APPENDIX B: CONTROL TECHNOLOGY DESCRIPTIONS AND COST DATA

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001 Wet Scrubber (General, Not Classified)

For PM Control

Description

This control equipment code applies in situations when the type of scrubber is unknown, different than, or a modification of other wet scrubbers presented in this report.

Application

Wet scrubbers can be applied to a wide variety of emission sources in many industries because they can collect basically any type of dust including flammable, explosive, moist, or sticky dusts. Although scrubbers have many potential applications, there are some limitations to their use. The most significant consideration is the relatively low collection efficiency for fine PM [i.e., <1 micrometers (μm)]. Therefore, conventional scrubbers may not be suitable for controlling flue gas streams with a high concentration of fine PM. Venturi, condensation, and charged scrubbers are the exception to this limitation because they are designed to achieve a high control of fine PM. In addition, the use of wet scrubbers may not be desirable when the collected dust can be recycled or sold as a dry product or when the gas stream contains constituents that will corrode the scrubber. Because of design constraints, wet scrubbers are generally not used to control large gas flow rates [e.g., >60,000 to 75,000 actual cubic feet per minute (cfm)] because large gas flowrates must be controlled with more than one scrubber.

Control Efficiency

AP-42 (EPA, 1995) chapters were reviewed to identify particle size distribution profiles for scrubbers that could be used to calculate control efficiencies for PM and the cumulative mass for particles $\leq$10 μm and $\leq$2.5 μm. A total of 11 particle size distributions were identified for different industries. For 8 of the particle size distributions, AP-42 (EPA, 1995) did not specify the type of scrubber. Three of the particle size distributions are for venturi scrubbers. The PM, PM10, and PM2.5 control efficiencies calculated from the venturi scrubber profiles were within the range of control efficiencies calculated from the 8 profiles for which the type of scrubber was not specified. Thus, all 11 particle size distribution profiles were used in developing the control efficiency ranges for this control equipment code.

For PM, the lowest control efficiency calculated from the 11 profiles was 89.74 percent. For PM10, the lowest control efficiency calculated from the 11 profiles was 68 percent. However, in EPA (1973b), a PM control efficiency of 70 percent was identified for spray chamber scrubbers and 55 percent for tray-type scrubbers. Therefore, 55 percent was selected as the low-end control efficiency for scrubbers in general.

For PM10, no other control efficiency data were identified other than the data provided by the particle size profiles. The low-end PM10 control efficiency was assumed to be the same as those identified for PM. The low-end PM10 control efficiency for scrubbers in general was set at 55 percent, based on the low-end PM efficiency for tray-type scrubbers. The low-end control efficiency for spray chamber scrubbers was set at 70 percent based on the low-end PM control efficiency identified for this type of control

device and also on the lowest control efficiency (which was 68 percent) calculated from the 11 profiles in AP-42 (EPA, 1995).

For PM2.5, the lowest control efficiencies calculated from the profiles were 25, 30, and 50 percent. Given the variability in possible scrubber designs for the wide variety of applications to which scrubbers may be applied, 25 percent was selected as the low-end of the range for PM2.5.

The high-end of the range for PM and PM10 is based on the assumption that scrubber design, operation, and maintenance technology has advanced over the past 20 years such that some types of scrubbers (e.g., venturi, condensation, and charged) could be designed to achieve >99.9 percent control of PM and PM10. For PM2.5, the high-end of the control efficiency range is based on the high-end control efficiency calculated from AP-42 particle size distribution profiles, which is 96.67 percent. This value was rounded to 97 percent. Given that the form of the PM National Ambient Air Quality Standards (NAAQS) is now PM2.5 instead of PM10, it is assumed that vendors will be optimizing scrubber systems to achieve high PM2.5 control efficiencies.

Cost
The average cost per ton of PM controlled is approximately $60,000. This average is derived from data which represents a broad range of applications for this control technology (Pechan, 1995).

For SOx Control

Description
Wet scrubbers are a general category of control device in which, for SO_2 control, a liquid solution or liquid/solid slurry is used to absorb, and, in most cases, react with SO_2 in a waste gas stream. A vessel, into which both the solution or slurry and the waste gas are introduced, is used to maximize the contact between the SO_2 in the waste gas and the reacting compounds in the solution or slurry. The design of the vessel and the manner in which the waste gas and the solution or slurry are introduced to the vessel are the means by which the reagent contact is controlled. Types of wet scrubber designs include: tray-type column, packed-bed column, mobile-bed column, venturi, and spray tower. Reagents used in wet scrubber systems include: calcium oxide (from lime), calcium carbonate (from limestone), magnesium oxide, sodium carbonate (soda ash), sodium hydroxide (caustic), sodium citrate, and ammonium hydroxide. Some wet scrubbing systems use a reagent which can be treated and reused and/or produces a saleable product, while other wet systems require that the spent reagent be treated and disposed of appropriately (EPA, 1981).

Application
Wet scrubbing systems have been the most popular type of FGD system used to control SO_2 in waste gas flows from coal- and oil-fired boilers at utilities and industrial facilities, metal smelters, pulp mills, and other sources of SO_2 (EPA, 1981).

Control Efficiency

The typical control efficiency range is from 50 to >99 percent (EPA, 1981; Sondreal, 1993). The control efficiency is dependent upon the type of wet scrubber system used, the absorbing and/or reacting solution or slurry used, and the concentration of SO_2 in the treated waste gas flow.

Cost

The cost ranges from $300 to $700 per ton SO_2 controlled (Smith, 1994; Radcliffe, 1992; Torrens, 1990).

002 Electrostatic Precipitator (Dry)

Description

Dry ESPs are add-on control devices that are designed to remove PM from the flue gas stream using electrical fields. An intense electric field is maintained between high-voltage discharge electrodes, typically wires or rigid frames, and grounded collecting electrodes, typically plates. An electric discharge from the discharge electrodes ionizes the gas passing through the ESP and gas ions subsequently ionize particles in the gas stream. The electric field drives the negatively charged particles to the collecting electrodes. Because the collection forces act only on the particles, ESPs can treat large volumes of gas with low pressure drops. In a dry ESP, the collecting electrodes are mechanically rapped periodically to dislodge collected PM, which falls into hoppers for removal (STAPPA/ALAPCO, 1996).

The most common ESP designs are wire-plate and wire-pipe collectors, but plate-plate and rigid frame-plate designs are also used. Collecting plates are arranged parallel to the gas flow, normally 9 to 18 inches apart, with discharge electrodes between them.

Most ESPs have three to five independent electrical sections in series. Each independent section removes a fraction of the PM in the gas stream. This arrangement allows the use of higher voltages in the first sections of the ESP, where there is more PM to be removed. Lower voltages must be used in the final, cleaner ESP sections to avoid excessive sparking between the discharge and collecting electrodes (STAPPA/ALAPCO, 1996).

Application

Approximately 80 percent of all ESPs in the United States are used in the electric utility industry. Many ESPs are also used in pulp and paper (7 percent), cement and other minerals (3 percent), iron and steel (3 percent), and nonferrous metals (1 percent) industries (Cooper and Alley, 1994). The dust characteristics can be limiting factors in the applicability of dry ESPs to various industrial operations. Sticky or moist particles and mists can be easily collected but often prove difficult to remove from the collection electrodes of dry ESPs. Dusts with very high resistivities are also not well-suited for collection in dry ESPs. Dry ESPs are susceptible to explosion in applications where flammable or explosive dusts are found (McIlvaine, 1996).

ESPs are usually not suited for use in processes which are highly variable because frequent changes in operating conditions are likely to degrade ESP performance. ESPs are also difficult to install in sites which have limited space since ESPs must be relatively

large to obtain the low gas velocities necessary for efficient PM collection (Cooper and Alley, 1994).

Control Efficiency

While several factors determine ESP collection efficiency, ESP size is most important. Size determines treatment time; the longer a particle spends in the ESP, the greater its chance of being collected. Maximizing electric field strength will maximize ESP collection efficiency (STAPPA/ALAPCO, 1996). The resistivity of the particles to be collected is also important. Resistivity is the resistance of particles to the flow of electric current. Particles with intermediate resistivities [10^7 to 10^{10} ohms per centimeter (cm)] are amenable to collection with ESPs; these particles are easy to charge and only slowly lose their charge once deposited on a collecting electrode (STAPPA/ALAPCO, 1996).

Factors limiting dry ESP performance include flow nonuniformity and dust re-entrainment, which may occur during rapping (STAPPA/ALAPCO, 1996). The particles re-entrained during rapping are then processed again by later ESP sections, but the particles re-entrained in the last section of the ESP escape the unit (AWMA, 1992).

AP-42 (EPA, 1995) chapters were reviewed to identify particle size distribution profiles that could be used to calculate ESP control efficiencies for PM and the cumulative mass for particles ≤ 10 μm and ≤ 2.5 μm. For PM, the lowest control efficiency calculated was 95.00 percent. For PM10, the lowest control efficiency calculated was 89.76 percent. For PM2.5, the lowest control efficiencies calculated was 95.35 percent. Based on professional judgement, 90, 85, and 80 percent were selected to represent typical low-end control efficiency values for PM, PM10, and PM2.5, respectively. The control efficiency values calculated from the AP-42 particle size profiles are considered to be reliable because they have undergone peer review before publication. The low-end control efficiency values represent existing units that have been operating for several years and suffered slight deterioration in performance, or were installed to meet emission limits established several years ago that would be considered relatively lenient compared to current emission limits.

The highest PM control efficiency calculated was 99.89 percent. For PM10, the highest control efficiency calculated was 99.40 percent. For PM2.5, the highest control efficiency calculated was 99.35 percent. The high-end control efficiency values for PM, PM10, and PM2.5 selected were >99.9, 99.5, and >99.0 percent, respectively. The high-end of the ranges are based on the assumption that ESP design, operation, and maintenance technology has advanced over the past 20 years such that most types of ESPs could be designed to achieve these control efficiency levels. Given that the form of the PM NAAQS is now PM2.5 instead of PM10, it is assumed that vendors will be optimizing ESP systems to achieve high PM2.5 control efficiencies.

Cost

The average cost per ton of particulate matter controlled is approximately $200,000. This average is derived from data which represents a broad range of applications for this control technology (Pechan, 1995).

003 Electrostatic Precipitator (Dry) With Flue Gas Conditioning

Description
    Flue gas conditioning is used to modify the characteristics of the gas stream and particles to enhance PM removal in the ESP. Typically, flue gas conditioning involves the addition or injection of chemicals into the flue gas steam prior to it entering the ESP to improve electrical conductivity of PM for collection in the ESP. Flue gas conditioning can be used to improve the electric field strength and ion density, adhesive and cohesive properties of the PM, and particle size and distribution. Conditioning agents improve ESP collection efficiency by one or more of the following mechanisms: (1) reduce the surface resistivity of PM; (2) change the adhesion/cohesion properties of PM; (3) increase fine PM concentration for space charge improvement; (4) increase sparkover voltage of flue gas (reduce back corona); (5) increase mean particle size; and (6) decrease acid dew point in flue gas (EPA, 1985).

    Common conditioning agents include sulfur trioxide (SO_3), ammonia (NH_3), ammonium compounds, organic amines, and dry alkalis (McIlvaine, 1996). The most common ammonium compounds used for conditioning include sulfamic acid, ammonium sulfate, and ammonium bisulfate. Research on organic amines as conditioning agents has been conducted in laboratories and pilot-scale ESPs. The most research has been conducted using triethylamine, which is an organic nitrogen compound which behaves similar to NH_3 but is a stronger base than NH_3. Dry alkali conditioning involves the use of sodium compounds such as sodium sulfate and sodium carbonate (EPA, 1985; McIlvaine, 1996).

Applicability
    Flue gas conditioning is frequently used to retrofit ESPs which are not operating at design efficiency or because process parameters have been changed leading to a decrease in design efficiency. For example, flue gas conditioning is frequently used to condition coal-fired boiler flue gas to improve the resistivity properties of the fly ash and electrical conditions of the ESP when the boiler fuel is changed from high- to low-sulfur coal (Cooper and Alley, 1994; McIlvaine, 1996). Low-sulfur coal produces a high resistivity fly ash when burned that is difficult to collect in an ESP. Fabric filters and scrubbers are far less dependent on the chemical composition for PM removal. Gas conditioning for fabric filters and scrubbers usually consists of controlling the temperature and moisture of the gas stream.

Control Efficiency
    The control efficiency ranges for flue gas conditioning for ESPs are based on the expected control efficiency for the ESP after conditioning is applied. Because flue gas conditioning is typically used to improve the efficiency of existing ESPs to design levels, the control efficiency ranges are based on those specified for ESPs without flue gas conditioning.

Cost
    The average cost per ton of particulate matter controlled is approximately $200,000. This average is derived from data which represents a broad range of applications for this control technology (Pechan, 1995).

004 Electrostatic Precipitator (Wet)

Description

Wet ESPs are add-on control devices that are designed to remove PM from the flue gas stream using electrical fields and water. They can collect dry materials, fumes, or mist. The basic design of a wet ESP is the same as that for a dry ESP, except that water spray is used to remove the PM captured on the electrode. A typical wet ESP configuration has vertical cylindrical collecting electrodes, with discharge electrodes located in the centers of the cylinders (STAPPA/ALAPCO, 1996). The water flow may be applied intermittently or continuously to wash the collected PM into a sump for disposal (AWMA, 1992).

Application

Wet ESPs can collect sticky particles and mists, as well as highly resistive or explosive dusts. In addition, wet ESPs have no problems with rapping re-entrainment and with back corona. Also, wet ESPs are useful in obtaining low opacities through the removal of acid gases and mists in addition to fine PM. The disadvantage of these devices is the increased complexity of the wash and the additional handling activities (and costs) associated with the collected slurry versus the dry product from a dry ESP. These devices are generally not limited by dust characteristics but are limited by gas temperatures. Typically, the operating temperatures of wet ESPs cannot exceed 170°F (AWMA, 1992; STAPPA/ALAPCO, 1996).

Control Efficiency

Only one particle size distribution profile was identified in AP-42 (EPA, 1995). The profile provided control efficiencies for PM10 and PM2.5 but not PM. The PM10 and PM2.5 control efficiencies are 94.01 and 89.29 percent, respectively. According to AWMA (1992), wet ESPs can achieve PM control efficiencies ranging from 99.0 to 99.5 percent for a new wood-waste fired boiler that must meet a 0.1 pound per million British thermal unit (lb/MMBtu) PM emission limit. A wet ESP used to control PM emissions from a vertical stud Soderberg cell used in the electroreduction of aluminum ore achieved and average control efficiency of 96 percent (EPA, 1973b).

The results of emissions test on three wet ESPs used to control emissions from wood chip dryers were identified (EPA, 1989). For one ESP, the average control efficiency was 90.47 percent and ranged from 88.19 to 92.66 percent for three test runs. For another wet ESP, the average control efficiency was 94.81 percent and ranged from 94.64 to 96.60 percent for four test runs. For a third wet ESP, the average control efficiency was 85.40 percent and ranged from 68.7 to 96.4 percent for three test runs.

For two of the ESPs, the control efficiency for total nonmethane organic gases (TNMOG) and formaldehyde were tested. For one unit, the control efficiency for TNMOG averaged 69.95 percent and ranged from 54.51 to 86.89 percent for three test runs. The control efficiency for formaldehyde averaged 52.18 percent and ranged from 45.02 to 62.13 percent for three test runs. For the other unit, the control efficiency for TNMOG averaged 56.90 percent and ranged from 52.30 to 77.20 percent for three test runs. The control efficiency for formaldehyde averaged 1.30 percent and ranged from -12.00 to 16.7 percent for three test runs. Based on this data, the efficiency range for TNMOG is estimated to be 50 to 70 percent.

Wet ESPs are also used in the wool fiberglass insulation manufacturing industry to control emissions from forming, curing, and cooling operations. Test results for four ESPs indicated that average PM control efficiencies ranged from 78 to 93 percent, average formaldehyde control efficiencies ranged from 78 to 83 percent, average phenolic compound control efficiencies ranged from 62 to 93 percent, and average phenol control efficiencies ranged from 1 to 40 percent (EPA, 1983).

Based on this data, 80 percent was selected to represent the low-end of the range for PM. Based on professional judgement, the low-end control efficiencies for PM10 and PM2.5 were estimated to be 75 and 70 percent. The high-end control efficiencies for PM, PM10, and PM2.5 are based on those specified for dry ESPs.

Cost

The average cost per ton of particulate matter controlled is approximately $200,000. This average is derived from data which represents a broad range of applications for this control technology (Pechan, 1995).

005   Fabric Filter

For PM Control

Description

In a fabric filter, flue gas is passed through a tightly woven or felted fabric, causing PM in the flue gas to be collected on the fabric by sieving and other mechanisms (STAPPA/ALAPCO, 1996). Fabric filters may be in the form of sheets, cartridges, or bags, with a number of the individual fabric filter units housed together in a group. Bags are most common type of fabric filter. The dust cake that forms on the filter from the collected PM can significantly increase collection efficiency. Fabric filters are frequently referred to as baghouses because the fabric is usually configured in cylindrical bags. Bags may be 20 to 30 feet long and 5 to 12 inches in diameter. Groups of bags are placed in isolable compartments to allow cleaning of the bags or replacement of some of the bags without shutting down the entire fabric filter (STAPPA/ALAPCO, 1996).

Operating conditions are important determinants of the choice of fabric. Some fabrics (e.g., polyolefins, nylons, acrylics, polyesters) are useful only at relatively low temperatures of 200 to 300°F. For high-temperature flue gas streams, more thermally stable fabrics such as fiberglass, Teflon®, or Nomex® must be used (STAPPA/ALAPCO, 1996).

The three major fabric filter types, classified by cleaning method, are mechanical shaker, reverse-air, and pulse-jet. In mechanical shaking units, the tops of bags are attached to a shaker bar, which is moved briskly (usually in a horizontal direction) to clean the bags. In reverse-air units, the flue gas flows upward through the insides of vertical bags that open downward, fly ash collects on the insides of the bags, gas flow keeps the bags inflated, and cleaning is accomplished by reversing the gas flow (STAPPA/ALAPCO, 1996). In pulse-jet units, dirty air flows from the outside of the bags inward, bags are mounted on cages to keep them from collapsing, and dust is removed by a reverse pulse of high-pressure air (STAPPA/ALAPCO, 1996).

Sonic horns are increasingly being used to enhance the collection efficiency of mechanical shaker and reverse-air fabric filters. The horns are typically powered by compressed air, and acoustic vibration is introduced by a vibrating metal plate which periodically interrupts the gas flow (AWMA, 1992).

The advantages of fabric filters include very high collection efficiencies and the flexibility to treat may types of dusts and a wide range of volumetric gas flows. In addition, they can be operated with low pressure drops. Disadvantages of fabric filters are that, in general, fabric filters are limited to filtering dry streams; high temperatures and certain chemicals can damage some fabrics; there is a potential for fire or explosion; and they can require a large area for installation (AWMA, 1992).

Application

Fabric filters are useful for collecting particles with resistivities either too low or too high for collection with ESPs.

The applicability of fabric filters is limited by the dust characteristics, as well as the potential for explosion, temperature, and humidity. Particles that are moist or very adhesive may present clogging problems.

Shaker-cleaned fabric filters are very flexible in design, allowing for different types of fabrics, bag arrangements, and fabric filter sizes. This enables shaker-cleaned fabric filters to have many applications, with only some limitations (McIlvaine, 1996).

Reverse-air cleaning alone is used only in cases where the dust releases easily from the fabric, and in many instances, reverse-air is used with shaking or pulsing. Reverse-air cleaning with sonic assistance has become a very popular method for fabric filters at coal-burning utilities (Cooper and Alley, 1994).

Control Efficiency

Determinants of fabric filter performance include the fabric chosen, the cleaning frequency and methods, flue gas characteristics (e.g., temperature and moisture content), and particle size distribution. Fabric filters often are capable of 99.9 percent removal efficiencies and commonly can reduce utility boiler emissions to below 0.03 lb/MMBtu and often to below 0.01 lb/MMBtu. Fabric filter removal efficiency is relatively level across the particle size range, so that excellent control of PM10 and PM2.5 can be obtained (STAPPA/ALAPCO, 1996).

Cleaning intensity and frequency are important variables in determining removal efficiency. Because the dust cake can provide a significant fraction of the fine PM removal capability of a fabric, cleaning that is too frequent or too intense will lower the removal efficiency. If cleaning is too infrequent or too ineffective, the fabric filter pressure drop will become too high (STAPPA/ALAPCO, 1996).

AP-42 (EPA, 1995) chapters were reviewed to identify particle size distribution profiles for fabric filters that could be used to calculate control efficiencies for PM and the cumulative mass for particles ≤ 10 μm and ≤ 2.5 μm. For PM, the lowest control efficiency calculated was 94.20 percent. For PM10, the lowest control efficiency calculated was 87.60 percent. For PM2.5, the lowest control efficiency calculated was 85.53 percent. Based on

professional judgement, 90, 85, and 80 percent were selected to represent low-end control efficiency values for PM, PM10, and PM2.5, respectively. The control efficiency values calculated from the AP-42 particle size profiles are considered to be reliable because they have undergone peer review before publication. The low-end control efficiency values represent existing units that have been operating for several years and suffered deterioration in performance or were installed to meet emission limits established several years ago that would be considered relatively lenient compared to current emission limits.

The highest control efficiency calculated from the profiles was 99.99 percent for both PM and PM10. For PM2.5, the highest control efficiency calculated was 99.92 percent. Based on these data, the high-end control efficiency values selected for PM, PM10, and PM2.5 were >99.9, >99.9, and 99.9 percent, respectively.

Cost

The average cost per ton of particulate matter controlled is approximately $60,000. This average is derived from data which represents a broad range of applications for this control technology (Pechan, 1995).

For SOx Control

Description

Fabric filters remove dust from a gas stream by passing the stream through a porous fabric. Dust particles form a more-or-less porous cake on the surface of the fabric. It is normally this porous cake that actually does the filtration. While chiefly intended to remove particulates, such as fly ash, from a gas flow, fabric filters can also remove some SO_2 when used as part of a dry injection scrubbing system. The fabric filter provides a site for unreacted sorbent to have a "second chance" to absorb any SO_2 which failed to react with injected sorbent in the ductwork leading to the filter. The manner in which the cake on the filter is removed is critical to filter operation. Removal of too much of the cake will result in dust and SO_2 leakage, while insufficient removal will result in an unacceptable pressure drop (Buonicore, 1992; EPA, 1981).

Application

Fabric filters are used as part of a dry sorbent injection system for control of SO_2 emissions from coal- or oil-fired boilers for utilities or industrial facilities.

Control Efficiency

The typical control efficiency range is from 15 to 30 percent (Buonicore, 1992). Control efficiency varies depending upon the operating conditions of the dry scrubbing system or spray drier, as well as those of the fabric filter (Buonicore, 1992).

Cost

When coupled with certain SO_2 control systems, most notably spray dry and sorbent injection systems, fabric filters do contribute to the overall control efficiency, but a cost per ton of SO_2 controlled is inappropriate for fabric filters alone.

006 Venturi or Orifice Scrubber

For PM Control

Description

Venturi and orifice scrubbers are perhaps the most common PM removal devices, in part because they provide higher control of small particles than most other types of scrubbers (EPA, 1982).

In a venturi scrubber (also called a gas atomizing spray scrubber), the static pressure of the incoming gases is converted to velocity pressure (i.e., kinetic energy) as the gases move through the narrow (usually less than 15 cm wide) throat. The required dispersion of target droplets is created by accelerating the gas stream to a high velocity and then using this kinetic energy to shear the scrubbing liquid into fine droplets. The motive force comes primarily from gas-stream kinetic energy, usually injected into the system by a fan. The energy imparted to the gas stream acts on the high-velocity center of the throat. Scrubbing liquid can be injected into the venturi scrubber at the throat zone, at the gas inlet, or against the gas flow in the throat. Venturi scrubbers are typically considered high-energy PM control devices (AWMA, 1992).

In an orifice scrubber, the gas stream passes over a pool of scrubbing liquid at high velocity just before entering an orifice. The high velocity of the gas entrains a spray of scrubbing liquid droplets, which interact with the PM in and immediately after the orifice (EPA, 1982).

Application

Venturi scrubbers have been applied to control PM emissions from utility, industrial, commercial, and institutional boilers fired with coal, oil, wood, and liquid waste. They have also been applied to control emission sources in the chemical, mineral products, wood, pulp and paper, and asphalt manufacturing industries; lead, aluminum, iron and steel, and gray iron production industries; and to municipal solid waste incinerators. Typically, venturi scrubbers are applied where it is necessary to obtain high collection efficiencies for fine PM. Thus, they are applicable to controlling emission sources with high concentrations of submicron particles.

