies, which are not commonly used in the U.S., have been used in other countries.
- Three of the evaluated control technologies are capable of achieving simultaneous reductions of SO<sub>2</sub>, NO<sub>x</sub>, and mercury and show potential to achieve above 80 % reductions of all three pollutants.

The environmental control technologies are summarized in Table 2. This summary includes the status of commercialization: pilot (P), demonstration (D), and commercial (C); environmental performance relative to SO<sub>2</sub>, NO<sub>x</sub>, and mercury; and applicability. Some of these technologies are combinations of commercial technologies that are being used to control at least one pollutant, while others are under development with the specific goal of controlling multiple pollutants. Issues related to cost, byproduct management, residue or waste disposal, and scale up are currently being addressed to make these technologies more cost-effective and broadly applicable.

Table 2. Summary of Environmental Control Technologies.

Technology	Status	Emission Reductions	Applicability
<b><u>SO<sub>2</sub>/NO<sub>x</sub>/Mercury Control</u></b>			
Activated Coke	C	SO <sub>2</sub> : 90-98%; NO <sub>x</sub> : 60-80%; Hg: 90-99%	New and retrofit
Electro-Catalytic Oxidation	D	SO <sub>2</sub> : 40-50%; NO <sub>x</sub> : 60-80%; Hg: 70+%	New and retrofit
SCR + Wet FGD	C	SO <sub>2</sub> : 95%; NO <sub>x</sub> : 90-95%; Hg: 86+% (bituminous coals)	Plants with SCR and wet scrubber technologies
<b><u>SO<sub>2</sub>/Mercury Control</u></b>			
Dry Scrubbers (conventional)	C	SO <sub>2</sub> : >95%; Hg: 5- 85%	Low- to medium-sulfur coals
SO <sub>2</sub> Sorbents	P/C	SO <sub>2</sub> : 40-85%; Hg: n/a	Units with ESP or FF for particulate control
Activated Carbon with SO <sub>2</sub> Sorbent Processes	P/C	SO <sub>2</sub> : 40-85%; Hg: n/a	Units with ESP or FF for particulate control
Wet FGD with Mercury Oxidation Processes	P	SO <sub>2</sub> : 95%; Hg: 80+%	Wet scrubber plants
Wet FGD with WESP	C/P	SO <sub>2</sub> : 99%; Hg: 80+%	Integration with wet scrubbers, retrofit dry ESPs, new units
Advanced Dry FGD	P/C	SO <sub>2</sub> : 90-98%; Hg: <90%	Low- to medium-sulfur coals

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## **KEY WORDS**

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16. ABSTRACT The paper presents and analyzes nine existing and novel control technologies designed to achieve multipollutant emissions reductions. It provides an evaluation of multipollutant emission control technologies that are potentially available for coal-fired power plants of 25 MW capacity or larger in the U.S. The paper primarily addresses technologies that are capable of simultaneously controlling nitrogen oxides (NOx), sulfur dioxide (SO2), and mercury emissions from electric utility sources. Technologies that are capable of simultaneously controlling SO2 and mercury are also addressed because of high interest in controlling mercury emissions. Provided for each technology are a brief technology description, the level of commercial readiness and industrial experience, and emission control performance. Three of the evaluated control technologies are capable of simultaneously reducing SO2, NOx, and mercury and show potential to achieve above 80% reductions of all three pollutants. Issues related to cost, byproduct management, residue or waste disposal, and scaleup are currently being addressed to make these technologies more cost effective and broadly applicable.		
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