Control Efficiency

Three particle size distribution profiles were identified in AP-42 (EPA, 1995) for venturi scrubbers. The highest PM, PM10, and PM2.5 control efficiencies calculated from these profiles were slightly lower than those calculated for other profiles for which the type of scrubber was not identified [see discussion of "typical control efficiency range" for "wet scrubbers (general, not classified)"]. The lowest control efficiencies calculated from the three profiles for venturi scrubbers were 92.2 percent for PM, 68 percent for PM10, and 25 percent for PM2.5. These values were selected for the low-end of the control efficiency range for venturi and orifice scrubbers, except that the PM and PM10 control efficiency values were rounded to 90 and 70 percent, respectively. The high-end of the control efficiency range for venturi and orifice scrubbers is based on engineering judgement. The high-end of the range for PM and PM10 was assumed to be >99.0 percent because the pressure drop of a venturi scrubber can be increased to the level needed to achieve control

efficiencies of more than 99.0 percent. For PM2.5, it was assumed that new venturi scrubbers can be designed and operated to achieve 99.0 percent control.

Cost

The average cost per ton of particulate matter controlled is approximately $9,000. This average is derived from data which represents a broad range of applications for this control technology (Pechan, 1995).

For SOx Control

Description

In a venturi scrubber, the SO_2-laden gas is introduced at the top, then passed through the converging section of the scrubber (the venturi throat), and then exited from the scrubber through a diverging section. The venturi shape imparts a high velocity to the gases in the throat, which leads to turbulent mixing of the gases with the absorbent or reactant, which promotes more complete absorption and/or reactions. Absorbent or reactant solutions or slurries are introduced to the gas flow in a variety of ways. Some inject into the throat, others at the gas inlet, and still others, upward against the gas flow in the throat (Buonicore, 1992; EPA, 1981).

Application

Venturi scrubbers are often used before a tower-type absorber in order to remove particulates from the flow as well and sometimes to cool and humidify the gas, but are also used to introduce a scrubbing liquor or slurry to a gas flow in nonregenerable systems where any particulate in the waste gas is collected with the reacted solution or slurry.

Control Efficiency

The typical control efficiency range is from 80 to >99 percent. The control efficiency of the absorber component of a scrubbing system depends upon the overall design of the system and the absorbent used in the system.

Cost

Costs per ton of SO_2 controlled are dependent upon the overall design of the scrubbing system and cannot be determined for the absorber component of the system alone.

For VOC Control

Description

[See PM writeup.]

Application

Venturi scrubbers have a relatively low effective mass transfer capability and are generally limited to use for particulate removal and with high-solubility gases (EPA, 1992d).

Control Efficiency
The typical control efficiency range is from 50 to 70 percent (Grossman, 1997) (VOC). VOCs are not usually the pollutant intended for control by a venturi scrubber. Any control of VOC emissions would be coincidental to the intended control of particulate matter, for which Venturi scrubbers are better suited.

Cost
Since Venturi scrubbers are not usually intended for control of VOCs, any incidental control of VOCs would probably not be used to justify costs.

007 Single Cyclone (Conventional)

008 Single Cyclone (High-Efficiency)

009 Single Cyclone (High-Throughput)

Description
Cyclones use inertia to remove particles from the gas stream. The cyclone imparts centrifugal force on the gas stream, usually within a conical shaped chamber. Cyclones operate by creating a double vortex inside the cyclone body. The incoming gas is forced into circular motion down the cyclone near the inner surface of the cyclone tube. At the bottom of the cyclone, the gas turns and spirals up through the center of the tube and out of the top of the cyclone (AWMA, 1992).

Particles in the gas stream are forced toward the cyclone walls by the centrifugal force of the spinning gas but are opposed by the fluid drag force of the gas traveling through and out of the cyclone. For large particles, inertial momentum overcomes the fluid drag force so that the particles reach the cyclone walls and are collected. For small particles, the fluid drag force overwhelms the inertial momentum and causes these particles to leave the cyclone with the exiting gas. Gravity also causes the larger particles that reach the cyclone walls to travel down into a bottom hopper. While they rely on the same separation mechanism as momentum separators, cyclones are more effective because they have a more complex gas flow pattern (AWMA, 1992).

Cyclones are generally classified into four types based on how the gas stream is introduced into the device and how the collected dust is discharged. The four types include tangential inlet, axial discharge; axial inlet, axial discharge; tangential inlet, peripheral discharge; and axial inlet, peripheral discharge. The first two types are the most common (AWMA, 1992).

Pressure drop is an important parameter because it relates directly to operating costs and control efficiency. Higher control efficiencies for a given cyclone can be obtained by higher inlet velocities, but this also increases the pressure drop. In general, 60 feet per second is considered the best operating velocity. Common ranges of pressure drops for cyclones are 2 to 4 inches of water column for low-efficiency units (high throughput), 4 to 6 inches of water column for medium-efficiency units (conventional), and 8 to 10 inches of water column for high-efficiency units (AWMA, 1992).

Another high-efficiency unit, the wet cyclonic separator, uses a combination of centrifugal force and water spray to enhance control efficiency.

Application

Cyclones are designed for many applications and are typically categorized as high efficiency, conventional, or high throughput. High efficiency cyclones are likely to have the highest pressure drops of the three types. High throughput cyclones are designed to treat large volumes of gas with a low pressure drop. Each of the three types have the same basic design, but the cyclone dimensions are varied to achieve different collection efficiencies, pressure drops, and operating requirements (AWMA, 1992; EPA, 1982).

Control Efficiency

Many factors affect the collection efficiency of cyclones. Cyclone efficiency generally increases with (1) particle size and/or density, (2) inlet duct velocity, (3) cyclone body length, (4) number of gas revolutions in the cyclone, (5) ratio of cyclone body diameter to gas exit diameter, (6) dust loading, and (7) smoothness of the cyclone inner wall. Cyclone efficiency will decrease with increases in (1) gas viscosity, (2) body diameter, (3) gas exit diameter, (4) gas inlet duct area, and (5) gas density. A common factor contributing to decreased control efficiencies in cyclones is leakage of air into the dust outlet (EPA, 1973a).

Control efficiency ranges for single cyclones were developed for the three different classifications (i.e., conventional, high-efficiency, and high-throughput). Although the literature uses these classifications when discussing the different designs of cyclones, published reports containing control efficiency test data for existing units generally do not identify the cyclone classification. Thus, it is difficult to classify published control efficiency data by the type of cyclone. The control efficiency ranges developed are based on professional judgement and some guidance obtained from references.

High efficiency single cyclones are designed to achieve higher control of smaller particles than conventional cyclones. According to Cooper and Alley (1994), high efficiency single cyclones can remove 5 μm particles at up to 90 percent efficiency, with higher efficiencies achievable for larger particles. The control efficiency range for high efficiency single cyclones is estimated to be 80 to 99 percent for PM, 60 to 95 percent for PM10, and 20 to 70 percent for PM2.5.

The control efficiency range for conventional single cyclones is estimated to be 70 to 90 percent for PM, 30 to 90 percent for PM10, and 0 to 40 percent for PM2.5. The control efficiency ranges for conventional cyclones were selected to represent existing units that have been minimally maintained and/or were installed to meet emission limits established several years ago that would be considered relatively lenient compared to current emission limits.

According to Vatavuk (1990), high throughput cyclones are only guaranteed to remove particles greater than 20 μm, although collection of smaller particles does occur to some extent. The control efficiency range for high-throughput cyclones is estimated to be 80 to 99 percent for PM, 10 to 40 percent for PM10, and 0 to 10 percent for PM2.5.

010 Multiple Cyclone w/o Fly Ash Reinjection

Description

A multiple cyclone (or multi-tube cyclone) consists of many small diameter cyclone units in parallel. Multiple cyclones are used when high efficiency (which requires small cyclone diameters) and large throughput (i.e., large volumetric gas flow rates) are desired. However, this arrangement results in higher pressure losses relative to single cyclones, thus increasing the energy needed to operate them. The housing of a multiple cyclone contains a large number of tubes that have a common gas inlet and outlet in the chamber. The gas enters the tubes through axial inlet vanes that impart a circular motion on the gas flow. The arrangement and diameter of the tubes affect the overall control efficiency of a multiple cyclone (AWMA, 1992; EPA, 1982).

Dust reentrainment in the cyclone tubes can compromise control efficiency. Control efficiency can be improved by hopper evacuation or slip streaming, in which about 15 percent of the total gas flow is drawn off through the hopper. Hopper evacuation reduces dust reentrainment into the cyclone tubes such that the collection efficiency of the multiple cyclone can be increased by 40 to 50 percent. The dust in the slip stream can be cleaned by a small fabric filter and the cleaned slip stream returned to the cyclone exit. This type of arrangement has been used as a retrofit to improve multiple cyclone control efficiencies (AWMA, 1992). An alternative solution to reducing dust reentrainment is to use a straight-through type cyclone rather than a reverse-flow type cyclone. Multiple tube arrangements of this type have been commonly installed to control particulate emissions from older coal-fired boilers (AWMA, 1992).

Application

Multiple cyclones are most frequently used on large fossil fuel-fired boilers because they can handle large gas volumes effectively as a precleaner control device (AWMA, 1992). However, they can be used in most situations where it is necessary to achieve relatively high control efficiencies while handling large gas flow volumes.

Control Efficiency

According to STAPPA/ALAPCO (1996), multiple cyclones can achieve PM control efficiencies of 70 to 90 percent. However, cyclone efficiency declines with particle size. While no accurate estimate of control efficiency can be made without precise details of the cyclone design and fly ash properties, control efficiencies can be 90 percent or more for PM10, but will drop to perhaps 70 percent for PM2.5, and 50 percent for PM10. According to another reference, multiple cyclones can achieve control efficiencies of 80 percent for 5 μm particles (Vatavuk, 1990).

Only one uncontrolled and controlled particle size distribution profile was identified in AP-42 (EPA, 1995) for a multiple cyclone without fly ash reinjection. This profile is for an electric utility bark-fired-boiler. The PM and PM10 control efficiencies are 80 percent, and the PM2.5 control efficiency is about 83 percent for this control device.

AP-42 (EPA, 1995) contains seven profiles where the type of multiple cyclone (i.e., without or with fly ash reinjection) is not identified. It was assumed that these profiles are for multiple cyclones without fly ash reinjection. Five of the profiles are for coal-fired electric utility boilers, one is for an oil-fired industrial boiler, and one is for a castable

refractory rotary calciner used in the mineral products industry. One profile for a pulverized anthracite coal-fired electric utility boiler indicated PM, PM10, and PM2.5 control efficiencies of 80, 52, and 20 percent, respectively. A second profile for a spreader stoker lignite coal-fired electric utility boiler indicated PM, PM10, and PM2.5 control efficiencies of 80, 59, and 25 percent, respectively. A third profile for a traveling grate (overfeed) bituminous coal-fired electric utility stoker indicated PM, PM10, and PM2.5 control efficiencies of 44, 17, and -73 percent, respectively. A fourth profile for a pulverized lignite coal-fired tangential electric utility boiler indicated PM, PM10, and PM2.5 control efficiencies of 80, 62, and 45 percent, respectively. A fifth profile for a pulverized bituminous pulverized coal dry bottom electric utility boiler indicated PM10 and PM2.5 control efficiencies of 75 and 90 percent, respectively. A sixth profile for an industrial residual oil-fired boiler indicated PM, PM10, and PM2.5 control efficiencies of 80, 78, and 93 percent, respectively. A seventh profile for a multiple cyclone for a rotary calciner in the mineral products industry provided a PM efficiency of 50 percent.

The PM2.5 control efficiencies for three profiles are higher than the PM10 and PM control efficiencies and for one other profile is negative, indicating that the multiple cyclone increased PM2.5 emissions. The wide range in PM2.5 control efficiencies may be associated with the possibility that the profiles were developed to represent average emissions based on test results for several multiple cyclones which would compromise the comparability of uncontrolled and controlled profiles for calculating control efficiencies.

For the low-end of the range of control efficiencies for multiple cyclones without fly ash reinjection, 80 percent control was selected for PM. For PM10, the control efficiencies ranged from about 17 percent to 81 percent. However, five of the seven profiles had efficiencies ranging from 52 to 78 percent. An efficiency of 50 percent was selected to represent the low-end of the range for PM10. For PM2.5, the AP-42 profile data are inconclusive. For existing units, an efficiency of 20 percent was selected to represent the low-end of the range for PM2.5.

The upper-end of the control efficiency range for multiple cyclones for PM control is assumed to be 99 percent. This value is based on the assumption that vendors can optimize the design of multiple cyclones to achieve high PM control efficiencies for some applications. For PM10, 95 percent control efficiency was selected based on the assumption that new installations could be designed and operated to achieve high PM10 control efficiencies. For PM2.5, 70 percent was selected for the upper-end of the control efficiency range based on STAPPA/ALAPCO (1996).

011 Multiple Cyclone w/ Fly Ash Reinjection

Description
    The description for multiple cyclones with fly ash reinjection is the same as the description for multiple cyclones without fly ash reinjection. Fly ash collected in the hopper of a multiple cyclone is reinjected into the combustion unit by use of a slip stream drawn from the collection hopper of the cyclone.

Application
    Multiple cyclones with fly ash reinjection are used on large electric utility or industrial fossil fuel-fired boilers. Ash is formed from inorganic impurities, which are

defined as anything other than carbon and hydrogen, contained in the fossil fuel. The ash can also contain unburned carbon resulting from incomplete combustion of coal or oil. Not all ash is released to the atmosphere (in the absence of controls). Ash may melt to form slag or may be in the form of very large particles which settle to the bottom of the furnace and are collected as bottom ash. The finer particulates released to the atmosphere are called fly ash (STAPPA/ALAPCO, 1996). The amount of ash and unburned carbon generated by a boiler depends on several factors including the type of boiler design, ash and carbon content of the fuel, size of coal burned, and boiler operating characteristics (e.g., age, temperature).

Fly ash collected in the hopper of the multiple cyclone is drawn off by a slip stream and injected into the boiler to combust unburned carbon. As discussed for multiple cyclones without fly ash reinjection, drawing a slip stream from the collection hopper of the cyclone can help to reduce dust reentrainment into the cyclone tubes and increase the efficiency of the cyclone. However, reinjection of collected dust increases the particulate loading considerably and can result in lowering control efficiencies for small particles (EPA, 1995).

Control Efficiency
Control efficiencies for multiple cyclones with fly ash reinjection would be similar to those discussed for multiple cyclones without fly ash reinjection. However, control efficiencies could be lower if reinjection of small fly ash particles into the boiler result in a large mass of small particles passing through the cyclone uncollected. AP-42 (EPA, 1995) contains two sets of uncontrolled and controlled particle size profiles for multiple cyclones where the units are identified as having fly ash reinjection (EPA, 1995). One profile is for a bark-fired electric utility boiler, and the other profile is for a wood/bark fired electric utility boiler. The PM, PM10, and PM2.5 control efficiencies for the multiple cyclone for the bark-fired boiler are 70, 35, and 44 percent, respectively. The PM, PM10, and PM2.5 control efficiencies for the multiple cyclone for the wood/bark-fired boiler are 17, 16, and 41 percent, respectively. From a review of AP-42 (EPA, 1995), it is not clear why the PM2.5 control efficiency for PM2.5 is 9 percent higher than for PM10 for one profile, and 24 and 25 percent higher than the PM and PM10 control efficiency, respectively, for the other profile. However, in comparison with an AP-42 particle size profile for a unit without fly ash reinjection on a bark-fired boiler, the control efficiencies for the units with fly ash reinjection are significantly lower.

Data are limited for defining values for the low-end of the control efficiency range for multiple cyclones with fly ash reinjection. For the particle size profile for the multiple cyclone controlling a wood/bark-fired boiler, the PM, PM10, and PM2.5 control efficiencies of 17, 16, and 41 percent, respectively, are considered atypical. Unique characteristics of the process such as sticky residue or poor design and operation of the boiler and/or multiple cyclone may be reasons for the poor performance of the cyclone. The profile for the multiple cyclone controlling a bark-fired boiler is considered more typical of the performance of an existing unit, at least for PM and PM10. The PM and PM10 control efficiencies for this unit are 70 are 35 percent, respectively, and these values were used to define the low-end of the control efficiency range for PM and PM10. The low-end of the range for PM2.5 was based on that used for multiple cyclones without fly ash reinjection. Typical high-end control efficiencies for PM are estimated to be 99 percent; the same as units without fly ash reinjection. For PM10 and PM2.5, high-end control efficiencies were

estimated to be 85 and 60 percent, respectively. These values are 10 percent lower than the high-end control efficiencies for multiple cyclones without fly ash reinjection. These high-end PM10 and PM2.5 control efficiency values are based on professional judgment due to a lack of data.

012   Mist Eliminator - Blade-Type

Description
> Blade-type mist eliminators consist of one or more sets of parallel, chevron-shaped baffles (blades) arranged in a horizontal-flow configuration. Each blade changes the direction of the gas flow four times, which causes droplets to impinge on the surface of the blades as a result of inertial force. Water sprays mounted at the inlet of the mist eliminator and directed toward the blades are activated periodically to wash the blades. For units used to control mist from chromium electroplating and chromic acid anodizing tanks, the wash water is drained to the plating tank to make up for evaporative losses of plating solution and to recover chromic acid. Otherwise, the wash water is drained to a wastewater treatment system (EPA, 1993c).

> Two blade designs commonly used are overlapping and sinusoidal wave. The overlapping design consists of a set of blades with overlapping edges. In contrast, the sinusoidal wave design consists of a set of blades with rounded edges and catchments located between the rounded edges. The overlapping edges, or catchments, act as collection troughs for droplets and facilitate drainage of the droplets into a collection sump. Blades typically range from 15 to 30 cm (6 to 12 inches) in depth. The spacing between blades may vary but is normally 3.18 cm (1.25 inches) (EPA, 1993c).

Application
> Blade-type mist eliminators are most frequently used in scrubbers to eliminate mist from carrying pollutants out the stack of the scrubbers; however, they can also be used as stand-alone control devices to control acid mists. Horizontal-flow chevron-blade mist eliminators typically are used to control chromic acid mist because the horizontal-flow configuration is more effective than the vertical-flow configuration for the high inlet velocities and pollutant loadings common for chromium plating operations (EPA, 1993c).

Control Efficiency
> Major factors that affect the performance of chevron-blade mist eliminators include the face velocity of the gas stream across the blades, the spacing between blades, and the tightness of seals between the blades and the walls of the unit. Gas stream velocities must be maintained within design specifications to maximize the operating efficiency of the unit. Gas velocities less than the specified minimum will not provide the inertial force required to maximize impingement of chromic acid droplets on the blades, and gas velocities greater than the specified maximum may cause droplets to become reentrained in the gas stream.

> EPA (1993c) provides control efficiency data for chevron-blade mist eliminators used to control chromic acid mist from hexavalent chromium electroplating baths. For test conducted on three chevron-blade mist eliminators at three separate plants, average control efficiencies ranged from 87.9 to 98.4 percent for chromic acid mist. All three of these mist eliminators are stand-alone units that are used as the primary control device to control acid mist. Control device vendors estimate that removal efficiencies range from 80

to 90 percent (EPA, 1993c). Control efficiency data for PM10 and PM2.5 could not be identified. Based on professional judgement, PM10 control efficiencies were assumed to be the same as the range for PM control efficiencies. PM2.5 control efficiencies were estimated to range from 50.0 to 70.0 percent. These control efficiency ranges are for stand alone units that are used as the primary control device.

Cost

The average cost per ton of particulate matter controlled is approximately $1,000. This average is derived from data which represents a broad range of applications for this control technology (Pechan, 1995).

013   Mist Eliminator - Mesh-Type

Description

Mesh-pad mist eliminators consist of layers of interlocked filaments densely packed between two supporting grids. The principal control mechanisms are inertial impaction and direct interception. Inertial impaction occurs when particles larger than about 3 μm (0.12 million), traveling with sufficient velocity, collide with the filaments and adhere to their surface. Other particles, because of their size and relative velocity, are intercepted by the fluid layer surrounding the surface of the filament. Collected liquid droplets flow along the fibers to a point where adjacent filaments cross. These crossover points rapidly become loaded with liquid, and droplets drain to the bottom of the mist eliminator as a result of gravity (EPA, 1993c).

The mesh pads consist of thin, multiple layers of interwoven fibers. These layers are compacted and fastened together with thin filaments. Pad thicknesses vary from 10 to 15 cm (4 to 6 inches), but occasionally pads as thick as 30.5 cm (12 inches) are used. Often two mesh-type separators in series are used to remove particles in the 1 to 5 μm (0.04 to 0.20 million) diameter range. The first mesh, normally made of fine fibers, coalesces the small drops, and the second mesh, made of standard fibers, removes them (EPA, 1993c).

In recent years, mesh-pad mist eliminators equipped with internal spray systems to clean the pads have been developed, avoiding potential plugging problems. These newer units contain multiple mesh pads in series that are designed to remove chromic acid mist in stages. The first stage removes the bulk of the mist, which is comprised of fairly large particles (>5 μm), and the second stage removes the smaller particles (3 to 5 μm). Because the internal spray system protects the pads from plugging, these units contain pads with a smaller fiber diameter than the older models. These units are installed for horizontal gas flow through the unit, rather than vertical gas flow, which allows for better drainage (EPA, 1993c).

Application

Mesh-type mist eliminators are used to control mist emissions. They have been demonstrated to be effective for controlling chromic acid mists from hexavalent chromium electroplating tanks (EPA, 1993c).

Control Efficiency

One of the major factors that affects mesh-pad mist eliminator performance is the tendency of the unit to plug. The mesh pad must be flushed frequently with water to

prevent pollutant buildup and eventual plugging. Mesh-pad mist eliminators should be washed down at least once a day. Velocity of the gas stream and the particle size of the entrained pollutant are additional factors that affect the performance of the mesh pad assembly. Gas velocities should be maintained high enough to optimize collection through inertial impaction yet not cause reentrainment.

EPA (1993c) provides control efficiency data for mesh-pad mist eliminators used to control chromic acid mist from hexavalent chromium electroplating baths. For test conducted on three mesh-blade mist eliminators at three separate plants, average control efficiencies ranged from 98.7 to 99.7 percent for chromic acid mist. The vendor of this technology estimates a control device efficiency between 96 and 99 percent. Control efficiency data for PM10 and PM2.5 could not be identified. Based on professional judgment, PM and PM10 control efficiencies were assumed to be 95 to >99 percent. PM2.5 control efficiencies were estimated to range from 90.0 to 99.0 percent. These control efficiency ranges are for stand-alone units that are used as the primary control device.

Cost
The average cost per ton of particulate matter controlled is approximately $1,000. This average is derived from data which represents a broad range of applications for this control technology (Pechan, 1995).

014   Spray Chamber Wet Scrubber

For PM Control

Description
In spray chambers, particulate-laden gas is introduced into a chamber where it comes into contact with liquid droplets generated by spray nozzles. Particles collide with the droplets, are collected into the liquor, and carried out of the scrubber. Types of spray chambers include spray towers, cyclonic spray towers, and vane-type cyclonic towers (EPA, 1982).

Application
Spray chamber wet scrubbers have been used in the following industries to control PM emissions: primary and secondary non-ferrous metals processing (e.g., copper, lead, and aluminum), steel production, pulp and paper manufacturing, asphaltic concrete manufacturing, and surface coating (EPA, 1973b; EPA, 1982).

Control Efficiency
Published PM, PM10, and PM2.5 control efficiency data for determining low-end control efficiencies for existing spray chambers are limited. PM control efficiencies reported in EPA (1973b) are listed as follows by industry (the process type on which the scrubbers were used is shown in parentheses):

- 70 percent – steel production (basic oxygen furnace);
- 70 percent – aluminum ore production (bauxite crushing and handling);
- 71 percent – aluminum ore production (horizontal stud Soderberg process);
- 75 percent – aluminum ore production (vertical stud Soderberg process);

- 80 to 83 percent – aluminum ore production (electroreduction, prebake cells);
- 90 percent – surface coating (varnish and shellac); and
- 99.9 percent – asphaltic concrete manufacturing (rotary dryer).

Based on these data, 70 and >99.5 percent were selected to represent the PM control efficiency range for spray chamber wet scrubbers. No control efficiency data could be identified for PM10 and PM2.5. The low-end PM10 control efficiency value was assumed to be the same as that for PM, and the high-end PM10 control efficiency value was assumed to be 99 percent. For PM2.5, the range is based on the control efficiency range discussed for the "scrubber (general, not classified)" control equipment code.

For SOx Control

Description
A spray tower scrubber can be vertical or horizontal. The absorbing or reactive material slurry or solution is introduced in the scrubber in atomized droplets through the spray nozzles at the top. The flow of gas and absorbing slurry or solution is crosscurrent in a horizontal design and countercurrent in a vertical design. Absorbate of varying degrees of richness can be introduced at different stages in the tower. Often the fresh absorbate (recycle and makeup streams) is introduced at the rear or top of the absorber (the last stage) where the SO_2 content of the gas stream is lowest. The absorbate collected in the last stage is pumped forward to the next stage. In effect, the absorbate "flows" countercurrent to the gas flow. The first stage of the absorber has the highest SO_2 concentration gas stream and an absorbing slurry or solution that has had much of its active absorbent or reactive ability exhausted (EPA, 1981).

Application
Spray towers have been used in many different scrubbing systems and are becoming the predominant absorber vessel due to their simplicity (Smith, 1994; Soud, 1993; Satriana, 1981).

Control Efficiency
The typical control efficiency range is from 80 to >99 percent. The control efficiency of the absorber component of a scrubbing system depends upon the overall design of the system and the absorbent used in the system.

Cost
Costs per ton of SO_2 controlled are dependent upon the overall design of the scrubbing system and cannot be determined for the absorber component of the system alone.

For VOC Control

Description
The spray tower is another wet scrubbing device for the control of gaseous pollutants by absorption. Spray towers are vertical enclosed columns with nozzles that atomize an absorbent liquid suitable for the waste gas stream. Flow is usually countercurrent, with liquid flowing down and gas upward. Spray towers are an

inexpensive option used to remove gas, vapor, and odors in cases involving highly soluble VOCs or where a low control efficiency is acceptable. Although not as common, cocurrent and crossflow configurations are also used.

Mist scrubbers are essentially once-through (non-regenerable) co-current spray towers, in which the absorbing liquid is finely atomized. Both the absorbing mist and the waste gas stream enter the column at the top. The absorbing liquid is generally softened water and hypochlorite, to which other chemicals can be added to enhance absorption in specific cases. The atomizing nozzle creates droplets of absorbing liquid as small as ten micrometers, which provide a large surface area for maximum absorption. The tower is sized to provide the necessary residence time to achieve the desired control efficiency (RTI, 1995).

Application
Spray towers have the least effective mass transfer capability and are generally limited to use for particulate removal and with high-solubility gases (EPA, 1992d). Mist scrubbers have been installed to control odors from wastewater treatment and rendering plants.

Control Efficiency
The typical control efficiency range is 50 to 95 percent. Lower control efficiencies represent flows containing insoluble compounds at low concentrations, while the higher efficiencies are for flows which contain readily soluble compounds at high concentrations. Traditional spray towers generally are in the lower part of the range, while mist scrubbers can achieve high control efficiencies for highly soluble contaminants (RTI, 1995; Perry, 1984).

Cost
Little cost information is available for control of VOCs with spray towers or for mist scrubbers in general.

015 Gravity Collector

Description
Gravity collectors, also called gravity settling chambers or settling chambers, are add-on control devices that rely on gravity as the mechanism for removing large particles from a gas stream. There are three general types of settling chambers -- the expansion chamber, multiple-tray settling chamber, and elutriator. Settling chambers are designed for low velocities with a minimum of turbulence so that the settling of particles is not reentrained in the gas stream exiting the device. To prevent reentrainment, uniform gas stream distribution across the chamber inlet is important. Typical superficial velocities range from 0.3 to 3 meters per second (EPA, 1982).

In the expansion chamber, the velocity of the gas stream is significantly reduced as the gas expands into a large chamber. The reduction in velocity allows larger particles to settle out of the gas stream. Expansion chambers are most effective for controlling large and/or dense particles. The efficiency of gravity chambers increases with the residence time of gas in the chamber. Therefore, they are designed to operate at the lowest possible

gas velocity to prevent dust from becoming reentrained but not so low that the chamber is unreasonably large.

A multiple-tray settling chamber is an expansion chamber with a number of thin trays closely spaced horizontally within the chamber. The trays act as collection plates that reduce the distance a particle must fall to reach the collection surface. Because small particles settle more slowly than large particles, trays are included in a settling chamber to improve the collection of small particles by decreasing the particle settling distance. In both types of settling chambers, the particles settle into collection hoppers at the base of the chamber which are cleaned periodically (EPA, 1982).

The elutriator consists of one or more vertical tubes or towers. The gas stream is passed upward through a tube, allowing particles with terminal settling velocities greater than the upward gas velocity to settle and collect at the bottom of each tube. Removal of different size classifications of particles can be achieved by using a series of tubes with different diameters. The gas stream is passed through the small diameter tube first to collect the largest particles and then through tubes with larger diameters to allow the smaller particles to settle out (EPA, 1982).

Application
Mechanical collectors are used on a wide variety of processes in many different industries. According to one reference, elutriators are typically used to control PM emissions from secondary metal operations, food and agricultural processes, and processes in the petrochemical industry (EPA, 1982).

Control Efficiency
Mechanical collectors are most effective for controlling large and/or dense particles. The efficiency of mechanical collectors decreases as particle size decreases.

EPA (1982) presents fractional collection efficiencies based on a number of studies on high density iron oxide particles and low-density quartz dust particles. Based on this data, it is concluded that overall control efficiencies would range from 10 to 99 percent depending on the size of particles to be controlled. The low-end of the range applies to gas streams with a high concentration of particles with diameters ranging from 10 to 40 μm, and the high-end of the range applies to gas streams with a high concentration of particles with diameters $\geq$90 μm. The control efficiencies for mechanical collectors is minimal for particle sizes $\leq$10 μm. Thus, PM10 and PM2.5 control efficiencies for mechanical collectors is assumed to be zero percent.

016 Centrifugal Collector

Description
Centrifugal collectors or separators are add-on control devices that rely on inertia as the mechanism for separating particles from a gas stream. They are also called mechanically-aided separators and dry dynamic separators. These devices involve the use of a rotary vane (e.g., radial blade fan) to mechanically impart a centrifugal force on the particles in the gas stream causing them to separate from the gas stream. The particles are collected in a dust hopper for removal and disposal. The most common design is a modified radial blade fan where the particulate laden gas stream enters the device

perpendicular to the blade rotation, and momentum forces the particles to cross the gas stream and collect in the side of the collector casing. The rapid acceleration of the gas stream imparted by the rotation of the blades maintains the concentrated particles in a narrow band which is then drawn off for particle separation in a more efficient collector. Many collectors use this design principle to concentrate particles into a smaller gas volume (EPA, 1982).

Application

      Centrifugal collectors are compact and are particularly useful where a large number of individual collectors are required. These devices cannot be generally used to collect particles that cake or tend to accumulate on the rotary vane or blades causing clogging or unbalancing of the blades. Also, they are subject to abrasion by the action of large-diameter particles at medium to high velocities (EPA, 1982).

Control Efficiency

      EPA (1982) presents theoretical fractional collection efficiency curves for two types of centrifugal collectors. The fractional efficiency curve for one type is very similar to that discussed for momentum separators. The fractional efficiency curve for the other type is significantly below that discussed for momentum separators. As a result of a lack of control efficiency data for centrifugal collectors, the control efficiency ranges for this type of control were assumed to be the same as those for momentum separators.

017 Momentum Separator

Description

      Momentum separators are add-on control devices that use both gravity and particle inertia (momentum) to separate particles from the gas stream. Separation occurs by forcing the gas flow to sharply change direction so that the momentum of the particles carries the particles across the gas flow direction and into a collection hopper. The simplest designs provide a 90- to 180-degree turn in the gas flow to separate large particles. In some designs, baffles are added to increase the number of turns in the gas flow direction providing for a modest increase in collection efficiency. Typically, the gas flows downward and then is forced by the baffles to suddenly flow upwards. Inertial momentum and gravity act in the downward direction on the particles, which causes larger particles to collect in the bottom of the chamber. Momentum separators require less space but have higher pressure drops than expansion chambers and multiple-tray chambers (EPA, 1982).

Application

      Momentum separators are used on a wide variety of processes in many different industries.

Control Efficiency

      Because momentum separators use inertia and gravity as particle removal mechanisms, they can achieve higher control efficiencies and collect smaller particles than gravity collectors. The control efficiency of a momentum separator increases as the gas velocity through the device increases. However, the pressure drop and operating costs also increase with gas velocity; therefore, the optimum velocity must be selected to balance efficiency and operating costs. EPA (1982) presents a fractional collection efficiency curve

for a momentum separator controlling fly ash. Fractional collection efficiencies are ≤5 percent for a particle size of 5 μm, 10 to 20 percent for a particle size of 10 μm, and up to 99 percent for particle sizes ≥90 μm.

For PM, it is concluded that overall control efficiencies range from 30 to 99 percent depending on the size of the particles controlled. The low-end of the range applies to gas streams with a high concentration of particles with diameters ranging from 10 to 40 μm, and the high-end of the range applies to gas streams with a high concentration of particles with diameters ≥90 μm. The control efficiencies for momentum separators is low for particle sizes ≤10 μm. PM10 control efficiencies were assumed to be ≤10 percent, and PM2.5 control efficiencies were assumed to be ≤5 percent.

018   Tray-Type Scrubber

Description
A tray-type scrubber typically consists of a vertical chamber with one or more perforated plates mounted horizontally inside a hollow shell. The liquid flows from top to bottom, and the gas flows from bottom to top. Gases mix with the liquid passing through the openings in the plates. After the bottom plate, the liquid and collected PM flow out of the bottom of the chamber. Types of tray-type scrubbers include sieve-type towers, perforated plate scrubbers, impingement-plate scrubbers, and horizontal impingement-plate (baffle) scrubbers. Scrubbers equipped with perforated plates are typically called "sieve tray towers," and scrubbers equipped with rigid baffles placed opposite each perforation are typically called "impingement plate" scrubbers (AWMA, 1992). Particles greater than 1 μm in diameter can be collected effectively by impingement plate scrubbers, but many particles less than 1 μm will penetrate these devices (EPA, 1982).

Application
Tray-type wet scrubbers have been used in the following industries to control PM emissions: chemical manufacturing, pulp manufacturing, gray iron foundry production, lime manufacturing, and coal cleaning (EPA, 1973b; EPA, 1982).

Control Efficiency
Published PM, PM10, and PM2.5 control efficiency data for determining low-end control efficiencies for existing tray-type scrubbers are limited. PM control efficiencies reported in EPA (1973b) are listed as follows by industry (the process type on which the scrubbers were used is shown in parentheses):

- 55 to 85 percent – pulp manufacturing (sulfate pulping recovery boilers);
- 81 percent – diammonium phosphate fertilizer manufacturing (granulator);
- 91 percent – gray iron foundry production (cupola furnace);
- 95 percent – lime manufacturing (crushing operations and rotary and vertical kilns); and
- 99 percent – coal cleaning (thermal, flash, and fluid-bed dryers).

Based on these data, 55 and 99 percent were selected to represent the PM control efficiency range for tray-type wet scrubbers. No control efficiency data could be identified for PM10 and PM2.5. The PM10 control efficiency range was assumed to be the same as

the range for PM. For PM2.5, the range is based on the control efficiency range discussed for the "scrubber (general, not classified)" control equipment code.

019 Mat or Panel Filter

Description
Mat or panel filters are used to remove paint particles from the air in paint spray booths. Emissions of paint particles result from the use of air atomization spray guns (EPA, 1973a). Paint that is not deposited on the substrate being painted is called overspray. The amount of overspray depends on the shape of the substrate, the type of spray gun used, the solids content of the paint, and the experience of the spray gun operator. Overspray is lowest for flat surfaces and higher for irregular surfaces. Electrostatic spraying also decreases overspray.

Mat or panel filters are similar to air filters used in heating and air conditioning systems. Each unit consists of a rigid frame and a pad of filter material. Filters are classified as either viscous or dry. Viscous filters are coated with a viscous material such as an oil with a high flash point and low volatility to help catch dust and prevent dust reentrainment. A ventilation system is used to draw air through mat or panel filters located at the back of the paint booth to remove PM emissions. Filter materials used include glass fibers, hemp fibers, corrugated fiberboard, split wire, or metal screening. Viscous filters can be operated at air velocities ranging from 300 to 500 feet per minute. Dirty filters can be disposed of or washed or steamed clean, reoiled, and replaced (EPA, 1973a).

Dry filters are supplied in units similar to viscous filters, except that the depth is usually greater. The filter materials usually have smaller air passages than the viscous filters, and, therefore, lower air velocities must be used to prevent excessive pressure drop. Dry filters can be operated at air velocities ranging from 30 to 60 feet per minute. To increase the filtering area, the filter pads are often arranged in an accordion form with pleats and pockets. Dirty dry filters are disposed because they cannot be cleaned and reused (EPA, 1973a).

Application
Dry filters are frequently used in paint spray booths to control PM emissions. A common industrial application of the wire screen-type filter is in collection of mist generated from cutting oils used by metal-cutting machines.

Control Efficiency
According to EPA (1973a), mat or panel filters can control paint particles as high as 98 percent. No information was identified on typical low-end control levels for mat or panel filters. Therefore, the low-end of the control effectiveness range was assumed to be 10 percent based on the value used in the previous version of the CEC data base. No information was identified on the control effectiveness of mat or panel filters for PM10 and PM2.5. PM10 control efficiency is estimated at 10 to 90 percent.

Cost
No cost information was identified for mat or panel filters. Costs would vary depending on the volume of air treated and the how frequently the paint booth is used.

020 Gravel Bed Filter

Description

The gravel-bed filter consists of several cylindrical compartments. Each compartment consists of quartz granules of about 2 to 5 millimeters in diameter lying on a wire mesh. As dirty gases are drawn through the beds, the dust drops out of the gas stream and remains in the bed. The beds are individually cleaned at regular intervals by reversing the airflow and agitating the gravel with an internal rake system. The gravel-bed filter is somewhat sensitive to flow volume changes that tend to result in PM emissions that are higher than normal (AWMA, 1992).

Application

Gravel-bed filters were developed for use in controlling emissions from kilns used to manufacture cement. However, they have been applied in other industries (e.g., ferroalloy production, ceramic clay manufacturing, and stone quarrying and processing) to control PM emissions from high-temperature flue gas streams. The advantage of the gravel-bed filter relative to a fabric filter is its ability to tolerate high-temperature gas temperatures, or high-temperature excursions, without permanent damage to the filter media (AWMA, 1992).

Control Efficiency

Published PM, PM10, and PM2.5 control efficiency data for existing gravel-bed filters are limited for determining low-end control efficiencies. When EPA developed the NEDS in the early 1970s [(predecessor to the Aerometeric Information Retrieval System/ Facility Subsystem (AIRS/FS)], it prepared control equipment codes for use in defining control equipment types in the point source emissions inventory. The average overall PM control efficiency for the control equipment in a given industry is summarized in EPA (1973). The control efficiency data were obtained from technical background information documents and published articles. The PM control efficiencies reported in EPA (1973) are listed as follows by industry:

- 98.2 percent – ferroalloy production (open furnace);
- 99.1 percent – ceramic clay manufacturing (dryer);
- 99.2 percent – stone quarrying and processing (crushing and screening);
- 99.6 percent – dry cement production (clinker cooler); and
- 99.8 percent – wet cement production (dryers and grinders).

State submitted fabric filter PM control efficiencies for point sources contained in EPA's AIRS/FS data base ranged from about 90.00 to 99.80 percent. Based on the data from these two information sources, 90.0 and >99.5 percent were selected to represent the PM control efficiency for gravel-bed filters. No control efficiency data could be identified for PM10 and PM2.5. The high-end control efficiency value for PM10 and PM2.5 was assumed to be 99 percent. The low-end control efficiency values for PM10 and PM2.5 were assumed to be 85 and 80 percent, respectively.

Cost

No cost information was identified for gravel-bed filters.

021 Gravel Bed Moving Filter

022 Gravel Bed Moving Filter - Electrostatically Augmented

Description

An alternative design of the gravel-bed filter involves the use of a slow moving bed of granular rock as the filtration medium. Gravel is held between front and rear louver sets to form the filter bed. The louver structure provides large, nonfouling passages for the gas while retaining gravel by its angle of repose. The gravel is removed from the filter bed and cleaned externally in a pneumatic conveyor on a continuous basis. The dust removed from the gravel is conveyed to a small pulse-jet fabric filter, and the cleaned gravel is returned to the filter bed. Gravel-bed moving filters are also called granular-bed moving filters (AWMA, 1992).

To enhance efficiency, gravel-bed moving filters can be electrostatically augmented (10 to 20 watts/1,000 actual cfm of flue gas flow). Prior to entering the filter bed, the gas stream is ionized to impart a negative charge on particles in the gas stream. Gravel-bed moving filters are also called electrostatically augmented granular-bed moving filters or electrified filter beds (EPA, 1989).

Application

Gravel-bed moving filters have been designed to remove PM emissions from high-temperature gas streams to eliminate the potential for fire hazard associated with the use of fabric filters, and they are designed to remove PM emissions from gas streams with a high moisture content that otherwise would foul and corrode a fabric filter. In addition, the filters collect fine PM that would otherwise require the use of a high-pressure drop scrubber (AWMA, 1992; EPA, 1989). Gravel-bed moving filters are most frequently used to control emissions from oriented strand board, particleboard, chipboard, plywood veneer dryers in the waferboard manufacturing industry, but also have been applied to control PM emissions from wood/bark waste fired boilers, coal fired boilers, asphalt saturators, polyethylene and polyvinyl chloride curing ovens, silicone rubber curing ovens, glass bubble formers, hospital and municipal solid waste incinerators. They have also been applied to control PM emissions from sources in the metal polishing, brass smelting, aluminum production, fiberglass curing, and plastics industries (EPA, 1989).

Control Efficiency

According to AWMA (1992), gravel-bed moving filters can achieve PM control efficiencies ranging from 90 to 95 percent for a new wood waste fired boiler that must meet a 0.1 lb/MMBtu PM emission limit. Electrostatically augmented gravel-bed moving filters can achieve PM control efficiencies ranging from 98 to 99.2 percent for a new wood waste fired boiler that must meet a 0.1 lb/MMBtu PM emission limit. According to EPA (1989), PM control efficiencies for electrostatically augmented gravel-bed moving filters range from 79 to 94 percent based on test data obtained for units used to control dryers in the waferboard industry.

The low-end of the PM control efficiency range for gravel-bed moving filters with and without electrostatic augmentation is assumed to be 80 percent based on the range of control efficiencies presented in EPA (1989). The high-end of the PM range for gravel-bed

moving filters without electrostatic augmentation is estimated at 95 percent based on data presented in AWMA (1992). The high-end of the PM range for gravel-bed moving filters with electrostatic augmentation is estimated at >99.0 percent based on data presented in AWMA (1992).

No data were identified to determine control efficiency ranges for PM10 or PM2.5, but the low end of the PM10 control efficiency range is estimated to be 70 percent, the high end of the PM10 range for gravel-bed moving filters without electrostatic augmentation is estimated at 90 percent, and the high-end of the PM10 range for gravel-bed moving filters with electrostatic augmentation is estimated at 95.0 percent, based on professional judgment.

023 Mechanically-Aided Scrubber

Description
In a mechanically-aided scrubber, the droplet dispersion is created by a whirling mechanical device, usually a fan wheel or disk. Liquid is injected into or onto the disk and mechanical energy is added to the system to break the liquid into fine droplets. The mechanically driven device acts on both the liquid and the gas (AWMA, 1992). Mechanically-aided scrubbers have also been referred to as wet dynamic separators.

Application
Mechanically-aided wet scrubbers have been used in the following industries to control PM emissions: metal can fabrication, phosphate rock processing, starch manufacturing, and asphaltic concrete manufacturing (EPA, 1973b).

Control Efficiency
Published PM, PM10, and PM2.5 control efficiency data for determining low-end control efficiencies for existing mechanically-aided scrubber are limited. PM control efficiencies reported in EPA (1973b) are listed as follows by industry (the process type on which the scrubbers were used is shown in parentheses):

- 96 percent – phosphate rock processing (grinding);
- 97.5 percent – starch manufacturing (general);
- 99 percent – metal can fabrication (spray coating);
- 99 percent – phosphate rock processing (transfer and storage); and
- 99.9 percent – asphaltic concrete manufacturing (rotary dryer).

Based on these data, >99 percent was selected to represent the high-end PM control efficiency for mechanically-aided wet scrubbers. The low-end PM control efficiency (i.e., 70 percent) was based on that for spray chamber wet scrubbers to represent existing units that have been operating several years and suffered deterioration in performance or were installed to meet emission limits established several years ago that would be considered relatively lenient as compared to current emission limits.

No control efficiency data could be identified for PM10 and PM2.5. The low-end PM10 control efficiency value was assumed to be the same as that for PM, and the high-end PM10 control efficiency value was assumed to be 99 percent. For PM2.5, the range is

based on the control efficiency range discussed for the "scrubber (general, not classified)" control equipment code.

024 Condensation Scrubber

Description

Condensation scrubbing is a relatively recent development in wet scrubber technology. In a condensation scrubber, the PM acts as condensation nuclei for the formation of droplets. Generally, condensation scrubbing depends on first establishing saturation conditions in the gas stream. Once saturation is achieved, steam is injected into the gas stream. The steam creates a supersaturated condition and leads to condensation of water on the fine PM in the gas stream. The large, condensed droplets are then removed by conventional devices (McIlvaine, 1995; Sun et al., 1994).

Application

Condensation scrubbers have been applied to control PM emissions from incinerators. Typically, they are applied where it is necessary to obtain high control efficiencies for fine PM. Thus, they are applicable to controlling emission sources with high concentrations of submicron particles.

Control Efficiency

Information on control efficiency ranges for condensation scrubbers was not identified. Based on professional judgement, the control efficiency range for condensation scrubbers was assumed to be the same as that specified for venturi scrubbers.

025 Charged Scrubber

Description

Charged scrubbers use electrostatic effects to improve collection efficiencies for fine PM with wet scrubbing. Pre-charging the PM in the gas stream can significantly increase scrubber collection efficiency for submicron particles, without increasing the pressure drop of the scrubber and thus operating costs. However, electric power costs associated with charging the scrubber increase scrubber operating costs. When both the particles and droplets are charged, collection efficiencies for submicron particles are highest, approaching that of an ESP. The PM can be charged negatively or positively, with the droplets given the opposite charge (McIlvaine, 1995).

Application

Charged scrubbers have been applied to control PM emissions from coke manufacturing and the lead and aluminum production industries. Typically, they are applied where it is necessary to obtain high collection efficiencies for fine PM. Thus, they are applicable to controlling emission sources with high concentrations of submicron particles.

Control Efficiency

Information on control efficiency ranges for charged scrubbers was not identified. Based on professional judgement, the control efficiency range for charged scrubbers was assumed to be the same as that specified for venturi scrubbers.

026 Packed-Bed Scrubber

Description

In vertical-flow packed-bed scrubbers, liquid is introduced above the packing and flows down through the bed. The packing material, such as raschig rings, pall rings, berl saddles, and crushed rock, is held in place by wire mesh retainers and supported by a plate near the bottom of the scrubber. As the liquid flows through the packing, it forms a thin film on the packing material. This film collects the PM in the gas stream as the gas is forced through the packing. Types of packed-bed scrubbers include standard single and double packed-bed scrubbers, fiber- or filter-bed scrubbers, moving-bed scrubbers, cross-flow scrubbers, and grid-packed scrubbers (EPA, 1982; McIlvaine, 1995).

Packed-bed scrubbers used to control chromic acid mist are either horizontal or vertical countercurrent-flow units equipped with one or two packed beds followed by a chevron-blade mist eliminator. Control device vendors estimate that removal efficiencies for these units range from 95 to 99 percent. The scrubber also contains a mist elimination section located downstream of the packed bed(s) to collect any water carry-over. Generally, a conventional chevron-blade mist eliminator is used. The packing media used to control chromic acid mist typically are ballast rings or saddle-shaped packing made of polypropylene (EPA, 1993c).

Fan-separator packed-bed scrubbers are also used to control acid mists. They consist of two stages: a dynamic scrubbing stage followed by an impingement stage. In the first stage, ventilation air is ducted into the eye of a backward-blade centrifugal fan, where it is sprayed with a small volume of water or other scrubbing liquid under high pressure. In the second stage, the exhaust gas flows into an expansion chamber containing one or two packed beds of tubing made of polypropylene. Control efficiencies are estimated to range from 95 to 99 percent (EPA, 1993c).

Application

Packed-bed wet scrubbers have been used in the following industries to control PM emissions: primary and secondary non-ferrous metals processing (e.g., aluminum), coke production, pulp and paper manufacturing, chemical manufacturing, electroplating, and incineration of hazardous, liquid, and gaseous wastes (EPA, 1973b; EPA, 1982; EPA, 1993c; McIlvaine, 1995).

Control Efficiency

The primary operating parameters affecting the performance of packed-bed scrubbers are the liquid-to-gas ratio and the superficial gas velocity entering the packed bed. Other factors that affect the performance of a packed-bed scrubber are the surface contact area of the packing media and the distribution of the packing media in the packed bed. Another factor affecting performance is the excessive pollutant buildup on the packing material that may lead to reentrainment of the pollutant droplets from the packed bed or plugging of the bed.

Published PM, PM10, and PM2.5 control efficiency data for determining low-end control efficiencies for existing packed-bed scrubbers are limited. PM control efficiencies reported in EPA (1973b) are listed as follows by industry (the process type on which the scrubbers were used is shown in parentheses):

- 85 percent – aluminum ore production (electroreduction, prebake cells);
- 94.5 percent – electroplating (general);
- 95.5 percent – phosphoric acid manufacturing (general); and
- 99 percent – hydrochloric acid manufacturing (HCl mist).

EPA (1993c) provides control efficiency data for packed-bed scrubbers used to control chromic acid mist from hard chromium electroplating baths. For test conducted on three packed-bed scrubbers at three separate plants, average control efficiencies ranged from 96.2 to 99.4 percent for chromic acid mist.

Based on the data presented in the two EPA publications, the PM control efficiency range was assumed to be 85 to >99 percent. The low-end PM10 control efficiency value was assumed to be the same as that for PM, and the high-end PM10 control efficiency value was assumed to be 99 percent. For PM2.5, the range is based on the control efficiency range discussed for the "scrubber (general, not classified)" control equipment code.

027 Fluid-bed Dry Scrubber

Description
        Fluid-bed dry scrubbers are used in the primary aluminum manufacturing industry to control PM emissions from pot rooms and anode bake furnaces. The PM emissions consist of gaseous and particulate fluoride, carbon dust, and alumina. Alumina is used to scrub the gaseous fluoride emissions and the alumina containing fluoride is fed to manufacturing process. The dry scrubbing system consists of a fluid-bed reactor with a fabric filter located on top of the reactor. The potroom gases containing fluoride are reacted with alumina in the reactor and then passed through the fabric filter. The fabric filter captures and returns the entrained alumina particles to the reactor, as well as particulate fluoride and carbon particles produced by the cells in the potroom. Most of the fabric filters used are of the mechanical-shaker type; however, pulse-jet fabric filters have also been used (AWMA, 1992).

Application
        Fluid-bed dry scrubbers are used exclusively to control PM, fluoride, and hydrocarbon emissions from potroom prebake cells and anode baking furnaces in the manufacture of primary aluminum.

Control Efficiency
        According to AWMA (1992), fluid-bed dry scrubber systems can achieve over 99 percent control of PM and fluoride emissions from potroom prebake cells and anode baking furnaces. PM emissions consists of gaseous and particulate fluoride, carbon dust, and alumina. Based on professional judgement, the control efficiency ranges for PM, PM10, and PM2.5 were assumed to be the same as those specified for fabric filters.

        According to AWMA (1992), these systems can achieve 90 percent control of hydrocarbon emissions from anode baking furnaces. Therefore, 90 percent was selected to represent the high-end control efficiency. Based on professional judgement, 80 percent was selected as the low-end control efficiency to represent control levels associated with malfunctions or process upsets.

028 Dust Suppression by Water Sprays

029 Dust Suppression by Chemical Stabilizers or Wetting Agents

Description

Wet suppression is a temporary measure for controlling fugitive PM emissions, which uses liquid sprays of water, a water solution of a chemical agent (a surfactant or a foaming agent), oil, or micron-sized foam to control emissions. Wet suppression controls emissions by agglomeration (i.e., combining small dust particles with larger particles/aggregates or liquid droplets) to prevent or suppress the PM from leaving the surface and becoming airborne (AWMA, 1992). Use of surfactants reduces the surface tension of the water and can reduce the quantity of liquid needed to achieve good dust control. Foam systems also use less water (or moisture) than spray systems. Data indicate, however, that for some operations, foam systems do not achieve a measurable level of control until a threshold application rate is reached (EPA, 1996b).

Application

Wet suppression can be used to control emissions from sources such as unpaved roads, unpaved parking lots and staging areas, construction sites, exposed areas, material handling and conveying (including batch drop operations such as front-end loaders, shovels, etc., and continuous drop operations such as conveyor transfer points, stacking/reclaiming activities, etc.), pushing (dozing, grading, scraping), storage piles, waste heaps, and cattle feedlots (EPA, 1982; AWMA, 1992).

For materials handling sources, the point of application is most commonly at the conveyor feed and discharge points, but some are at conveyor transfer points and equipment intakes (EPA, 1982).

Control Efficiency

The typical control efficiency range is 30 to 95 percent. Control efficiencies of unpaved road watering depend on the following conditions: the amount of water applied per unit of road surface; the time between reapplications; the traffic volume during that period; and prevailing meteorological conditions during the period (AWMA, 1992). Control efficiencies for the use of oil on unpaved roads have been estimated to be 95 percent for PM10 (EPA, 1994d).

Extensive wetting at construction sites can reduce fugitive soil emissions as much as 70 percent (Siebel, 1976). Wetting of access roads at construction sites twice a day with approximately 5 gallons of water per 100 square feet will suppress fugitive dust from normal construction practices by 30 to 50 percent (EPA, 1982).

Current data show a wide range of control efficiencies for wet suppression at material handling operations such as conveyor transfer points and storage piles (EPA, 1996b). Spray systems on material handling operations are estimated to reduce emissions by 70 to 95 percent. For conveyor transfer points, the range of measured control efficiencies is 42 to 75 percent for liquid sprays and 0 to 92 percent for foam systems. Control efficiencies of 80 percent were reported for spray systems at rail car unloading

stations at iron and steel plants (EPA, 1978). Using wet suppression techniques, estimated control efficiencies of 80 percent have been reported for cattle feedlots (Siebel, 1976).

Based on a review of the references discussed in this section, the PM control efficiency range for properly applied wet suppression by water and by chemical stabilizers or wetting agents is estimated to be 30 to 99 percent. For PM10, the range was estimated to be 30 to 95 percent. For PM2.5, the range was estimated to be 30 to 90 percent. The ranges are wide because many factors determine the effectiveness of dust suppression by water and by chemical stabilizers or wetting agents. No information was identified on the effectiveness of these techniques for controlling PM2.5; this estimate is based solely on professional judgment

The period of time over which these control efficiencies are effective is another important consideration. When atmospheric conditions are favorable, such as calm winds, medium to high relative humidity, and overcast skies, wet suppression will be effective for a longer period of time than when conditions are windy, dry, and sunny.

Cost
The average cost per ton of particulate matter controlled is approximately $6,000 for water dust suppression, and $1,000 for chemical glass absorption. These averages are derived from data which represents a broad range of applications for these control technologies (Pechan, 1995).

030 Water Curtain

Description
Water curtains (or water sprays) are used to remove paint particles from the air in paint spray booths. Emissions of paint particles result from the use of air atomization spray guns (EPA, 1973a). Paint that is not deposited on the substrate being painted is called overspray. The amount of overspray depends on the shape of the substrate, the type of spray gun used, the solids content of the paint, and the experience of the spray gun operator. Overspray is lowest for flat surfaces and higher for irregular surfaces. Electrostatic spraying also decreases overspray.

A ventilation system is used to draw air through a water curtain or sprays located at the back of the booth. A water circulation rate of 10 to 38 gallons per 1,000 cubic feet of exhaust air is recommended. Surface active agents may be added to the water to aid in the removal of paint from the circulating tank (EPA, 1973a).

Application
Water curtains (or water sprays) are used in paint spray booths to control PM emissions.

Control Efficiency
According to EPA (1973a), well designed water curtain or spray systems can control paint particles as high as 95 percent. No information was identified on typical low-end control levels for mat or panel filters. Therefore, the low-end of the control effectiveness range was assumed to be 10 percent based on the value used in the previous version of the

CEC data base. In addition, no information was identified on the control effectiveness of mat or panel filters for PM10 and PM2.5.

Cost

No cost information was identified for mat or panel filters. Costs would vary depending on the volume of air treated and the how frequently the paint booth is used.

031 Chemical Fume Suppressants for Electroplating and Anodizing Tanks

Description

Chemical fume suppressants are surface-active compounds that are added directly to chromium plating and chromic acid anodizing baths to reduce or inhibit misting. Fume suppressants are classified as temporary or as permanent. Temporary fume suppressants are depleted primarily by decomposition of the active chemical components, and permanent fume suppressants are depleted by drag-out of the solution. Fume suppressants, which are manufactured in liquid, powder, or tablet form, include wetting agents, foam blankets, and combinations of both wetting agents and foam blankets (EPA, 1993c).

Wetting agents are surface-active compounds that reduce or inhibit misting by lowering the surface tension of the plating or anodizing bath. When the surface tension of the solution is lowered, gases escape at the surface of the plating solution with less of a "bursting" effect, forming less mist. Fume suppressants that produce a foam blanket do not preclude the formation of chromic acid mist, but rather trap the mist formed under the blanket of foam (EPA, 1993c).

Combination fume suppressants (wetting agent plus a foam blanket) reduce the surface tension of the plating bath while forming a foam blanket over the surface. Because of the synergistic effects of the two components, less product is required than if either the wetting agent or the foam blanket were used alone (EPA, 1993c).

Application

Fume suppressants are used widely by decorative chromium electroplaters. In contrast, hard chromium electroplaters seldom use fume suppressants. Fluorinated wetting agents have a tendency to aggravate pitting, which affects the quality of the hard chromium plate. Also, when foam blankets are used, there is a potential for explosion of the entrapped hydrogen gas. These tendencies are more pronounced in hard chromium plating than in decorative chromium plating because of the higher current densities and longer plating times associated with hard chromium electroplating operations (EPA, 1993c).

Control Efficiency

EPA (1993c) presents the results of tests conducted to evaluate the control effectiveness of a foam blanket, and a combination foam blanket and wetting agent, for controlling chromic acid mist from a decorative chromium electroplating tank. For the foam blanket, the control effectiveness averaged 99.5 percent and ranged from 99.3 to 99.6 percent. For the combination foam blanket and wetting agent, the control effectiveness averaged 99.8 percent and ranged from 99.7 to 99.9 percent. Based on these test results, it

was assumed that PM control efficiencies for chemical fume suppressants range from 99.0 to 99.9 percent. The PM10 control efficiency range was assumed to be the same as that for PM. For PM2.5, it was assumed that control efficiencies could range from 95 to 99.0 percent based on professional judgement.

032 Plastic Balls for Electroplating Tanks

Description

Floating polypropylene balls are often used in plating baths to reduce heat loss, evaporation, and (to a limited extent) misting. The balls are approximately 3.2 cm (1.25 inches) in diameter and are typically recommended to be two layers deep across the surface of the plating solution (EPA, 1993c).

Application

Polypropylene balls are generally used on hard chromium plating baths to reduce evaporation of plating solution and inhibit misting. They are generally not used in automated plating or anodizing operations because plating racks drag the balls out of the baths. The balls tend to be pushed away from the anodes and cathodes where the surface of the bath is agitated by gassing, thus reducing their effectiveness for inhibiting misting (EPA, 1993c).

Control Efficiency

EPA (1993c) presents the results of tests conducted to evaluate the control effectiveness of polypropylene balls for controlling chromic acid mist from a hard chromium electroplating tank. The control effectiveness averaged 74.9 percent and ranged from 68 to 81.9 percent. Two layers of balls were used on the surface of the plating solution during testing. The control effectiveness of the balls depends on how well the plating tank operator maintains coverage of the plating solution with the balls. Based on professional judgement, it was assumed that PM control efficiencies for plastic balls could range from 50 to 80 percent. The low-end value of the range reflects situations where the plastic ball layer is not maintained. The PM10 control efficiency range was assumed to be the same as that for PM. For PM2.5, it was assumed that control efficiencies could range from 20 to 50 percent based on professional judgement.

080 Gas Scrubber (General, Not Classified)

Description

A gas scrubber is a general category of control device in which a gaseous pollutant is removed from a waste gas stream by a wet or dry scrubbing solution, slurry, or powder. In general, some system of fans, pumps, ducts, piping, and specialty scrubbing devices is used to introduce the waste gas to the scrubbing material, which absorbs, and, in many cases, reacts with, the SO_2 present in the waste gas.

Application

Gas scrubbers of various types are used extensively in flue gas desulfurization systems to absorb SO_2 from a waste gas stream into a solution or slurry where it may undergo a chemical reaction.

Control Efficiency

The typical control efficiency range is from 20 to >99 percent.

081 Wellman-Lord/Sodium Sulfite Scrubbing

Description

In this process an aqueous sodium sulfite solution is used to absorb SO_2, usually in a counter-current tray-type column absorber. Sodium bisulfite is formed as the SO_2 is absorbed from the gas steam. The SO_2 is then released in a concentrated stream in the stripping step, in which sodium sulfite is recovered and returned to the absorber loop. The concentrated SOx stream with water vapor enters a condenser, where most of the water is removed. If necessary, the resulting SO_2 stream may be further dried in a concentrated sulfuric acid drying tower. Sulfur compounds from the SOx stream may be recovered as liquid SO_2, liquid SO_3, sulfuric acid, or elemental sulfur, as determined by potential use, market demand, and cost of transportation to the destination (EPA, 1997b; EPA, 1981).

Before reaching the tray tower absorber, particulates or fly ash are removed from the stream by an electrostatic precipitator, fabric filter, wet particulate scrubber, or other device. The stream is normally cooled to its adiabatic saturation temperature in a wet scrubber or presaturator. Humidification of the stream helps to reduce the evaporation of water in the absorbing scrubber. This step also serves to remove most of the chlorides in the stream, which can cause the scrubber water to become acidic, leading to stress corrosion (EPA, 1981).

Application

The Wellman-Lord process is used to reduce SO_2 in waste or tail gas from oil-fired, coke-fired, and coal-fired boilers at electric generation and industrial plants, Claus process sulfur recovery plants, and sulfuric acid plants (Buonicore, 1992; EPA, 1981).

Control Efficiency

The typical control efficiency range is from 90 to >99 percent (EPA, 1997b; EPA, 1981).

Cost

The cost ranges from $500 to $800 per ton of SO_2 controlled (Radcliffe, 1992).

082 Magnesium Oxide Scrubbing

Description

In this FGD process, magnesium oxide, a regenerable SO_2 absorber, is used to reduce the SO_2 concentration in a waste gas stream. A magnesium hydroxide slurry is used in a counter-flow absorber column to absorb SO_2. The magnesium hydroxide slurry is made by slaking magnesium oxide with water. Particulates and fly ash are removed from the gas stream before entry into the absorption tower, usually by an electrostatic precipitator or a wet scrubber. In the absorber, the magnesium hydroxide slurry is introduced to the upper portion of the absorber and reacts with the SO_2 on contact to form hydrated magnesium sulfite, which falls into a recirculation tank at the bottom of the absorber. A portion of the recirculation tank is bled off and sent to a clarifier/thickener

and then a centrifuge. The removed liquid is either sent back to the recirculation tank or used to slake fresh magnesium oxide. The wet cake from the centrifuge is sent to a dryer to remove more water. Typically, a rotary kiln dryer is used, though fluid-bed dryers do exist. After drying, the crystals of magnesium sulfite is sent to a calciner (either rotary or fluid-bed type) to regenerate the magnesium oxide and to liberate the SO_2 in the off-gas. The regenerated magnesium oxide is stored for future use in the gas scrubber system. The off-gas is cooled, cleaned, and processed to yield sulfuric acid, liquid SO_2, or elemental sulfur (EPA, 1997b; EPA, 1981).

Application

Magnesium oxide scrubber systems have been used on coal- and oil fired boilers at electric power generation facilities, at copper smelters, sulfuric acid plants, and Claus process sulfur plants (EPA, 1997b; EPA, 1981).

Control Efficiency

The control efficiency range is from 85 to >99 percent (EPA, 1997b).

Cost

The cost is from $500 to $800 per ton SO_2 controlled (Radcliffe, 1992).

083 Dual Alkali Scrubbing

Description

Several FGD systems may be classified as double or dual alkali systems. Basically, double alkali scrubbing involves absorption of SO_2 in a sodium solution in an absorber, followed by regeneration of the sodium absorbent by a calcium-based alkaline slurry. This process avoids some of the plugging and scaling problems which occur with calcium-based scrubbing systems. The basic absorbent is generally sodium carbonate or sodium hydroxide added to water, though potassium or NH_3 compounds may be used. The flue gas is introduced to the absorber, generally a packed bed or tray-type column, where it reacts with the absorbent. A series of reactions result in sodium sulfite, sodium bisulfite, and some sodium sulfate. After the SO_2 is absorbed, the spent absorbing liquor is bled to the regeneration system, where the absorbent is regenerated with slaked lime or limestone. The calcium sulfite and sulfate species are separated from the regenerated scrubbing liquor, which is recycled to the absorption loop. It may be necessary to add sodium hydroxide or sodium carbonate to the recycled scrubbing liquor for makeup sodium or reduction of residual calcium ions. The calcium-based sludge is sedimented, dewatered, fixated, and transported for disposal or oxidized for sale as gypsum (EPA, 1981; Satriana, 1981).

Application

The dual-alkali scrubbing system has been used to treat the waste gas from coal- and oil- fired boilers for electric utilities and industrial facilities. Originally, this process, was intended as a more efficient and reliable alternative to limestone-based processes, but advances in limestone systems and the relative complexity of the dual-alkali system has prevented its wide application (EPA, 1997b; Dennis, 1993; EPA, 1981).

Control Efficiency

The control efficiency range is from 85 to 95 percent (EPA, 1997b; Sondreal, 1993; EPA, 1981).

Cost

The cost range is from $400 to $700 per ton SO$_2$ controlled (Radcliffe, 1992). The range of costs is dictated largely by reagent availability, transportation, and storage on-site. The added complexity of having two reagent loops adds to the cost of the dual-alkali system.

084 Citrate Process Scrubbing

Description

The citrate process of FGD uses water, buffered by citric acid, to absorb SO$_2$ from the treated waste gas in a wet scrubber. Sodium citrate is used to form a stable buffer system, which is used to inhibit the pH drop which makes the absorption of SO$_2$ into water self-limiting. The scrubbing solution is usually used in a packed-bed column counter-current scrubber, where it reacts with the waste gas flow, which has been cooled and had particulates removed from it. Either sodium hydroxide or sodium carbonate are added to the scrubbing solution to make up for sodium atoms lost in the purge stream from the scrubber. The purge stream is regenerated by one of two processes, the selection of which it determined by the desired byproduct. The bisulfite formed by the reaction of water and SO$_2$ can either be reduced by hydrogen sulfide to give elemental sulfur, or heated to evolve water and SO$_2$, which may be recovered as liquid SO$_2$ or converted to sulfuric acid in an acid plant (EPA, 1981).

Application

This process has been used only at the demonstration and pilot plant level (Lurgi, 1997; Satriana, 1981).

Control Efficiency

The control efficiency range is from 90 to 99 percent (EPA, 1981).

Cost

The citrate process has not been significantly applied beyond the pilot plant stage, and, as a result, there is little commercial cost information available.

085 Ammonia Scrubbing

Description

In this process, an ammonia liquor is used to react with SO$_2$ in a waste gas stream. The waste gas generally requires pretreatment, usually the removal of particulates as required, and cooling and humidification in a quencher. The gas stream is then passed to an absorber, where the scrubbing liquor reacts with the SO$_2$ in the waste gas. The reacted liquor is passed to a tank where the ammonium bisulfite is neutralized to ammonium sulfite by adding NH$_3$. This neutralized liquor is oxidized to ammonium sulfate by compressed air. The ammonium sulfate solution can be can be sold, or concentrated and crystallized to be used as a fertilizer. An ammonia-based scrubbing system has been

developed in which the absorbing liquor is regenerated by thermal stripping to ultimately produce elemental sulfur, but it is not considered as economically viable as the ammonium sulfate-producing nonregenerable process (EPA, 1981; Satriana, 1981).

Application

Ammonia-based SO_2 scrubbers are used primarily to treat the waste gas from pulp and paper plants, sulfuric acid plants, nonferrous smelting plants, as well as some boilers. Regenerative NH_3 systems have been used at the demonstration and pilot plant level (Buonicore, 1992; IEA, 1989; EPA, 1981).

Control Efficiency

The control efficiency range is from 90 to 95 percent (Buonicore, 1992; Satriana, 1981)

086 Catalytic Oxidation - Flue Gas Desulfurization

Description

Both the single- and double-contact processes used to make sulfuric acid from SO_2 involve catalytic oxidation. In both the double- and single-contact processes, the SO_2-containing waste gas must be pretreated, which usually involves dust removal, cooling, and scrubbing for further removal of particulate matter and heavy metals, mist, and moisture. After pretreatment, the gas is heated and passed through a catalytic converter (platinum mass units or units containing beds of pelletized vanadium pentoxide) to oxidize the SO_2 to SO_3. The exothermic, reversible oxidation reaction results in a conflict between high equilibrium conversions at lower temperatures and high reaction rates at high temperatures. Because of this, the gas is passed between the catalyst and two or three different heat exchangers in order to achieve conversion of SO_2 to SO_3 of about 92.5 to 98 percent. The gas leaving the final catalyst stage is cooled and introduced to an absorption tower by a stream of strong (98 to 99 percent) acid, where the SO_3 reacts with water in the acid to form additional sulfuric acid. Dilute sulfuric acid or water is added to the recirculating acid to maintain the desired concentration. The double-contact process differs from the single-contact in that it adds a second absorption tower between the second-to-last and the last catalytic stages (EPA, 1981; EPA, 1997b).

Application

Catalytic oxidation using vanadium pentoxide catalyst is the primary means for turning SO_2 into SO_3, and then sulfuric acid. This process is chiefly used in sulfuric acid plants at nonferrous metal smelters, though it has been applied to coal-fired boiler flue gas (IEA, 1989; Freidman, 1981; EPA, 1981).

Control Efficiency

The typical control efficiency range is from 90 to 99 percent (Friedman, 1981; EPA, 1981). The control efficiency depends upon the overall process used and how many passes the waste gas stream makes through the catalytic reactor (EPA, 1981; Friedman, 1981).

Cost

Catalytic oxidation is a part of several SO_2 control systems, and it is inappropriate to estimate a cost per ton of SO_2 controlled for this portion of an overall process.

087 Dry Sorbent Duct Injection

088 Circulating Dry Scrubbing

Description

The dry sorbent injection process generally involves pneumatically introducing a dry, powdery alkaline material, generally calcium-based (lime or limestone), although sodium-based (nahcolite or trona) sorbents are also used, into a waste gas stream with subsequent particulate collection. The injection point has been varied from the boiler furnace exit to the entrance to an electrostatic precipitator (ESP) or, more typically, a baghouse. The sorbent material reacts with the SO_2 in the gas stream and is collected on filter bags. Filter bags are more popular than ESPs since there is evidence that the removal reaction between SO_2 and the sorbent material takes place, in large part, on the bag surface. The reacted sorbent is disposed of after periodic baghouse cleanings Another process uses a circulating fluidized bed of lime or hydrated lime as a sorbent (EPA, 1997b; Soud, 1993; EPA, 1981).

Application

This technology is typically used to control emissions from smaller coal-fired boilers burning low-sulfur coal, and existing boilers with a limited remaining service life (Sondreal, 1993).

Control Efficiency

The typical control efficiency range for Dry Sorbent Duct Injection is from 50 to 80 percent (EPA, 1997b; Smith, 1994; Sondreal, 1993; EPA, 1981). The range for Circulating Dry Scrubbing is from 70 to 90 percent (Smith, 1994; Soud, 1993). Dry duct injection of lime can achieve 50 to 75 percent removal efficiency, and sodium duct injection can achieve 70 to 80 percent. Circulating fluid bed systems can reach 70 to 90 percent control efficiency (Smith, 1994; Soud, 1993; Sondreal, 1993; Torrens, 1990; EPA, 1981).

Cost

The cost is from \$400 to \$1500 per ton SO_2 removed (Smith, 1994; Sondreal, 1993; Soud, 1993). The range of costs is determined primarily by reagent cost, system size, the amount of redundancy required for adequate system availability, the costs associated with treatment and disposal of spent reagent, and whether the system is a retrofit or a new system. The high end of the cost range is made up of retrofit systems which have high reagent costs due to low reagent usage efficiency coupled with high volumes of low sulfur fuel combustion.

089 Wet Sorbent Injection/Spray Drying

Description

In a spray-dryer system, waste gas at air preheater temperatures (generally, 275° to 400°F) is contacted with a solution or slurry of alkaline material, generally lime or sodium carbonate, in a vessel for five to fifteen seconds residence time. The hot gas is adiabatically humidified to within 50°F of its saturation temperature by the water evaporated from the solution or slurry. As the slurry or solution is evaporated, liquid phase salts are precipitated and the remaining solids are dried to generally less than one

percent free moisture. These solids, along with any ash in the waste stream, are entrained by the waste gas to a particulate collection device, either an ESP or a fabric filter (baghouse). Reaction between the alkaline material and waste gas SO_2 proceeds both during and following the drying process. The by-product is a dry mixture of sulfite, sulfate, fly ash, and unreacted reagent. Generally, part of the by-product is recycled and mixed with fresh reagent to enhance sorbent utilization (EPA, 1997b; Smith, 1994; EPA, 1981).

Application

Wet sorbent injection or spray drying has been used to control SO_2 emissions from small to medium capacity coal combustion boilers burning low to medium sulfur coal and waste incinerators (EPA, 1997b; Smith, 1994; Buonicore, 1992).

Control Efficiency

The typical control efficiency range is from 30 to 90 percent (Smith, 1994; Dennis, 1993). Systems which operate in the higher efficiency range are those which treat waste gas streams with a high enough concentration of SO_2 to efficiently utilize reagent and recycle reagent for maximum reagent usage (Smith, 1994; Dennis, 1993).

Cost

The cost range is from \$300 to \$500 per ton SO_2 reduced (Smith, 1994). The high end of the cost range is made up of systems which treat waste gas from processes which have low SO_2 concentrations. This situation results in low rates of reagent usage, which is already somewhat low compared to other control systems. Capital costs for spray dryer systems are quite low compared with other systems (Smith, 1994).

090 Sulfuric Acid Plant -- Contact Process

Description

The contact process is used to produce sulfuric acid from waste gas which contains SO_2. First, the waste gas must be pretreated, which usually involves dust removal, cooling, and scrubbing for further removal of particulate matter and heavy metals, mist, and moisture. After pretreatment, the gas is heated and passed through a catalytic converter (platinum mass units or units containing beds of pelletized vanadium pentoxide) to oxidize the SO_2 to SO_3. The exothermic, reversible oxidation reaction results in a conflict between high equilibrium conversions at lower temperatures and high reaction rates at high temperatures. Because of this, the gas is passed between the catalyst and two or three different heat exchangers in order to achieve conversion of SO_2 to SO_3 of about 92.5 to 98 percent. The gas leaving the final catalyst stage is cooled and introduced to an absorption tower by a stream of strong (98 to 99 percent) acid, where the SO_3 reacts with water in the acid to form additional sulfuric acid. Dilute sulfuric acid or water is added to the recirculating acid to maintain the desired concentration (EPA, 1981; EPA, 1997b).

Application

Typically, the single-contact process is designed for use in plants where elemental sulfur is oxidized specifically in order to make acid. In recent decades, both elemental-sulfur-burning plants as well as acid plants which treat waste gas are designed for the double-contact process. Nonferrous metals smelting plants, as well as some petroleum refineries, typically have high enough concentrations of SO_2 in waste gases to warrant construction of a sulfuric acid plant (EPA, 1981; Freidman, 1981).

Control Efficiency

The typical control efficiency range is from 95 to 98 percent (EPA, 1997b). The indicated control efficiency range is the conversion efficiency of most single-contact plants converting SO_2 to SO_3 (EPA, 1981; Freidman, 1981).

091 Sulfuric Acid Plant -- Double Contact Process

Description

The double contact, or double absorption, process for making sulfuric acid from waste gas containing SO_2 is essentially the same as the single contact process with the addition of an interpass absorption tower. The waste gas is cleaned and dried as in the single contact process before entering the process. Upon leaving the second or third catalyst bed, depending upon the process, the gas is cooled and introduced to a packed bed, counter-current absorption tower where it contacts 98 to 99 percent sulfuric acid. After the absorbing tower, the gas is reheated and passed to the third or fourth catalyst bed, where approximately 97 percent of the remaining SO_2 is converted to SO_3 and passed to the final absorption tower for conversion to sulfuric acid as in the single contact process (EPA, 1981; EPA, 1997b).

Application

Nearly all sulfuric acid plants, both Frasch process plants that burn elemental sulfur and those used to control SO_2 emissions at smelters or petroleum refineries, use the double contact process to produce sulfuric acid (EPA, 1981; Friedman, 1981).

Control Efficiency

The typical control efficiency is from 98 to >99 percent (EPA, 1997b; EPA, 1981). The indicated control efficiency range is the conversion efficiency of most double-contact plants converting SO_2 to SO_3 (EPA, 1981; Freidman, 1981).

Cost

Costs for a double-contact process plant are generally 10 to 15 percent higher than for single-contact process plants (Friedman, 1981).

092 Claus Process Sulfur Plant, Without Tail Gas Treatment

Description

A Claus process sulfur plant can be used to convert SO_2 gas to salable elemental sulfur. A separate system is used to concentrate the SO_2 present in a waste gas stream. In the Claus process, the SO_2 gas stream is reacted with methane to produce carbon dioxide, water, sulfuric acid, and elemental sulfur. The created sulfuric acid reacts with additional SO_2 to form more water and elemental sulfur. Since the conversion of sulfuric acid and SO_2 is an equilibrium reaction, it is not possible for all the sulfur compounds to be converted to elemental sulfur. For this reason, multiple stages are used to recover more of the sulfur, with each stage recovering half to two-thirds of the incoming sulfur. Other reactants which can be used in place of methane are CO, hydrogen, higher hydrocarbons up through propane, and the products of coal gasification (EPA, 1997b; EPA, 1981).

Application

The Claus process sulfur plant is used to obtain elemental sulfur from concentrated waste SO_2 from coal- and oil-fired boilers, oil refineries, and nonferrous metals smelters (EPA, 1981; Friedman, 1981).

Control Efficiency

The typical control efficiency range for a Claus process sulfur plant is from 95 to 99 percent (EPA, 1997b; EPA, 1981). A two-stage catalytic Claus plant can achieve 94 to 96 percent efficiency, while a three-stage ranges from 96 to 97.5 percent, and a four-stage from 97 to 98.5 percent. The addition of a low-temperature stage after the final normal-temperature stage can extend control efficiencies to the 98 to 99 percent range (EPA, 1997b).

Cost

The cost range is from $100 to $200 per ton SO_2 controlled (Friedman, 1981). The range of costs for sulfur plants includes only the costs associated with the sulfur plant, which is assumed to receive an SO_2-rich (80 to 100 percent) inlet stream. Another system may be needed to concentrate the SO_2 in the waste gas stream.

093 Claus Process Sulfur Plant With Tail Gas Treatment

Description

Tail gas from a sulfur plant contains unused SO_2, sulfuric acid, and other sulfur compounds (carbonyl sulfide, carbon disulfide, and sulfur). The SO_2 and other sulfur compounds are hydrogenated or hydrolyzed in a catalyst bed with a reducing atmosphere to create sulfuric acid. The hot gas is cooled and passed to a quench column to remove excess water. The sulfuric acid-rich stream is oxidized to sulfur after return to the sulfur plant, or converted directly to sulfur by one of several other processes (Buonicore, 1992; EPA, 1981).

Application

This process is used to recover sulfur and sulfur compounds in sulfur plant tail gas, as well as to reduce emissions from the plant, usually to meet regulatory requirements since the value of the sulfur recovered does not equal the additional capital and operating costs (Buonicore, 1992; EPA, 1981).

Control Efficiency

The typical control efficiency range is from 98 to >99 percent. Tail gas treatment can increase Claus sulfur plant overall recovery to greater than 99 percent and reduce SO_2 emissions to essentially zero for all practical purposes. The reduction system may, however, result in some sulfuric acid, carbonyl sulfide, and carbon disulfide emissions (EPA, 1981).

Cost

The cost of recovering the incremental sulfur in the tail gas of a sulfur plant is high and varies from 50 to 100 percent of the cost of a new Claus sulfur plant. Costs vary with location, process differences that effect energy requirements, need for chemicals and supplies, and regenerability of the catalyst (EPA, 1981).

094 Adsorption: Various Adsorbents

For SOx Control

Description

Sulfur dioxide in a waste gas stream is adsorbed onto activated carbon (coke from peat, lignite, or hard coal), generally in a cross-flow adsorber. The adsorbed SO_2 reacts with oxygen and water to form sulfuric acid, filling the pores in the carbon. Before regeneration, the carbon bed can be screened to remove fly ash. The spent carbon is regenerated in a desorber by hot gas or hot sand, creating a stream of concentrated (20 to 30 percent by volume) SO_2 which can be passed to a Claus plant to make elemental sulfur, an acid plant to make sulfuric acid, or condensed to form liquid SO_2. Some of the carbon is consumed as a reductant used to convert SO_3 to SO_2 (IEA, 1989; Satriana, 1981).

Application

Carbon adsorption systems for SO_2 control have been used at demonstration and pilot-scale coal- and oil-fired power plants (IEA, 1989).

Control Efficiency

The typical control efficiency range is from 70 to 80 percent (IEA, 1989; Satriana, 1981).

Cost

The cost range is from \$600 to \$900 per ton SO_2 controlled (Radcliffe, 1992; Satriana, 1981). The cost of a carbon adsorption system for control of SO_2 is dependent on the type of carbon used, the rate at which the carbon is consumed, and the scale of the system. Please note that these costs are extrapolated from pilot and demonstration-scale systems (Satriana, 1981).

For VOC Control

Description

Adsorption devices are used to recover solvent from airstreams with a high concentration of homogeneous organic vapors. Recovered solvent can often be reused directly in the process stream.

Adsorption occurs when organic molecules are captured on the extensive surface of a micro-porous solid such as activated carbon. Adsorption may be physical and/or chemical. Other suitable media for the process of adsorption for air pollution control include hydrophobic zeolites, silicates, aluminas, aluminosilicates (molecular sieves), and synthetic resins (AWMA, 1992).

Adsorption with activated carbon is the most widely used method. An activated carbon adsorption device is typically a two-bed system. VOC-laden air is passed through one bed at a time and treated. Over time, the carbon pore spaces begin to fill progressively through the bed. When the entire bed becomes saturated, the working capacity is exceeded; this is referred to as "breakthrough." Breakthrough is detected by either a measured decrease in efficiency or by a increase in pressure drop across the bed. To

maintain constant high efficiency , the bed should be taken offline and the gas shifted to the other bed before the working capacity is approached.

After being taken offline, the saturated bed is regenerated, or desorbed, by backflushing the carbon with steam, by reducing the pressure in the bed to a sufficiently low pressure (vacuum desorption), or by replacing the carbon and disposing of or desorbing the satruated adsorbent offsite. If steam is used, the steam discharge is condensed and the vapors can be incinerated or recovered. About three to five percent of organics remain on virgin activated carbon and cannot be desorbed.

The cycle time of an adsorption bed may be several hours to several days. The carbon adsorbate can only be regenerated a finite number of times before it must be replaced. Typically, replacement is necessary every one to five years.

Some systems are nonregenerable, that is, they are shipped off-site for desorption or reactivation. These systems are applicable at sites where the inlet waste gases contain less than 100 ppmv of organic vapor and/or are difficult to desorb, such as when used for odor control or control of indoor air (RTI, 1995).

Application
Adsorption is best suited for control of VOCs and HAPs with intermediate molecular weights between 40 and 150 and with boiling points between 100°F and 500°F. Carbon adsorption is well suited to variations in process air streams and VOC concentration. Smaller compounds do not adsorb well, and larger compounds cannot be removed (desorbed) during regeneration.

Carbon adsorption is particularly well suited to the recovery of aromatic and saturated (straight) hydrocarbons and acetates. A partial list of other recoverable solvents includes toluene, heptane, hexane, cellosolve, carbon tetrachloride, acetone, ethyl alcohol, ethyl acetate, methylethyl ketone (MEK), napthalene, and methylene chloride (Ruhl, 1994).

The maximum practical inlet concentration is approximately 10,000 ppmv. Permissible inlet concentrations are typically limited by the adsorption capacity of the carbon bed or safety problems posed by high bed temperatures produced by the heat of adsorption and presence of flammable vapors. Outlet concentrations of about 50 ppmv can be routinely achieved and concentrations as low as 10 to 20 ppmv can be achieved with some compounds (EPA, 1991).

Gas entering the adsorber should be "dry." If the entering gas is "wet" with either water or organic droplets, they will tend to clog the surface of the carbon particle and reduce its effective life. Carbon adsorption systems are often preceded by refrigeration systems which condense much of the water and heavy organics to prevent clogging.

Carbon adsorption using conventional and chemically impregnated carbons is also widely used for controlling inorganic vapors such as Hg, nickel carbonyl, phosgene, and amines. When Hg vapors are passed through a bed of sulfur-impregnated carbon, the Hg

vapors react with sulfur to form a stable mercuric sulfide. Over 95 percent of the Hg removed in this way can be recovered for reuse (EPA, 1991).

Adsorption is used to control organic vapors in a wide variety of industries.

Control Efficiency
The typical control efficiency range is from 90 to 99 percent (EPA, 1991; EPA, 1995). Ketones (acetone, MEK) are chemically very active and may pose difficulties to a carbon adsorption system and result in lower efficiency than otherwise expected. At concentrations greater than 1000 ppmv, efficiencies can exceed 95 percent. At gaseous pollutant concentrations from 200 to 1000 ppmv, carbon adsorption can achieve >90 percent control efficiency (AWMA, 1992).

Most reported removal efficiencies for inorganic vapors are for activated carbon and impregnated activated carbon, and they range from 90 to >99 percent (EPA, 1991).

Cost
The cost range is between $120 and $16,000 per ton VOC controlled (STAPPA/ALAPCO, 1993) and between $20 and $30 per cfm (Hart, 1997).

Graphics arts facilities, whiskey distilleries, and marine vessel loading operations account for the low end of the cost range ($120 - $3500), and aluminum rolling facilities using a fluidized bed carbon adsorber account for the high end ($7200 - $16,000) (STAPPA/ALAPCO, 1993).

095 Adsorption: Copper Oxide

Description
Copper oxide adsorption is a dry scrubbing process which uses copper oxide supported on alumina to remove SO_2 from a waste gas stream. Both alternating fixed bed and fluidized bed systems have been developed, but the general principle is the same for both. Sulfur dioxide reacts with the copper oxide and oxygen to form copper sulfate. The bed is regenerated by purging with gas containing hydrogen, CO, or light hydrocarbons to reduce the copper sulfate to copper, creating a concentrated SO_2 stream, which can be condensed to liquid SO_2, or passed to a Claus plant to create elemental sulfur. The remaining elemental copper is oxidized to copper oxide when it is exposed to the oxygen-containing waste gas (IEA, 1989; Satriana, 1981).

Application
Copper oxide adsorption systems have been developed to the pilot plant level, but they have not been used on a commercial scale (IEA, 1989).

Control Efficiency
The control efficiency range is from 80 to 90 percent (IEA, 1989). Control efficiency will vary depending upon life of the sorbent and the effectiveness of the gas used for regeneration of the sorbent (Satriana, 1981).

Cost

No cost data has been found relating to copper oxide absorption systems for the control of SO_2, although costs are expected to be high compared to other systems (Satriana, 1981).

096 Packed Column -- Gas Absorption

For SOx Control

Description

A packed scrubber consists of an absorption tower filled with packing material designed to provide a large surface area for gas/liquid contact. The absorbent or reagent solution or slurry is fed to the top of the column and travels downward, wetting the packing surfaces; the gas travels upward from the bottom through the packing material. The packed tower design offers a large area for contact of absorbent or reagent and SO_2-laden gas and provides the longest residence time of any scrubber type (EPA, 1981).

Application

Packed absorption columns are popular in several types of scrubbing systems. Packed-bed absorbers generally experience a lower pressure and are cheaper to construct than tray-type absorbers (Buonicore, 1992).

Control Efficiency

The typical control efficiency range is from 80 to >99 percent. The control efficiency of the absorber component of a scrubbing system depends upon the overall design of the system and the absorbent used in the system.

Cost

Costs per ton of SO_2 controlled are dependent upon the overall design of the scrubbing system, and they cannot be determined for the absorber component of the system alone.

For VOC Control

Description

The packed column is the most commonly used device for the control of gaseous pollutants by absorption. Packed columns are usually vertical columns that are filled with packing or devices of large surface area. The liquid is distributed over and trickles down through the packed bed, exposing a large surface area to contact the gas. Flow is usually countercurrent, with liquid flowing down and gas upward. Packed columns are used to remove gas, vapor and odors. Though not as common, cocurrent and crossflow configurations are also used.

Packings are ceramic, plastic, and metal, and come in a large variety of shapes and sizes, nominally from 0.25 to 3.5 inches. Selection is based on various performance criteria.

Application

Absorption is used for VOCs and inorganic gases. It is, however, more commonly employed for inorganic vapors (e.g., hydrogen sulfide, NH_3, chlorides, and fluorides) than for organic vapors, because of several limitations and problems. One problem is the availability of a suitable solvent. The vapor must be soluble in the absorbing liquid. Depending on the organic to be absorbed, water, mineral oils, or other nonvolatile petroleum oils may be used.

Water is generally the preferred solvent for inorganic vapor absorption. It is typically used on a once-through basis and then discharged to a waste-water treatment system. The effluent may require pH adjustment to precipitate metals and other HAPs as hydroxides or salts; these are typically less toxic and can be more easily disposed of.

VOC control by gas absorption is generally limited to packed or plate towers and for relatively high VOC concentrations (approximately 1,000 ppmv and higher) of readily water-soluble organics (most alcohols, ethylene oxide, organic acids, aldehydes, ketones, amines, and glycols) (AWMA, 1992). Packed columns are frequently used for handling corrosive materials, liquid with foaming or plugging tendencies, or where excessive pressure drops would result from use of plate columns. Packed columns are usually less expensive than plate towers for the same design application.

In chemical processing, absorption is most commonly applied to recover raw material and/or product in the separation and purification of gaseous streams containing high concentrations of organics (e.g., in natural gas purification and coke by-product operations).

Another consideration is the treatment or disposal of the material removed from the absorber. This must be addressed to effect complete control. In most cases, organics are stripped out (desorbed), either at elevated temperatures and/or under vacuum and then must be recovered as a liquid by a condenser. The stripped vapor may also be destroyed by incineration. In some cases, water containing absorbed VOCs is treated by other direct means, such as ozonation, chemical neutralization, or chemical oxidation.

For uncommon VOCs/HAPs, vapor/liquid equilibrium data for the specific (VOC/HAP)/solvent system may not be readily available. As these data are necessary in designing the absorber system, absorption is not a practical control method in these cases.

Absorption has been used to control VOCs from surface coating operations, waste handling and treatment ring plants, coffee roasters, chromium plating units, petroleum coker units, fish meal systems, smoke generators, and varnish and resin cookers. (EPA, 1992d)

Control Efficiency

The typical control efficiency range for VOCs is from 70 to >99 percent (Grossman, 1997; EPA, 1991). For inorganic HAP gases, the control efficiency range is from 85 to >99 percent (EPA, 1991). The packed tower is designed to meet the desired control efficiency for the specified operating conditions. The designer considers many variables, including solubility of the compound (or combination of compounds) in the absorbent, concentration, temperature, gas flow rate, liquid flow rate, packing factor, tower height and cross section.

Cost

The cost range is between $5 and $7 per standard cubic foot per minute (scfm) treated (Grossman, 1997).

097 Tray-Type Gas Absorption Column

For SOx Control

Description

A tray absorber promotes gas-slurry contact in a vertical column with transversely mounted perforated trays. The SO_2-laden gas enters at the bottom of the column and travels upward through the perforations in the trays; the reagent slurry is fed at the top and flows toward the bottom. Absorption of SO_2 is accomplished by countercurrent contact between the gas and reagent slurry. A variation of this absorber type is the mobile-bed absorption column, which adds mobile elements to the trays to produce highly turbulent zones for gas/liquid mixing (EPA, 1981).

Application

Tray-type absorber columns are used in wet scrubbing systems, but are not as popular as either spray towers or packed-bed absorber columns. Tray-type absorbers are more resistant to plugging than packed-bed absorbers (Buonicore, 1992)

Control Efficiency

The typical control efficiency range is between 80 and >99 percent. The control efficiency of the absorber component of a scrubbing system depends upon the overall design of the system and the absorbent used in the system.

Cost

Costs per ton of SO_2 controlled are dependent upon the overall design of the scrubbing system and cannot be determined for the absorber component of the system alone.

For VOC Control

Description

Plate or tray-type towers provide contact between the waste gas and liquid absorbent via a series of horizontal plates arranged in a step-like manner. Typically, the plates are designed to retain a layer of liquid on top of each plate as the liquid spills down through the tower from plate to plate. The gas is forced to bubble up through the liquid to achieve intimate mixing at each plate. The bubbling is induced by holes in the plates through which gases rise to the top of the tower. The number of required plates is determined by the difficulty of the mass transfer operation and the desired degree of absorption (EPA, 1992d).

Application

Absorption is used for VOCs and inorganic gases. It is, however, more commonly employed for inorganic vapors (e.g., hydrogen sulfide, chlorides, and fluorides) than for organic vapors, because of several limitations and problems. One problem is the

availability of a suitable solvent. The vapor must be soluble in the absorbing liquid. Depending on the organic to be absorbed, water, mineral oils, or other nonvolatile petroleum oils may be used.

Water is typically the preferred solvent for inorganic vapor absorption. It is typically used on a once-through basis and then discharged to a waste-water treatment system. The effluent may require pH adjustment to precipitate metals and other HAPs as hydroxides or salts; these are typically less toxic and can be more easily disposed.

VOC control by gas absorption is generally limited to packed or plate towers. Plate columns are preferred for large-scale operations where internal cooling is desired or where low liquid flow rates would inadequately wet the packing of a packed bed tower. However, plate towers tend to be more expensive than packed towers for the same design objective.

Control Efficiency
The typical control efficiency range is from 70 to >99 percent for VOCs (Grossman, 1997; EPA, 1991). For inorganic HAP gases, the range is from 85 to >99 percent (EPA, 1991).

For NOx Control

Description
Extending the gas absorption column increases absorption efficiency to reduce NOx emissions. This can be accomplished by either extending the height of an existing absorption column or, as in the typical retrofit case, adding a second column in series with the existing column. Additionally, increasing the volume and the number of trays in the absorber results in more NOx being recovered as nitric acid and a reduced emission level (STAPPA/ALAPCO, 1994).

As column efficiency improves, more of the product (NO_2) can be recovered and returned to the process. This will reduce overall production costs. The reduction in production costs may not be sufficient to offset the capital and annual costs associated with the installation of an extended column.

Application
Nitric acid and adipic acid production.

Control Efficiency
The typical control efficiency range is from 85 to 97 percent (EPA, 1992a; STAPPA/ALAPCO, 1994). NOx removal efficiencies average about 90 percent (STAPPA/ALAPCO, 1994).

Cost Effectiveness
Cost effectiveness varies as a function of the type of product and production capacity (STAPPA/ALAPCO, 1994):

Product	Plant Size	Cost Effectiveness $/ton (NOx)
Adipic Acid	190,000 tons per year	100
Nitric Acid	200 tons per day	80 - 300

098 Wet Lime/Limestone Slurry Scrubbing

Description

The lime slurry and limestone slurry scrubbing flue gas desulfurization systems are very similar. Both are wet, nonregenerative SO_2 absorption processes, which use an alkaline slurry, either slaked lime or limestone. Both slurry types provide calcium ions, calcium hydroxide from lime or calcium carbonate from limestone, which react with sulfite and sulfate ions to form calcium sulfite and calcium sulfate. In some systems, fly ash from the combusted coal or additives (magnesium compounds, formates, or acids) are used in the slurry to enhance the system SO_2 capture efficiency.

The reaction between the SO_2 and the slurry takes place in an absorption tower, from which the resulting sludge is collected. Sludge is made up of calcium sulfite, calcium carbonate (limestone system only), gypsum, lime or limestone impurities, fly ash (if not collected prior to the system), and any excess lime or limestone. The sludge is dewatered and disposed of. Many newer systems oxidize the produced sludge, which creates gypsum, desirable due to superior dewatering characteristics and potential marketability. A similar system, called the limestone emission control, uses quarry-sized limestone in a moving bed coated with water. The reaction takes place in the water film on the limestone granules, which is removed periodically and converted to gypsum (EPA, 1997b; Smith, 1994; Carr, 1994; Merrick, 1989; EPA, 1981).

Application

Lime and limestone wet scrubber systems have been the most popular flue gas desulfurization system, generally used to treat the waste gas from coal- and oil-fired utility boilers, though they have been applied to industrial boilers as well. Limestone has become more popular than lime, as well as systems which are designed to produce gypsum from the resulting sludge (EPA, 1997b; Smith, 1994; Merrick, 1989; EPA, 1981).

Control Efficiency

The typical control efficiency range is from 60 to 98 percent (EPA, 1997b; Sondreal, 1993; WGA, 1988). The lower end of the efficiency range consists of retrofit systems and older, early technology systems. Newer systems, and systems designed and built concurrent with a new facility are generally in the higher end of the range.

Cost

The cost ranges from $300 to $600 per ton SO_2 controlled (Smith, 1994; Radcliffe, 1992; Torrens, 1990). The range of costs in determined primarily by reagent cost, system size, the amount of redundancy required for adequate system availability, the costs

associated with sludge treatment and disposal, and whether the system is a retrofit or a new system.

099 Alkaline Fly Ash Scrubbing

Description
　　Fly ash from coal combustion is typically alkali in nature, and is, in some cases, used to augment wet lime or limestone scrubbing. Fly ash generally contains alkaline compounds such as calcium oxide, magnesium oxide, and sodium oxide, among others. Instead of removing particulate matter before the scrubber, the fly ash entrained with the waste gas stream is passed to the scrubber where the fly ash mixes with (if being added to lime or limestone) or forms (if used alone) the reagent slurry. Adding fly ash to the slurry in a wet lime or limestone scrubber, reduces reagent use as well as the amount of makeup reagent which must be added. In order to be used alone, the coal being burned must produce fly ash in sufficient quantities and of a sufficient alkalinity to achieve the desired SO_2 control efficiency (IEA, 1989; Buonicore, 1992; Belco, 1997).

Application
　　Alkaline fly ash scrubbing is generally used to reduce costs for nonregenerable scrubbing systems used to control SO_2 emissions from coal-fired operations, though fly ash-only scrubbers do exist. It reduces the amount of lime or limestone used, and provides a concurrent method for disposal of particulates in a waste gas flow. This scrubbing system is used only in cases where the combusted coal produces fly ash of adequate alkalinity, and in sufficient quantities. The sludge produced in systems where the fly ash is used to augment a lime or limestone system may not be able to be oxidized to saleable gypsum due to unacceptably high fly ash content (Belco, 1997; IEA, 1989).

Control Efficiency
　　The typical control efficiency ranges from 50 to 95 percent (Sondreal, 1993). Alkaline fly ash scrubbing is only used to treat waste gas from coal-fired boilers. Generally, alkaline fly ash from combusted coal is used to augment lime or limestone scrubbing, though in some cases, the fly ash is abundant and alkaline enough where it is the primary reagent, augmented with lime or limestone.

Cost
　　The cost ranges from $400 to $500 per ton SO_2 controlled (Radcliffe, 1992; EPA, 1984). The range of costs is dependent upon the properties of the fly ash produced by the combusted coal, the scale of the system, the cost of any additional reagent used, the amount of redundancy required for adequate system availability, and the costs associated with treating and disposing of the sludge.

100 Sodium Carbonate Scrubbing

Description
　　The sodium carbonate (soda ash) process is a wet, nonregenerable SO_2 absorbing system. The absorbing solution is a clear liquor which minimizes the plugging, scaling, and erosion usually associated with calcium-based scrubbing systems. Waste gas, after cleaning and cooling, is introduced to an absorber where it contacts the recirculating

scrubbing solution. The SO_2 in the gas reacts with the sodium carbonate to form sodium bisulfite, sodium sulfite, and sodium sulfate. The scrubbing liquor is bled off from the recirculation loop at a rate equivalent in sulfur content to that at which SO_2 is being absorbed. The scrubber liquor bleed is sent to treatment or disposal (EPA, 1997b; IEA, 1989; EPA, 1981).

Application
　　　The sodium carbonate scrubbing system is used to treat waste gas streams from coal- and oil-fired industrial boilers, though some utility boilers have employed it as well (EPA, 1997b; EPA, 1981).

Control Efficiency
　　　The typical control efficiency range is from 80 to 98 percent (EPA, 1997b; Sondreal, 1993; EPA, 1981). The higher end of the control efficiency range is comprised of systems which are designed and built with a new facility rather than a retrofit of an old facility, have access to inexpensive reagent as well as an inexpensive spent reagent disposal option (EPA, 1981).

Cost
　　　The cost range is from $400 to $600 per ton SO_2 controlled (Radcliffe, 1992; EPA, 1984). The range of costs is dependent upon the cost and availability of reagent, the scale of the system, the amount of redundancy required for adequate system availability, and the costs associated with treating and disposing of the sludge. The higher end of the cost range consists of systems with high reagent costs (sodium-based reagent tends to be less available than calcium-based reagents such as lime and limestone), and spent reagent treatment and disposal, which is typically more complicated than calcium-based scrubber sludge (EPA, 1981).

101 Sodium Hydroxide Scrubbing

Description
　　　The sodium hydroxide process is a wet, nonregenerable SO_2 absorbing system. The absorbing solution is a clear liquor which minimizes the plugging, scaling, and erosion usually associated with calcium-based scrubbing systems. Waste gas, after cleaning and cooling, is introduced to an absorber where it contacts the recirculating scrubbing solution. The SO_2 in the gas reacts with the sodium hydroxide to form sodium bisulfite, sodium sulfite, and sodium sulfate. The scrubbing liquor is bled off from the recirculation loop at a rate equivalent in sulfur content to that at which SO_2 is being absorbed. The scrubber liquor bleed is sent to treatment or disposal (EPA, 1981).

Application
　　　The sodium hydroxide scrubbing system is used to treat waste gas streams from coal- and oil-fired industrial boilers, though some utility boilers have employed it as well, though it is used less often than the sodium carbonate process (EPA, 1981).

Control Efficiency
　　　The typical control efficiency range is from 70 to 95 percent (EPA, 1981). The higher end of the control efficiency range is comprised of systems which are designed and

built with a new facility rather than a retrofit of an old facility, have access to inexpensive reagent as well as an inexpensive spent reagent disposal option (EPA, 1981).

Cost

The cost is from $400 to $600 per ton SO_2 controlled (Radcliffe, 1992; EPA, 1984). The range of costs is dependent upon the cost and availability of reagent, the scale of the system, the amount of redundancy required for adequate system availability, and the costs associated with treating and disposing of the sludge. The higher end of the cost range consists of systems with high reagent costs (sodium-based reagent tends to be less available than calcium-based reagents such as lime and limestone), and spent reagent treatment and disposal, which is typically more complicated than calcium-based scrubber sludge (EPA, 1981).

102 Dimethylaniline Scrubbing

Description

The dimethylaniline (DMA) absorption system is a cyclic-regenerative process that incorporates an absorber with trays on which most of the incoming SO_2 is absorbed in a countercurrent stream of DMA. The residual SO_2 in the gases is scrubbed with a weak sodium carbonate solution to give sodium sulfite or sodium bisulfite. Liquid sulfur dioxide is recovered as a product, and its absorbent is regenerated and recycled through the system (Buonicore, 1992; EPA, 1981).

Application

DMA scrubbing has been used to control SO_2 emissions from nonferrous smelters (Buonicore, 1992; EPA, 1981).

Control Efficiency

The typical control efficiency range is from 95 to 99 percent (Buonicore, 1992).

103 Hydrogen Peroxide Scrubbing

Description

In the hydrogen peroxide scrubbing process, SO_2 in the waste gas is reacted with hydrogen peroxide to produce sulfuric acid. Dilute sulfuric acid (typically less than 50 percent) containing a small amount of hydrogen peroxide (less than 0.1 percent) is circulated counter to the gas flow over polypropylene packing in a scrubbing tower made of fiber-reinforced plastic. Sulfur dioxide is absorbed in to the solution, where a rapid, high-yield reaction takes place to produce sulfuric acid (Buonicore, 1992; EPA, 1981).

Application

The hydrogen peroxide scrubbing system has been used to reduce SO_2 emission from at least two sulfuric acid plants. The acid produced by the system becomes part of the plant's production by blending with the high-strength acid in the drying or absorbing towers. There is no byproduct and no purge stream to dispose of (Buonicore, 1992; EPA, 1981).

Control Efficiency
     The typical control efficiency range is from 90 to 99 percent.

104 Seawater Scrubbing

Description
     The seawater scrubbing process uses the alkalinity of seawater to absorb and neutralize SO_2 from waste gas. Seawater contains bases corresponding to weak acids, such as bicarbonate, carbonate, borate, phosphate, arsenate, and sulfide, and has a considerably higher buffer capacity than freshwater. The waste gas stream is passed to a cyclone to remove particulates, then a venturi quencher before entering the scrubber. Particulates are collected to avoid discharging objectionable material into the sea. The scrubber is generally a packed tower counter-flow absorber, in which the sulfur dioxide is absorbed and converted mainly to bisulfite. The scrubbed waste gas is vented to the atmosphere after passing through a demister and a reheat unit. The liquid effluent from the scrubber is added to an alkaline sewer system containing calcium hypochlorite, where the bisulfite is neutralized and oxidized to sulfate (Satriana, 1981; Merrick, 1989).

Application
     Seawater scrubbing has been used to treat coal- and oil-fired boiler and smelter waste gas streams. This system requires that the facility be reasonably near the sea (Merrick, 1989; Satriana, 1981).

Control Efficiency
     Typical control efficiency range is from 85 to 98 percent (Strommen, 1993; Satriana, 1981). Control efficiency of a seawater scrubbing system for control of SO_2 will depend upon the nature of the seawater used, as well as any buffering solutions added to the seawater and the concentration of SO_2 in the treated waste gas stream (Satriana, 1981).

Cost
     The cost range is from $400 to $700 per ton SO_2 controlled (Radcliffe, 1992; Satriana, 1981). The range of costs for seawater scrubbing system depends upon the amount of electricity used for pumping seawater and for reheat of the cleaned gas stream, as well as the scale of the system. These costs are based on very few commercial systems, all of which are installed outside the United States. The capital costs required are generally low compared to other control systems (Satriana, 1981).

105 Dry Sorbent Furnace Injection Without Duct Humidification

Description
     The dry sorbent furnace injection process generally involves pneumatically introducing a dry, powdery alkaline material, generally calcium-based (lime or limestone), though sodium-based (nahcolite or trona) sorbents are used, directly into a furnace above the burners with subsequent particulate collection. The sorbent material reacts with the SO_2 in the gas stream and is collected on filter bags. Filter bags are more popular than ESP's since there is evidence that a significant part of the removal reaction between SO_2 and the sorbent material takes place on the bag surface. The reacted sorbent is disposed of after periodic baghouse cleanings (EPA, 1997b; Dennis, 1993; EPA, 1981).

Application

This technology is typically used to control emissions from smaller coal-fired boilers burning low-sulfur coal, and existing boilers with a limited remaining service life (Sondreal, 1993).

Control Efficiency

The typical control efficiency range is from 20 to 70 percent (EPA, 1997b; Smith, 1994; Sondreal, 1993; Dennis, 1993; EPA, 1981). Limestone furnace injection generally controls 20 to 50 percent, lime furnace injection is 35 to 60 percent, and sodium furnace injection can achieve 70 percent. Furnace injection followed by duct humidification can increase the capture efficiency from 40 up to 90 percent overall (Smith, 1994; Dennis, 1993; Sondreal, 1993; Torrens, 1990; EPA, 1981).

Cost

Costs range from \$400 to \$1500 per ton SO_2 removed (Smith, 1994; Sondreal, 1993; Soud, 1993). The range of costs is determined primarily by reagent cost, system size, the amount of redundancy required for adequate system availability, the costs associated with treatment and disposal of spent reagent, and whether the system is a retrofit or a new system. The high end of the cost range is made up of retrofit systems which have high reagent costs due to low reagent usage efficiency coupled with high volumes of low sulfur fuel combustion.

106 Dry Sorbent Furnace Injection with Duct Humidification

Description

Dry sorbent furnace injection SO_2 control systems have a certain amount of unreacted sorbent which can be reactivated by humidification in the duct immediately following the furnace (Dennis, 1993).

Application

This technology is typically used to control emissions from smaller coal-fired boilers burning low-sulfur coal, and existing boilers with a limited remaining service life (Sondreal, 1993).

Control Efficiency

The typical control efficiency range is from 40 to 90 percent (Dennis, 1993).

Cost

The cost range is from \$400 to \$1500 per ton SO_2 removed (Smith, 1994; Sondreal, 1993; Soud, 1993). The range of costs is determined primarily by reagent cost, system size, the amount of redundancy required for adequate system availability, the costs associated with treatment and disposal of spent reagent, and whether the system is a retrofit or a new system. The high end of the cost range is made up of retrofit systems which have high reagent costs due to low reagent usage efficiency coupled with high volumes of low sulfur fuel combustion.

107 Combustion-Zone Sorbent Addition

Description

Addition of sorbent, usually limestone or dolomite, to the combustion zone of an existing furnace is a relatively straightforward method of sorbent introduction. Though little additional equipment is necessary for sorbent introduction, burner or furnace modifications, as well as additional particulate collection capability, may be needed. Methods for introducing sorbent include mixing crushed or powdered sorbent with the coal before adding to the combustion bed, in the combustion bed, or formed into pellets already combined with the coal. Since high temperatures (> 1200°F) tend to reduce the activity of the sorbent through sintering of the sorbent or reversal or the absorbing reaction, combustion-zone sorbent addition is generally used with fluidized-bed combusters, which typically operate in the 850 to 950°F range. Older, stoker-fired boilers, with higher operating temperatures (1200 to 1500°F) are not conducive to SO_2 control, though cooling by direct injection of water into the fuel, has been tried (Dennis, 1993; Torrens, 1990; EPA, 1981).

Application

Combustion-zone sorbent addition has been applied to new and existing boilers and furnaces of various sizes and capacities. Retrofit is possible, though particulate capture capabilities must be enhanced and combuster modifications may be necessary.

Control Efficiency

The typical control efficiency range is from 15 to 90 percent (Dennis, 1993). Stoker-fired furnaces can only achieve 15 to 25 percent control, although water injection and pelletizing sorbent and coal together can raise the efficiency to 30 percent. Shallow (150 millimeter bed height before fluidization) "bubbling" fluidized bed combusters can achieve 30 to 50 percent control, while deeper (600 millimeter bed height before fluidization) raise the efficiency up to from 60 to 80 percent. Higher levels of control can be achieved with the addition of higher sorbent-to-fuel ratios. Circulating fluidized bed combusters, which are more complicated and costly, can achieve removal efficiencies of from 80 to 90 percent (Dennis, 1993; EPA, 1981).

Cost

Costs of combustion-zone sorbent addition control methods vary greatly, and many are still in development. Cost of sorbent and any sorbent preparation (such as pelletizing with coal) procedures, as well as additional particulate control equipment, will affect costs. Higher control efficiencies require large amounts of sorbent with low sorbent usage, which can increase the cost per ton of SO_2 controlled greatly.

160 Selective Non-Catalytic Reduction, Annealing Furnace

161 Selective Non-Catalytic Reduction, Glass Furnace

162 Selective Non-Catalytic Reduction, Industrial & Commercial Boiler, Gas

163 Selective Non-Catalytic Reduction, Industrial & Commercial Boiler, Coal/Oil

164 Selective Non-Catalytic Reduction, Cement Kiln, Precalciner

165 Selective Non-Catalytic Reduction, Process Heaters, Gas

166 Selective Non-Catalytic Reduction, Process Heaters, Residual/Distillate Oil

167 Selective Non-Catalytic Reduction, Utility Boiler, Coal

168 Selective Non-Catalytic Reduction, Utility Boiler, Oil or Gas

Description

The majority of selective non-catalytic reduction (SNCR) applications employ one of two commercially available SNCR technologies. These are the Thermal DeNOx® system developed by Exxon and the NOxOUT® process, developed by the Electric Power Research Institute (EPRI).

"Thermal DeNOx," developed and patented by Exxon Research and Engineering Company, is based on the reaction between NOx in flue gas and NH_3, which produces nitrogen and water. In the temperature range of 1650°F to 1850°F, the reaction occurs through the injection of NH_3 without the assistance of a catalyst. The addition of hydrogen along with NH_3, will increase the effective reaction temperature range by dropping the low point to 1300°F (CARB, 1997).

"NOxOUT" was originally developed for the EPRI and is currently licensed by Fuel Tech. This method injects urea or other similar amine salt compounds into the oxygen-rich upper furnace or high temperature convection section of the boiler to promote NOx reduction. With the addition of other proprietary reagents, NOxOUT has achieved acceptable levels of NOx reductions between 800°F to 2100°F (CARB, 1997).

For either technology, the temperature of the reaction is the primary variable for effective NOx control (EPA, 1992a).

Limitations

Both NH_3 and urea-based SNCR can produce unacceptable NH_3 slippage (STAPPA/ALAPCO, 1994). When combusting high-sulfur fuels, high levels of NH_3 in the boilers can lead to ammonium bisulfate deposition on downstream components. These depositions can lead to equipment failure (EPA, 1994a). When high-chloride coals are burned, NH_3 slip may cause the formation of ammonium chloride which exits the exhaust stacks as a highly visible, white plume. Nitrous oxide can be generated as a reaction byproduct of the SNCR systems at levels as high as 25 percent of the NOx reduction. While not a contributor to ground-level ozone, nitrous oxide is a greenhouse gas (STAPPA/ALAPCO, 1994).

Application

Utility boilers, glass furnaces, reciprocating, steel annealing furnaces, cement kilns, process heaters, and industrial and commercial boilers.

Control Efficiency

The typical control efficiency range is from 20 to 70 percent (STAPPA/ALAPCO, 1994). The control efficiencies are a function of the fuel type, the amount of NH_3 or urea injected, the reaction temperature, residence time, and application. Control efficiency ranges for specific sources are presented in Appendix A.

Cost
(STAPPA/ALAPCO, 1994)

Application	Fuel Type	Cost Effectiveness $/ton (NOx)
Utility Boiler	Coal	550 - 3,350
	Oil or Gas	700 - 5,500
Process Heater	Oil, Residual/Distillate	1,300 - 6,600
	Natural Gas	2,850 - 11,900
Industrial and Commercial Boilers	Coal	950 - 2,400
	Oil, Residual/Distillate	2,250 - 6,800
	Natural Gas	3,350 - 6,400
Rich-burn Internal Combustion Engine	Gas	200 - 350
Cement Kiln		850 - 1,200
Steel Annealing Furnaces		450 - 550
Glass Furnaces		880 - 1,900

169   Selective Catalytic Reduction, Glass Furnace

170   Selective Catalytic Reduction, Annealing Furnace

171   Selective Catalytic Reduction, Industrial & Commercial Boiler

172   Selective Catalytic Reduction, Utility Boiler, Oil or Gas

173   Selective Catalytic Reduction, Lean Burn Diesel or Dual Fuels

174   Selective Catalytic Reduction, Cement Kiln

175   Selective Catalytic Reduction, Nitric Acid Process

176   Selective Catalytic Reduction, Process Heaters, Residual Oil

177   Selective Catalytic Reduction, Process Heaters, Distillate Oil

178   Selective Catalytic Reduction, Process Heaters, Gas

179   Selective Catalytic Reduction, Utility Boiler, Coal

Description

Selective catalytic reduction (SCR) is the chemical reduction of NOx with a reducing agent (usually NH_3 or urea) over a catalytic bed in the presence of oxygen to produce nitrogen gas and water. SCR is potentially applicable to flue or exhaust gases under oxidizing conditions greater than one percent oxygen (CARB, 1997).

SCR catalysts are either base metals, zeolites, or precious metals. Base metal catalysts constructed of titanium or vanadium oxides are active at temperatures above 450°F, with an optimum temperature range above 570°F. Temperatures in excess of 800°F or 850°F can lead to thermal breakdown of base metal catalysts. Zeolite catalysts are active at temperatures above 675°F, with an operational temperature range exceeding 1000°F. Precious metal catalysts are constructed of platinum and palladium. These catalysts operate effectively at temperatures between 300°F and 550°F (CARB, 1997).

SCR has the potential for high control efficiencies (STAPPA/ALAPCO, 1994).

Limitations

The potential exists of catalyst fouling, erosion or poisoning. Typical catalyst life is approximately five years for coal and slightly longer for oil or gas. Some retrofitting may not be as effective as other due to the available space constraints imposed by furnace design (STAPPA/ALAPCO, 1994). As with SNCR technology, the potential for NH_3 slip

and associated problems exist. In some applications, forced air induction may be required to overcome the pressure drop across the catalyst bed (STAPPA/ALAPCO, 1994).

Application

Annealing furnaces, cement kilns, glass furnaces, internal combustion engines, industrial and commercial boilers, nitric acid process, process heaters, gas turbines and utility boilers.

Control Efficiency

The typical control efficiency range is between 50 and 95 percent. SCR has the potential of very high control efficiencies (STAPPA/ALAPCO, 1994). Maximum control efficiencies are limited by the amount of acceptable costs. Control efficiency ranges for specific sources are presented in Appendix A.

Cost

Application	Fuel Type	Cost Effectiveness $/ton (NOx)
Utility Boiler	Coal	450 - 14,500
	Oil or Gas	600 - 13,500
Process Heater	Oil, Residual/Distillate	1,000 - 3,600
	Natural Gas	2,200 - 4,100
Industrial and Commercial Boilers	Coal	1,900 - 2,400
	Oil, Residual/Distillate	1,400 - 6,400
	Natural Gas	2,300 - 6,000
Gas Turbines	Oil	650 - 2,500
	Gas	900 - 3,900
Internal Combustion Engine	Gas	600 - 5,200
	Diesel	850 - 5,100
	Dual Fuel	1,100 - 7,100
Cement Kiln		3,400 - 5,300
Steel Annealing Furnaces		450 - 700
Glass Furnaces		850 - 3,100
Nitric Acid Production		250 - 350

180 Non-Selective Catalytic Reduction, Rich Burn Gas

181 Non-Selective Catalytic Reduction, Nitric Acid Process

Description

Non-selective catalytic reduction is similar to the catalytic reduction systems used in automobile applications. The system is also referred to as a three-way catalyst as it reduces NOx, CO, and hydrocarbons to water, carbon dioxide , and nitrogen (EPA, 1993b). Primarily used to control NOx emissions from rich-burn internal combustion engines, a variant has been successfully used to control NOx generated during the manufacturing of nitric acid (STAPPA/ALAPCO, 1994).

The concentration of oxygen in the exhaust or tail gas should be kept below 0.5 percent to maximize the NOx reduction efficiency. To this end, an oxygen sensor is located in the exhaust, upstream of the catalytic bed. Either via logic controller or manually, the air/fuel mixture is adjusted to maintain a fuel-rich exhaust (EPA, 1993b).

Limitations

This control technology is not applicable to lean-burn engines (EPA, 1992a). For optimum efficiency, the catalyst must be maintained at a temperature between 700°F and 1500°F (EPA, 1993b). The sulfur content of the fuel must be limited to about 800 parts per million (ppm) by weight to prevent deactivation of the catalyst (CARB, 1997).

Application

This control is used in rich-burn internal combustion engines and nitric acid manufacturing.

Control Efficiency

The typical control efficiency range is between 90 and >99 percent (STAPPA/ALAPCO; EPA, 1993b). Control efficiency ranges for specific sources are presented in Appendix A.

Cost Effectiveness

Cost effectiveness varies as a function of the power out of the engine or the nitric acid production capacity (STAPPA/ALAPCO, 1994):

Application	Cost Effectiveness $/ton (NOx)
Rich-Burn Internal Combustion Engine	200 - 350
Nitric Acid Production	550 - 750

182 Non-Selective Catalytic Oxidation and Absorption, Gas Turbine

Description

    The SCONOx™ system, a proprietary process developed by Goal Line Environmental Technologies, utilizes a single catalyst for the control of CO and NOx. The SCONOx™ catalyst oxidizes CO and NOx to carbon dioxide and NO_2. The carbon dioxide is vented through the exhaust stack while the NO_2 is absorbed by the potassium carbonate coating of the catalyst. The system consists of two or more oxidation/absorption units, which are alternately operated. When the carbonate absorber coating becomes depleted, the system opens the back-up bed and isolates the spent bed for regeneration. The regeneration cycle is performed in place (Danziger, 1997).

    Since the catalyst system is effective from 280°F to 700°F, the system can be installed downstream of most heat recovery units. This allows for greater retrofit capabilities (Danziger, 1997).

Limitations

    The SCONOx™ is new technology and as of 11 September 1997, had been installed in two facilities. However, U.S. EPA has determined that SCONOx™ has demonstrated that it can achieve the NOx emission limit of 3.5 ppmv on a 3-hour rolling average (Danziger, 1997).

Application

    This control is used in gas turbine engines.

Control Efficiency

    The typical control efficiency range is > 99 percent. Control efficiency ranges for specific sources are presented in Appendix A.

Cost

Application	Fuel Type	Cost Effectiveness $/ton (NOx)
Gas Turbine	Gas	N/D

183 Thermal Reduction, Adipic Acid

Description

    Thermal reduction mixes a NOx tail gas stream with an excess amount of fuel which is then heated to the mixtures ignition temperature. The combusted gas is passed through a series of chambers to provide adequate residence time to ensure complete combustion. The heat generated during this process is typically recovered (STAPPA/ALAPCO, 1994).

Limitations

NOx lost during the manufacturing process is not recovered. There is an additional cost of the reduction fuel. However the heat generated by the thermal reduction can be recovered (STAPPA/ALAPCO, 1994).

Application

This control is used in adipic acid production.

Control Efficiency

The typical control efficiency range is from 70 to 95 percent (STAPPA/ALAPCO, 1994; EPA, 1992a). Control efficiency ranges for specific sources are presented in Appendix A.

Cost

Cost effectiveness varies as a function of the type of product and production capacity (STAPPA/ALAPCO, 1994):

Product	Plant Size tons/ yr	Cost Effectiveness $/ton (NOx)
Adipic Acid	300,000	550
	350,000	500

240 Catalytic Oxidizer

Description

The catalytic oxidizer is designed primarily for the destruction of dilute VOC emission streams. The system is referred to as an afterburner if it is used to control gases from a process where combustion was not complete.

In catalytic incineration, VOCs in an emission stream are oxidized with the help of a catalyst. The purpose of the catalyst is to accelerate the rate of the reaction at a given temperature without being appreciably changed during the reaction. Catalysts are typically noble metals such as platinum or palladium carried on a ceramic or metallic support capable of withstanding operating temperatures. Other formulations are also in use, including metal oxides for streams containing chlorinated compounds. Catalysts may be in the form of a metal-mesh mat, a ceramic honeycomb, or packed spheres or pellets.

For economic reasons, the great majority of catalytic oxidizers are equipped with a heat exchanger to recover waste heat from the exhaust gas. Thus equipped, the system may also be referred to as a "recuperative" system. The recovered heat is used to preheat the waste gas entering the system. The benefit of a heat exchanger is that it reduces the auxiliary fuel requirement of the system, resulting in lower operating costs. The presence or lack of a heat exchanger will affect the annualized costs, but not the control efficiency of the system.

In a catalytic incinerator, waste gas is typically delivered at 10 to 30 feet per second and heated between 600 to 800°F before entering the catalytic reactor. The oxidation reaction takes place in the catalyst bed, and the combustion products (water vapor, carbon dioxide, inerts, and unreacted vapors) are discharged at a higher temperature, typically 800 to 1300°F (Budin, 1995).

Destruction efficiency depends on temperature, residence time, adequate oxygen, and complete mixing. Oxidation occurs when VOCs are heated to their autoignition temperature in the presence of sufficient oxygen. Autoignition temperatures differ from chemical to chemical. The higher this temperature, the more expensive it is to destroy the compound. The longer the residence time at the autoignition temperature, the more complete the destruction. Adequate mixing with combustion air is also necessary to ensure complete oxidation.

Application

Catalytic oxidation is most suited to systems with lower exhaust volumes, when there is little variation in the type and concentration of VOCs, and where catalyst poisons or other fouling contaminants such as silicone, sulfur, heavy hydrocarbons and particulates are not present (Renko, 1994). These systems are popular in controlling air streams in wastewater, groundwater, and soil remediation projects. Emission streams with high VOC concentrations should not be treated by catalytic incineration without dilution since such streams may cause the catalyst bed to overheat and lose its activity.

Catalysts have been developed that are relatively tolerant of compounds containing sulfur or chlorine. Chrome/alumina, cobalt oxide, and copper oxide/manganese oxide catalysts have been demonstrated to control emission streams containing chlorinated compounds.

If sulfur and/or chlorine are present in the emission stream, the resulting gas will contain SO_2 and/or HCl. Depending on the concentration of these compounds in the flue gas and applicable regulations, scrubbing may be required to reduce the concentrations of these compounds.

The main advantage of catalytic incinerators is that they operate at much lower temperatures than thermal oxidizers, due to the use of catalysts that cause VOCs to react with oxygen at lower temperatures than in thermal units. Reduced operating temperatures mean greatly reduced fuel consumption and less stress on the materials of the system. Other advantages include relatively low NOx, CO, and carbon dioxide emissions, little or no insulation requirements, reduced fire hazards, and reduced flashback problems. Older catalyst systems had difficulty destroying chlorinated hydrocarbons, however, newer platinum and/or palladium catalyst formulations and other new catalyst developments have been effective in dealing with these streams (Herbert, 1993; Gay, 1997).

Disadvantages include: 1) high initial cost, 2) potential for irreversible damage such as catalyst poisoning (by phosphorous, bismuth, lead, arsenic, antimony, Hg, iron oxides, tin, zinc, fluorine, silicon dust) and excessive temperatures, which can sinter the catalyst, 3) potential for less serious reversible damage caused by sulfur, zinc, and solid

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organic materials, 4) particulate often must be removed before entering the catalyst bed or fouling can occur, and 5) need to dispose of spent catalyst.

Control Efficiency
        The typical control efficiency range is from 90 to 99 percent. Generally, for low pollutant concentrations (< 100 ppmv) control efficiencies range from 90 to 95 percent. For higher pollutant concentrations (> 100 ppmv), control efficiencies of between 95 and 99 percent can be achieved (AWMA, 1992; EPA, 1991).

        The relative destructibility of alcohols is high. Other compounds (listed in order of decreasing destructibility) are cellosolves/dioxane, aldehyde, aromatics, ketones, adcetates, alkanes, and chlorinated hydrocarbons. However, between 98 to 99 percent destruction efficiency can still be achieved with sufficiently low space velocities and/or high inlet temperature.

        The average VOC control efficiency at gravure printing presses ranges from 94 to 99.5 percent when a total enclosure capture system with an add-on destruction device (either catalytic, regenerative or thermal incineration, or carbon adsorption) is used (TRC, 1993). Flexographic printing presses controlled by catalytic incineration may achieve from 90 to 98 percent overall efficiency (AWMA, 1992). A metal oxide catalyst must be used on flexographic printing presses to avoid poisoning by chlorinated solvents.

Cost
        The cost range for this control is between $200 and $6000 per ton VOC destroyed (RTI, 1995; STAPPA/ALAPCO, 1993). Higher costs per ton destroyed are associated with low volume flows which have low heating values or low concentrations (<100 ppm) and contain halogenated hydrocarbons. High volume flows, while they require higher capital cost, result in lower annualized cost per ton of VOC destroyed over the life of the equipment. Higher heating value flows require little or no auxiliary fuel to achieve the designed destruction efficiency. Halogenated hydrocarbons generally poison catalysts and require higher temperatures which result in accelerated catalyst degradation. In addition, higher costs are associated with compounds or non-VOC components of the treated flow which may require pretreatment (filtering, etc.) in order to protect the catalyst. Flows which do not require pretreatment but result in more frequent catalyst replacement or regeneration due to fouling, catalyst deactivation, or loss of catalyst also result in higher costs (STAPPA/ALAPCO, 1993; EPA, 1991).

241   Direct Flame Thermal Oxidizer

Description
        The direct flame thermal oxidizer is a simple combustion device designed primarily for the destruction of VOCs. The system is referred to as an afterburner if it is used to control gases from a process where combustion was not complete.

        The typical direct flame thermal oxidizer consists of burners, which ignite the fuel and organic, and a chamber, which provides the residence time for the oxidation process.

        The four conditions necessary for maximum destruction are temperature, time, turbulence (for mixing), and the availability of oxygen. VOCs heated to the autoignition

temperature in the presence of sufficient oxygen will oxidize to form carbon dioxide and water. Autoignition temperatures differ from chemical to chemical. The higher this temperature, the more expensive it is to destroy the compound. Adequate residence time is necessary for complete combustion; other variables being equal, longer residence times result in higher destruction efficiencies. Adequate mixing with sufficient combustion air is imperative to ensure complete oxidation. These variables are inter-dependent, and all affect the rate and efficiency of the combustion process.

Direct flame oxidizers require auxiliary fuel to achieve the elevated temperatures needed for high chemical reaction rates. Thermal destruction of most organic compounds occurs between 590°C and 650°C (1100°F and 1200°F); however, most thermal oxidizers operate in the 1250 to 1600°F range for maximum destruction. Residence time is typically >0.5 seconds, but it may be less with systems with extremely good mixing. Average gas velocity ranges from 10 to 50 feet per second, with flows generally less than 50,000 scfm (AWMA, 1992).

For economic reasons, the great majority of thermal oxidizers are equipped with a heat exchanger to recover waste heat from the exhaust gas. Thus equipped, the system may also be referred to as a "recuperative" system. The recovered heat is used to preheat the waste gas entering the system. The benefit of a heat exchanger is that it reduces the auxiliary fuel requirement of the system, resulting in lower operating costs. The presence or lack of a heat exchanger will affect the annualized costs but not the control efficiency of the system.

Application

Thermal oxidizers are used to control VOCs from many industrial and commercial processes that use solvents directly or as a carrier media, such as electronics manufacturing, the aerospace industry, printing, painting, laminating, etc.

Design conditions depend on the type, concentration and quantity of organic vapor to be destroyed. Thermal oxidizers can be used only for relatively low organic vapor concentrations. The minimum inlet concentration is typically 20 ppmv. For safety, the concentration of the organics in the air entering the oxidizer is usually limited to less than 25 percent of the lower explosive limit (LEL). However, concentrations up to 50 percent of the LEL may be acceptable (Public Works, 1997).

Thermal oxidizers can accommodate minor fluctuations in flow, but are not well suited to streams with highly variable flow because the reduced residence time and poor mixing during increased flow conditions decreases the completeness of combustion. Incomplete combustion causes the combustion chamber temperature to fall, decreasing the equipment's destruction efficiency.

Depending on concentrations, thermal oxidizers are not recommended for halogenated VOCs or sulfur-containing gas streams because of the corrosive products (HCl, SO_2) that result unless there is an acid-gas scrubber downstream. This configuration may be uneconomic compared to other options.

Control Efficiency

The typical control efficiency range is from 95 to >99 percent (EPA, 1991). For pollutant concentrations between 20 and 100 ppmv, control efficiencies of 95 to 99 percent can be achieved. For concentrations above 100 ppmv, control efficiencies over 99 percent can be achieved. When treating very low pollutant concentrations (< 20 ppmv), control efficiencies may fall below 95 percent (EPA, 1991).

Cost

The cost range for this control is between $200 and $13,000 per ton VOC destroyed (STAPPA/ALAPCO, 1993). Higher costs per ton destroyed are associated with low volume flows which have low heating values or low concentrations (< 100 ppm) and contain halogenated hydrocarbons. High volume flows, while they require higher capital cost, result in lower annualized cost per ton of VOC destroyed over the life of the equipment. Higher heating value flows require little or no auxiliary fuel to achieve the designed destruction efficiency. Halogenated hydrocarbons require higher temperatures, which results in higher auxiliary fuel requirements, and may require a caustic scrubber at the exit (STAPPA/ALAPCO, 1993; EPA, 1991).

242   Flaring

Description

A flare is a direct combustion device in which air and all the combustible waste gases react at an external burner. Complete combustion must occur immediately, since there is no combustion chamber to provide any significant residence time. In a flare configuration, flame temperature is the primary variable in the destruction of waste gases.

Typically, large open flares are elevated to insure sufficient dilution and dispersion of the exhaust gases. In these cases, the organic-laden gas is fed to and discharged from an elevated stack, with combustion, characterized by a flame, occurring near the top. The discharge temperature is typically in the range of 1,500 to 3,000°F. Enclosed (ground) flares are composed of multiple gas burner heads at ground level in a stack-like enclosure that is usually refractory lined.

Flare configurations may include steam-assisted, air-assisted, and pressure head flares, all designed to improve combustion and limit smoke.

Application

A flare may be used when the concentration of organics in air exceeds the lower flammability level. Flares are used primarily in the petroleum and petrochemical industries for destroying VOCs during normal operation, process upsets (e.g., start-up and shutdown), and emergencies. They are designed to handle large fluctuations in flow rate and VOC content. Flaring is considered a good control option when the heating value of an emission stream cannot be recovered because of uncertain or intermittent flow. Flares are intended for nonhalogenated VOC emission streams. Auxiliary fuel may be required if the waste gas does not have sufficient heating value to sustain combustion.

Control Efficiency

The typical control efficiency range is between 98 and >99 percent (AWMA, 1992). A blue flame indicates good combustion and high efficiency of destruction. A yellow-orange

flame with a trail of black smoke may occur during upset conditions and is a sign of incomplete combustion and lower destruction efficiency.

Cost

The cost range for this control is between $500 and $6000 per ton VOC destroyed (STAPPA/ALAPCO, 1993). Higher costs per ton destroyed are associated with higher combustible contents and heating values of the waste gas flow. Lower heating value flows may require auxiliary fuel to achieve proper combustion. The compounds which make up the waste gas determine the design and need for steam- or air-assist to ensure proper mixing (EPA, 1991).

Supplement to 240, 241, 242   PM Control by Incinerators

Description

Incinerators/oxidizers vaporize and oxidize particles as part of the combustion process, and are the only PM control devices that do not concentrate the PM for subsequent disposal. PM control is usually the secondary "goal" of the incinerator — VOC control is the primary purpose. The type of PM that is usually controlled by an incinerator is generally soot (particles formed as a result of incomplete combustion of hydrocarbons), coke, or carbon residue. The basic types of incinerators used as control devices for PM removal are thermal incinerators and catalytic incinerators, but flares also provide similar control. However, the use of a catalytic incinerator for PM control is limited because it is prone to severe operating problems with particulate-laden gas streams (EPA, 1982).

The combustion (residence) time required for PM control in an incinerator is dependent on particle size and composition, oxygen content of the furnace, atmosphere, furnace temperature, gas velocity, and extent of mixing of the combustibles. For PM less than 100 μm in diameter, the combustion rate is controlled by chemical kinetics; for PM greater than 100 μm, the combustion rate is controlled by diffusion. Although residence time and incinerator temperature are the primary parameters affecting incinerator performance, other important parameters are the heat content and water content of the gas stream and the amount of excess combustion air (i.e., amount above the stoichiometric amount needed for combustion) (EPA, 1982; EPA, 1992c). Both thermal and catalytic incinerators are usually equipped with heat exchangers to recover a portion of the heat energy generated by the combustion process.

Applicability

Residence time and incinerator temperature required for PM control is much higher than for non-PM sources, based on operating condition requirements for various industrial applications reported by Perry and Green (1984). A review of data included in EPA's 1990 National Inventory showed that the primary source categories where incinerators were used for PM control were petroleum and coal production, chemical and allied product manufacturing, primary metal production, and electronic and other electric equipment manufacturing (EPA, 1996a).

Control Efficiency

Theoretically, all organic material, including VOC, are combustible with combustion efficiency limited only by cost. With sufficient temperature, mixing and residence time,

complete combustion should result in greater than 99 percent control of particles containing hydrocarbons (EPA, 1982; EPA, 1992c).

The types of sources, control efficiencies, and types of incinerators, for facilities using incineration for PM control as reported in the 1990 National Inventory are presented below. Based on this data, the general PM and PM10 control efficiency range, encompassing all types of PM, is between 25 and >99 percent. For control of POT, the control efficiency range is assumed to be the same as the VOC control efficiency for all VOC controls using combustion as the primary control method. For control of PIT, the control efficiency range is assumed to be the same as the PM10 control efficiency for all VOC controls using combustion as the primary control method. Industry applications and PM10 control efficiencies are as follows:

(EPA, 1996a)

Industry/Types of Sources	PM10 Control Efficiency (%)	Types of Incinerators
Petroleum and Coal Products asphalt roofing processes (blowing, felt saturation); mineral calcining; petroleum refinery processes (asphalt blowing, catalytic cracking, coke calcining, sludge converter); sulfur manufacturing	25 - 99.9	Thermal Thermal with Heat Exchanger Catalytic
Chemical and Allied Products carbon black mfg; charcoal mfg; liquid waste disposal; miscellaneous chemical mfg processes; pesticide mfg; phthalic anhydride mfg (xylene oxidation); plastics/synthetic organic fiber mfg; solid waste incineration (industrial)	50 - 99.9	Thermal Thermal with Heat Exchanger Catalytic Catalytic with Heat Exchanger
Primary Metals Industries by-product coke processes (coal unloading, oven charging and pushing, quenching); gray iron cupola and other miscellaneous processes; secondary aluminum processes (burning/drying, smelting furnace); secondary copper processes (scrap drying, scrap cupola, and miscellaneous processes); steel foundry miscellaneous processes; surface coating oven	70 - 99.9	Thermal Thermal with Heat Exchanger Catalytic Thermal and Catalytic

Industry/Types of Sources	PM10 Control Efficiency (%)	Types of Incinerators
Electronic and Other Electric Equipment chemical mfg miscellaneous processes; electrical equipment bake furnace; fixed roof tank; mineral production miscellaneous processes; secondary aluminum roll/draw extruding; solid waste incineration (industrial)	70 - 99.9	Thermal Thermal with Heat Exchanger Catalytic
Electric, Gas, and Sanitary Services internal combustion engines; solid waste incineration (industrial, commercial/ institutional)	90 - 98	Thermal Thermal with Heat Exchanger Catalytic
Stone, Clay, and Glass Products barium processing kiln; coal cleaning thermal dryer; fabricated plastics machinery; wool fiberglass mfg	50 - 95	Thermal Catalytic
Food and Kindred Products charcoal processing, miscellaneous; corn processing; miscellaneous; fugitive processing, miscellaneous; soybean processing, miscellaneous	70 - 98	Thermal Thermal with Heat Exchanger
Mining asphalt concrete rotary dryer; organic chemical air oxidation units, sulfur production	70 - 99.6	Thermal Catalytic with Heat Exchanger
National Security and International Affairs solid waste incineration (commercial/ institutional and municipal)	70	Thermal Thermal with Heat Exchanger
Textile Mill Products plastics/synthetic organic fiber (miscellaneous processes)	88 - 95	Thermal Catalytic
Educational Services solid waste incineration (commercial/ institutional)	80	Catalytic with Heat Exchanger

Industry/Types of Sources	PM10 Control Efficiency (%)	Types of Incinerators
Industrial Machinery and Equipment secondary aluminum processes (burning/ drying, smelt furnace)	80 - 98	Thermal
Lumber and Wood Products solid waste incineration (industrial)	70	Thermal
Paper and Allied Products boiler	95	Catalytic with Heat Exchanger
Printing and Publishing surface coating dryer; fugitives	95	Catalytic
Transportation Equipment solid waste incineration (industrial)	70 - 95	Thermal

243 Regenerative Thermal Oxidation

Description

Regenerative thermal oxidation (RTO) uses a high-density media such as a ceramic-packed bed still hot from a previous cycle to preheat the incoming VOC-laden stream. The preheated, partially oxidized gases then enter a combustion chamber where they are heated to final oxidation temperature (1400 to 2000°F) and maintained at this temperature to achieve maximum destruction. The purified, hot gases exit this chamber and are directed to one or more different ceramic beds cooled in an earlier cycle. Heat from the process gases is absorbed by these beds before the gases are exhausted to the atmosphere, at temperatures only slightly above inlet conditions.

Advantages of the RTO system are: 1) high operating temperatures provide greater destruction efficiency and better control of air toxics and malodorous gases, 2) RTOs are less susceptible to problems with chlorinated compounds, 3) high heat recovery (85 to 95 percent) results in lower auxiliary fuel costs, 4) generally lower NOx emissions than in thermal oxidation.

Disadvantages of the RTO system are 1) large size and weight, 2) expensive installation, 3) higher capital costs compared to other oxidizers, 4) more moving parts requiring maintenance.

Application

The regenerative system is most favorable for design scenarios with high flows (>10,000 scfm) and low solvent concentrations (less than 10 percent of the lower explosive limit). The high heat recovery of the system makes it economically advantageous (Renko, 1994).

Control Efficiency

The typical control efficiency range is from 95 to >99 percent (RTI, 1995; Power, 1996).

Cost

The cost range for this control is between $2500 and $6000 per ton VOC destroyed (RTI, 1995; STAPPA/ALAPCO, 1993). Higher costs per ton destroyed are associated with low volume flows which have low heating values and contain halogenated hydrocarbons. High volume flows, while they require higher capital cost, result in lower annualized cost per ton of VOC destroyed over the life of the equipment. Higher heating value flows require little or no auxiliary fuel to achieve the designed destruction efficiency. Halogenated hydrocarbons require higher temperatures, which result in higher auxiliary fuel requirements, and may require a caustic scrubber at the exit. This is essentially a thermal oxidizer with a sophisticated energy recovery system which reduces operating costs, but only for flows with a sufficient volume and consistency to warrant the high capital costs of these systems (STAPPA/ALAPCO, 1993; EPA, 1991).

244 Regenerative Catalytic Oxidizer

Description

The regenerative catalytic oxidizer is similar in operation to an RTO, except that it uses a precious metal catalyst in the packed bed, allowing oxidation to occur at lower temperatures (approximately 800°F). The lower oxidation temperature reduces the amount of natural gas needed to fuel the VOC abatement system. The RCO also destroys CO in the VOC-laden airstream. NOx emissions are also lower as the system burns less fuel and operates at lower temperatures than RTOs (Gay, 1997).

Application

This control is most effective in facilities that operate fairly continuously and have air flow rates exceeding 10,000 scfm. It is applicable in controlling VOCs from coating operations, automotive manufacturing, and forest and wood products manufacturing. It is not advised for airstreams containing silicon, phosphorous, arsenic, or other heavy metals, which will poison the catalyst. The catalyst's performance will also be affected by masking or fouling by particulates in the gas stream (Gay, 1997).

Control Efficiency

The typical control efficiency range is between 90 and 99 percent. For low pollutant concentrations (< 100 ppmv), control efficiencies are generally 90 to 95 percent. For higher pollutant concentrations (> 100 ppmv), control efficiencies of 95 to 99 percent can be achieved (AWMA, 1992; EPA, 1991; Chen, 1996).

The relative destructibility of alcohols is high. Other compounds (listed in order of decreasing destructibility) are cellosolves/dioxane, aldehyde, aromatics, ketones, adcetates, alkanes, and chlorinated hydrocarbons. However, 98 to 99 percent destruction efficiency can still be achieved with sufficiently low space velocities and/or high inlet temperature.

The average VOC control efficiency at gravure printing presses ranges from 94 to 99.5 percent when a total enclosure capture system with an add-on destruction device (either catalytic, regenerative or thermal incineration, or carbon adsorption) is used (TRC,

1993). Flexographic printing presses controlled by catalytic incineration may achieve 90 to 98 percent overall efficiency (AWMA, 1992). A metal oxide catalyst must be used on flexographic printing presses to avoid poisoning by chlorinated solvents.

Cost

The cost for this control ranges between $2500 and $5700 per ton VOC destroyed (STAPPA/ALAPCO, 1993). Higher costs per ton destroyed are associated with low volume flows which have low heating values and contain halogenated hydrocarbons. High volume flows, while they require higher capital cost, result in lower annualized cost per ton of VOC destroyed over the life of the equipment. Higher heating value flows require little or no auxiliary fuel to achieve the designed destruction efficiency. Halogenated hydrocarbons generally poison catalysts and require temperatures which result in accelerated catalyst degradation. This is essentially a catalytic oxidizer with a sophisticated energy recovery system which reduces operating costs, but only for flows with a sufficient volume and consistency to warrant the high capital costs of these systems. In addition, higher costs are associated with compounds or non-VOC components of the treated flow which may require pretreatment (filtering, etc.) in order to protect the catalyst. Flows which do not require pretreatment, but result in more frequent catalyst replacement or regeneration due to fouling, catalyst deactivation, or loss of catalyst also result in higher costs (STAPPA/ALAPCO, 1993; EPA, 1991).

245 Fluidized Bed Catalytic Incineration

Description

Fluidized bed catalytic incineration (FBCI) operates on a similar principle as the catalytic incinerator with a fixed bed, except the catalyst is in the form of small beads, through which the gas passes in an upward direction, then on to the burner/combustion chamber. A heat exchanger is usually incorporated into the design to recover heat from the exhaust gas prior to being vented to the atmosphere.

With the use of certain proprietary metal catalysts, the FBCI has been shown to be effective on both VOCs and CVOCs. Certain manufacturers also claim that their catalyst is not poisoned by lead, iron, zinc, or other metallic vapors (U.S. Filter, 1997).

Application

This control is used in most industries where VOCs and CVOCs are a problem -- adhesive coating, chemical processing, hydrocarbon processing, loading, unloading, paint finishing, pharmaceutical, printing, roasters, sheet/coil coating, soil/groundwater remediation, and wood furniture finishing.

Control Efficiency

The typical control efficiency range is from 70 to >99 percent. Pilot plant tests on several inlet gas mixtures indicate control efficiencies tend to be at the lower end of the range for CVOCs and at the higher end of the range for VOCs. Efficiencies tended to be higher at higher oxidation temperatures (approximately 950°F) than at lower oxidation temperatures (650°F). The destruction efficiency was found to be independent of the inlet concentration (RTI, 1995).

246 Flameless Thermal Oxidation

Description
　　FTO is used for destroying VOCs in process and waste stream off-gas treatment and in the treatment of VOCs and CVOCs from off-gases from soil remediation. FTO uses a heated packed-bed reactor typically filled with inert ceramic pieces. Oxidation of organic compounds occurs in a uniform thermal reaction zone contained in the ceramic-matrix packed bed at temperatures of 1600 to 1850°F. The large thermal mass of inert ceramic matrix enables it to store or release large amounts of heat without causing rapid changes in temperature and provides flame suppression within the reactor.

Application
　　FTO is applicable in the treatment of VOC off-gases from manufacturing and remediation processes. In large scale operations with CVOCs, a caustic scrubber should be placed in series to remove HCl gas.

Control Efficiency
　　The typical control efficiency range is from 99 to >99 percent (DOE, 1995; Hohl and Baer, 1997). During full-scale demonstration testing at the United State's Department of Energy's (DOE's) Savannah River Site (soil remediation) in 1995, DRE of > 99.995 percent was achieved for perchloroethylene (PCE) and >99.95 percent for trichloroethylene (TCE) and total CVOCs during continuous testing phase of the 22-day demonstration (DOE, 1995).

　　Low NOx (typically <2 ppmv) and low CO are produced due to the relatively low, steady oxidation temperature (DOE, 1995).

Cost
　　Costs were estimated for a commercial unit capable of treating 400 scfm of soil vapor extraction (SVE) wellhead/SVE gaseous effluent with concentration of 400 ppmv (equivalent to 3.7 lb/hr CVOC), based on extrapolation of demonstration unit costs. The cost analysis was developed by the Hazardous Waste Remedial Actions Program, under direction of DOE Office of Technology Development. Considering capital and operating costs, CVOC destruction with FTO is estimated at $1,500/ton. This estimate does not include the cost of an acid gas scrubber.

247 High Energy Corona

Description
　　The high energy corona (HEC) process uses high-voltage electricity to destroy VOCs at room temperature. The primary system components are an HEC reactor in which VOCs are destroyed and a secondary scrubber. The reactor is a glass tube filled with glass beads through which pretreated contaminated off gas is passed. The demonstration reactors are two inches in diameter and four feet long. A high voltage electrode is placed along the centerline of the reactor, and a grounded metal screen is attached to the outer glass surface of the reactor. A high voltage power supply is connected across the electrodes to provide up to 50 milliamps of 60-hertz electricity at 30 kilovolts. The electrode current and power

settings depend on the type and concentration of the contaminant. The prototype system contains 21 reactors. Each reactor can process up to 5 scfm of soil off-gas (FRTR, 1995).

The HEC system is packaged in a self-contained mobile trailer that includes gas handling equipment and on-line analytical capabilities.

Application
HEC technology is being developed by DOE as one of several approaches for decontaminating soil off-gasses produced during soil treatment operations. Contaminants treated include most VOCs and semi-volatile VOCs (SVOCs). The technique has been proven useful for chlornated VOCs (CVOCs) such as TCE, PCE, carbon tetrachloride, chloroform, and diesel fuel and gasoline. Both gas and liquid phase contaminants are treatable (FRTR, 1995).

When CVOCs are treated, the reactor effluent is scrubbed with a solution of either sodium hydroxide or baking soda to remove acid gases, HCl, and chlorine.

Control Efficiency
The typical control efficiency range is from 90 to >99 percent. Field test data indicate destruction of 99.9 percent of TCE and 90 to 95 percent of PCE.

Cost
Based on calculations accounting for the economics of large-scale production and customization, cost effectiveness is estimated at $20,000 per ton (FRTR, 1995).

248 Silent Discharge Plasma Technology

Description
SDPT is an oxidation and reduction process that uses a pulsed electrical discharge system to create highly reactive free radicals that decompose organic compounds in airstreams. Prototype testing has been conducted at McClellan and Tinker Air Force Bases by the Los Alamos Chemical and Environmental Research and Development Group. Oxidation of VOCs is accomplished with electrical energy.

Application
The primary application of this control has been in treating gases from air strippers, soil vapor extraction systems, and incinerators at McClellan Air Force Base, with potential for use in the petroleum, chemical, electronics, water and wastewater treatment industries. With chlorinated VOCs, the reaction products are hydrochloric acid and other compounds, which must then be treated by wet scrubbing.

Control Efficiency
The typical control efficiency range is from 95 to 99 percent (Reimers and Gross, 1996). The prototype demonstration system has achieved removal efficiencies greater than 95 percent for chlorinated VOCs such as TCE, trichloroethane, PCE, carbon tetrachloride, benzene, toluene, ehtylbenzene, and total xylenes, polychlorinated biphenyl surrogates and chlorofluorocarbons. Removal efficiencies for other VOCs were slightly higher, up to a maximum of 99.4 percent (Pollution Engineering, 1996; Reimers and Gross, 1996).

Cost

The costs for SDPT are reported to be comparable to most thermal combustion technologies and on-site remediation in a portable system that is easy to operate and maintain (Reimers and Gross, 1996).

249 Photocatalytic Oxidation

Description

VOC-laden effluent air from a standard soil vapor extraction air stripping process is delivered to a reactor where VOCs or chlorinated VOCs (CVOCs) are trapped on the surface of a proprietary catalytic adsorbent. In the presence of ultra-violet light, generated by black light ultra-violet bulbs, the trapped contaminants are catalytically destroyed (oxidized) on the adsorbent, continuously regenerating the adsorbent. For CVOCs, HCl and chlorine gas are formed and removed, if necessary, depending on their concentration (Kittrell and Quinlan, 1995).

Application

This technology is applicable to low concentrations of VOCs and CVOCs (up to 500 ppmv), such as those found in air stripper effluent from ground water remediation projects. The principal advantage offered by this technology is that oxidation occurs at ambient temperature, resulting in lower energy costs and lower costs for materials of construction.

First commercial operation is scheduled for spring of 1998 (Kittrell, 1997). Potential future commercial applications include electronics manufacturing industry, solvent degreasing, aircraft industry, and urethane foaming operations.

Control Efficiency

The typical control efficiency range is from 95 to >99 percent (Kittrell and Quinlan, 1995). Control efficiency range is based on demonstration test data collected at Dover AFB. The inlet airstream to the photocatalytic destruction unit was 50 to 60 scfm and contained between 900 parts per billion and 3 ppm of dichloroethane. No products of incomplete combustion (such as phosgene) were observed in the exhaust air.

Cost

Installed costs for the photocatalytic unit alone are estimated at $100/scfm for a 500 scfm unit (Kittrell, 1997). Annualized costs are estimated at $15 to $50/scfm. Cost effectiveness ($/ton) depends on concentration and type of contaminants and may vary widely.

250 Ozonation - Catalytic Oxidation

Description

Most applications for oxidizing VOCs with ozone use ozonated water to treat VOCs which are either in liquid phase, or had been absorbed by some liquid. At least one gaseous ozonation system has been developed, which uses a catalytic reactor to oxidize VOCs using small amounts of ozone at relatively low temperatures (160 to 220°F). The catalyst is heated by specific-wavelength ultraviolet lamps, then passed over a second catalyst to eliminate any excess ozone, and finally an adsorbent bed made up of bases to

capture any residuals or acids. Another system combines an ozone and ultraviolet light gas-phase reactor with a counter-current ozonated water scrubber and a carbon adsorber (RTI, 1995).

Application
Most of the information available on gas-phase ozonation systems is from laboratory or pilot plant studies, as this technology is not yet widely represented in the field (RTI, 1995).

Control Efficiency
The typical control efficiency range for this control is from 95 to >99 percent (RTI, 1995). This control efficiency range is based on limited industrial application and pilot plant data. The feed concentration ranges from <2 ppmv to 200 ppmv.

Cost
Little applicable cost data is available since this technology is still in the development stage.

251 Ozonation - Enhanced Carbon Adsorption

Description
An enhanced carbon adsorption system developed by Terr-Aqua Enviro Systems combines wet scrubbing, carbon adsorption, and ozone reaction to remove organic vapors from an airstream. The airstream is pre-filtered to remove particulates. The organic-laden air then enters a photolytic reactor where it is exposed to ultraviolet light and mixed with activated oxygen/ozone. The air then enters a countercurrent ozonated water scrubber, where the organic vapors are transfered to the liquid phase. The water is oxidized in a reactor recycle tank. The organics are oxidized to carbon dioxide, water, and HCl if clorine atoms are present. After the reactor, the airstream enters a coalescer to remove any water droplets entrained in the airstream. The air stream then enters one of two activated carbon beds which remove any remaining organics that did not dissolve in water. The off line bed is sealed and fed oxidant to regenerate the carbon.

Application
This system is applicable to paint booths and similar industrial systems where organic solvents are used.

Control Efficiency
The typical control efficiency range for this control is 95 to >99 percent (RTI, 1995). This control efficiency range is based on limited industrial application and pilot plant data.

Cost
This technology is still in the development stage, and little applicable cost data is available.

252 Biofiltration

Description

In biofiltration, vapor-phase organic contaminants are passed through a bed of biologically active material, (primarily mixtures based on soil, compost, or peat) and sorb to the material surface, where they are degraded by microorganisms in the material. Specific strains of bacteria may be introduced into the filter and optimal conditions provided to preferentially degrade specific compounds. Some newer systems have replaced soil with a specially prepared biomass support media that improves performance and has a lower pressure drop than soil (Harrison, 1996).

The gas to be treated is distributed over the bottom of the bed and forced upward through the media. The mechanism of the biofiltration process includes a combination of adsorption, absorption, and microbial degradation.

The filter does not require regeneration, as the contaminants are destroyed and not just adsorbed in the process.

Application

The effectiveness of biofiltration is dependent on the biodegradability of the contaminants. Under proper conditions, biofilters can remove an extremely high percentage of selected contaminants into carbon dioxide, water, and salts. Biofiltration is used primarily to treat odors, nonhalogenated VOCs, and fuel hydrocarbons. Halogenated VOCs may be treated, however the process is less effective and may not be economically feasible (Leson and Winer, 1991). Biofiltration is best suited for dilute gas streams; less than 1000 ppm of VOCs, typical commercial applications are in the 5 to 500 ppm range (Standefer, 1996). Maximum concentration is around 10,000 milligrams per cubic meter or 2,500 ppm for a compound with molecular weight of 100 (Harrison, 1996).

Biofiltration is subject to several limitations. The rate of influent flow is directly related to the size of the biofilter, which may result in relatively large space requirements. A large volume of filter media is usually required to provide adequate residence time for adsorption/destruction (up to 60 seconds) (Wani et al., 1997). Biofiltration is only effective for contaminants with high adsorption and degradation rates. Fugitive fungi may be a problem. Low temperatures may slow or stop removal unless the biofilter is climate controlled. A period of weeks or months may be necessary for the microbes to acclimate and condition themselves. Sources with highly variable concentrations are not well-suited to biofiltration.

Commercial VOC applications include chemical and petrochemical industry, oil and gas industry, synthetic resins, paint and ink, pharmaceutical industry, contaminated soil remediation, and waste and wastewater treatment. Odor abatement applications have included sewage treatment, slaughter houses, rendering, gelatin and glue plants, agricultural and food processing industry, meat and fish, packing, tobacco, cocoa and sugar industry, bulk handling terminals, and flavor and fragrance production (Harrison, 1996; Wani et al., 1997).

Control Efficiency

The typical control efficiency range is from 75 to 99 percent. When design criteria are met, removal rates for BTEX and halogenated hydrocarbons are in the range of 90 to 99 percent. For volatile PAHs, between 75 and 90 percent are removed (AirScience, 1996; Vembu and Walker, 1995). Other control efficiency data from commercial installations are (Wani, 1997):

Facility Type	Control Efficiency	Compounds
Composting	up to 99% 52 - 99% over 80%	odors VOCs reduced sulfur compounds
Landfill Operations	89 - 96% 84 - 86%	NH_3 NMHC
Wood Products	93%	VOC
Hardboard Plant	over 95%	odors
Pharmaceutical	over 99%	VOCs

Cost

Capital costs are moderate; operating costs are very low. Cost estimates range from $4,500 to $9,000/ton (FRTR, 1995) and $15 to $60 per cfm of gas treated (Bartikowski, 1997; Harrison, 1996). Wani et al. (1997) reports costs of $4.80 per scfm at the hardboard plant presented above.

253 Cryogenic Condensation

Description

Cryogenic condensation uses the cooling value of liquid nitrogen in a condenser to recover VOCs emitted during manufacturing processes. The system condenses VOC emissions by vaporizing liquid nitrogen to provide the cooling source to indirectly cool the process stream to low temperatures.

Successful condenser designs need precise temperature controls to minimize freezing and mist formation, and contain a defrosting system to remove frozen material from the heat exchanger surface (Zeiss and Ibbetson, 1997).

Application

Cryogenic condensation is best suited to industries that already use significant quantities of liquid nitrogen in their normal processes for inerting, blanketing, and purging, such as pharmaceutical and specialty chemicals. The nitrogen can be reused onsite, making additional nitrogen purchases unnecessary.

Control Efficiency

The typical control efficiency range is from 95 to >99 percent (Davis and Zeiss, 1997). The control efficiency varies according to the condensation temperature, which can

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be automatically controlled by adjusting the amount of nitrogen flow delivered to the process condensers.

Cost

If a facility is using nitrogen to blanket a process, the differential costs for VOC control are relatively minor. Based on a case study of this type of situation, annualized costs are estimated at $150 to $200/ton (Davis and Zeiss, 1997). In general, unless the use of liquid nitrogen is not already part of a facility's operation, the cryogenic condensation process is not economically feasible as a VOC control.

254 Water Blanket

Description

Water may be used as a blanketing medium for some volatile organic liquids that have low solubility in water and relatively high density, such as methylene chloride.

Application

Water blanketing has been used in the metal finishing industry to minimize VOC emissions from organic solvents used in paint stripping.

Control Efficiency

The typical control efficiency range for this control is from 90 to >99 percent.

255 Vapor Recovery System Stage I - Bulk Terminals

Description

Stage I vapor recovery systems at bulk terminals collect and process displacement vapors resulting from the loading of gasoline products onto trucks. As gasoline is pumped from the storage tank into a tank truck, the air/vapors mixture is displaced through a vapor collection header system of hoses and pipes to a vapor processor. Typically, the vapors are either recovered as product or destroyed. Multistage refrigeration units and double-bed self regenerating carbon adsorbers are the most common recovery devices used. Ground flares or thermal oxidizers are the most common types of destruction units used.

Application

This control is used at bulk gasoline terminals.

Control Efficiency

The typical control efficiency range for this control is 95 to 99 percent (AWMA, 1992, CARB, 1997). The control efficiency range of 95 to 99 percent represents an overall efficiency range and accounts for the capture efficiency of the collection system and fugitive emission losses due to transfer of product.

Cost

The cost range for this control is between $500 and $3,000 per ton of VOC controlled (Pechan, 1997; STAPPA/ALAPCO, 1993).

256 Vapor Recovery System, Stage I - Bulk Plants

Description

At bulk plants, the primary method for controlling emissions caused by displacement during loading and unloading is to transfer the vapors being displaced from the receiving container back to the dispensing container during the loading or unloading operation. This method is also referred to as vapor balancing.

Application

This control is used at bulk gasoline plants.

Control Efficiency

The typical control efficiency range for this control is from 90 to 95 percent (AWMA, 1992). The control efficiency range of 90 to 95 percent represents an overall efficiency range and accounts for fugitive emission losses due to transfer of product and temperature differences in liquids and vapor-air mixtures being transferred.

Cost

The cost range for this control is between $500 and $3,000 per ton of VOC controlled (Pechan, 1997; STAPPA/ALAPCO, 1993).

257 Tube and Shell Condenser

Description

A tube-and-shell condenser is a subcategory of the larger device category of surface condensers. The design of a surface condenser does not permit contact between the coolant and either the vapors or the condensate. Tube and shell condensers constitute the majority of surface condensers. The coolant usually flows through the tubes and the VOC-laden vapor condenses on the outside tube surface. The condensate forms a film on the cool tube which gravity drains from the exchanger. Air-cooled condensers may also be used. These are constructed with tubes with external surface fins through which air is blown. The vapor condenses inside the tubes.

Application

Surface condensers (as opposed to direct contact condensers) constitute the majority of the condensers used for air pollution control. Surface condensers are usually used in conjunction with other equipment to recover or destroy organic emissions. Surface condensers may be located upstream of absorbers, carbon beds, or incinerators to reduce the VOC load entering the more expensive control devices. They have been used successfully in petroleum refining, petrochemical manufacturing, asphalt manufacturing, coal tar dipping operations, degreasing operations, dry cleaning units, and sometimes the surface coating industry (EPA, 1992d).

Control Efficiency

The typical control efficiency range for this control is 50 to 90 percent. Surface condensers are typically operated at efficiencies between 50 and 90 percent (EPA, 1991). However, where solvent contamination is low and organic vapor concentration is relatively high, recovery efficiencies are reported greater than 96 percent (EPA, 1992d). In cases

where ambient air is mixed with the vapor and some contamination is present, efficiencies of about 90 percent are reported (EPA, 1992d).

Cost

The cost for this control runs between $300 and $2,300 per ton VOC controlled (Pechan, 1997; STAPPA/ALAPCO, 1993). Note that this range is for surface condensers in general, of which shell-and-tube condensers is a subcategory. The printing industry accounts for the higher end of the cost range ($1,300 to $2,300), while dry cleaners account for the lower portion ($300 to $600) (Pechan, 1997; STAPPA/ALAPCO, 1993).

258 Refrigerated Condenser

Description

Refrigerated recovery systems include a refrigeration unit, a heat exchanger/evaporator, storage for the chilled and defrost brines, and a vapor condenser. Such systems are sold as packaged units that contain all the necessary piping, controls, and components.

Application

Refrigeration systems are particularly well suited for applications with high value organics, such as the recovery of hydrocarbon vapors from gasoline marketing operations and recovery of dry cleaning solvents.

Control Efficiency

The typical control efficiency range for this control is 50 to 95 percent. Refrigerated condensers are operated at efficiencies between 50 and 95% (EPA, 1992d). For gasoline vapor recovery, refrigeration units have the capacity of recovering more than 90 percent of the organics when the gas entering the condenser consists of 35 percent gasoline vapors by volume. Refrigeration units will recover approximately 70 percent of the organics when the gas entering the condenser consists of 15 percent gasoline vapor by volume (EPA, 1992d). For recovery of dry cleaning solvents, efficiencies of 95 percent and above have been documented (AWMA, 1992). For recovery of organics from vent streams in the petroleum industry, efficiencies range between 85 and 95 percent (AWMA, 1992).

Cost

The cost of this control ranges between $300 and $2,300 per ton VOC controlled (Pechan, 1997; STAPPA/ALAPCO, 1993). This range is for surface condensers in general, of which shell-and-tube condensers is a subcategory. The printing industry accounts for the higher end of the cost range ($1,300 to $2,300), while dry cleaners account for the lower portion ($300 to $600) (Pechan, 1997; STAPPA/ALAPCO, 1993).

259 Contact Condensers

Description

Contact condensers recover VOCs by providing direct contact and intimate mixing between the cooling medium and vapors/condensate. Typical contact condenser types are barometric and jet.

The most common type of direct contact condenser is the countercurrent barometric condenser, which provides a rain of cooling water through which the vapor rises, condenses, and is carried away by the water. The condenser contains drip plates arranged in a staggered step fashion to enhance mixing. The condenser is elevated so that water can discharge by gravity from the vacuum in the condenser.

The jet, or wet, condenser uses high velocity jets of water in co-current flow with vapor. The high pressure jets promote condensation and force noncondensable gases out the tailpipe (Perry and Green, 1984).

Application
Surface condensers constitute the majority of condensers used for air pollution control. However, contact condensers are simpler, less expensive to install and operate, and require less auxiliary equipment and maintenance than indirect, or surface condensers. A disadvantage of contact condensers is that the condensate cannot be reused and further treatment or separation may be necessary (Theodore and Buonicore, 1988).

Control Efficiency
The typical control efficiency range for this control is 50 to 90 percent. Efficiencies for contact condensers are assumed to be the same as for surface condensers (e.g., tube and shell type).

320   Carbon Injection

Description
Primarily designed to control dioxin and furan emissions from medical and municipal waste combustors, carbon injection systems have been found to control Hg emissions as well. The system uses a powdered activated carbon produced from reactivated granular coal-based carbons. Once the powdered carbon is injected and has absorbed the contaminants, it is removed in a particulate collection device, such as an electrostatic precipitator or venturi scrubber, along with particulates and other solids in the waste gas stream (Roeck, 1996).

Application
Carbon injection systems have been used to control dioxin, furan, and Hg emissions from municipal and medical waste incinerators (Roeck, 1996).

Control Efficiency
The typical control efficiency range for this control is 95 to >99 percent for POT and VOT (dioxins and furans) 95 to >99 percent for GIT (Hg) (Roeck, 1996). Control efficiency varies for dioxins and furans, depending upon the particular compound. Mercury control efficiency has been reported in the same range, though excessive loading can lower the control efficiency considerably (Roeck, 1996).

400 Fuel Switching - High-Sulfur Coal to Low-Sulfur Coal

Description

Since SO_2 emissions are directly related to the sulfur content of the fuel combusted, the most straightforward method for reducing SO_2 emissions is to switch to a fuel with lower sulfur content. Switching from eastern high-sulfur coal to abundant western low-sulfur coal, entirely or in part, continues to be the most popular form of fuel switching. Switching from coal to oil or natural gas was practiced in the past, but realities concerning the long-term cost and domestic availability of oil and natural gas have diminished its attractiveness, though co-firing of coal or oil with natural gas has been applied (Dennis, 1993; WGA, 1988; EPA, 1981).

Control Efficiency

The typical control efficiency range for this control is 50 to 90 percent (WGA,1988). The control efficiency depends entirely on the sulfur contents of the original and replacement fuels (Dennis, 1993; EPA, 1981).

Cost

Cost per ton SO_2 controlled depends upon the original and replacement fuels, any additional transportation costs for the replacement fuel, and any equipment modifications required to adapt the existing facility to use of the replacement fuel (Dennis, 1993; EPA, 1981).

401 Fuel Switching - Coal to No. 4 or Distillate Oil

Description

Coal-fired boilers or process heaters could reduce PM, CO, SO_2, and NOx emissions by switching to light residual or distillate oil (No. 4 or No. 2). Switching from coal to oil may require retrofit of burners (STAPPA/ALAPCO, 1996).

For some types of boilers (e.g., coal-fired stokers) or process heaters, switching to oil may be problematic. Since many coal combustion operations have been located to reduce coal delivery costs (i.e. at or near a pithead), availability and transportation expense of the replacement oil must be taken into consideration as well. Thus, application of fuel switching may be feasible for some types of boilers or process heaters in some locations, and not for other types in other locations (STAPPA/ALAPCO, 1996).

Application

This control is used with industrial, commercial, or institutional coal-fired boilers or process heaters.

Control Efficiency

Based on emission factors for coal and light oil combustion from AP-42 (EPA, 1997b), the following control efficiencies result:

Pollutant	Control Efficiency Range (%)
CO	0 - 90
Total PM	90 - >99
PM10	80 - 99
PM2.5	70 - 99
NOx	0 - 90
SO$_2$	0 - 90

Control efficiencies will vary depending upon the original and the replacement fuels used in specific cases, as well as any equipment retrofit which influences emissions.

Cost

Costs per ton of pollutant controlled will depend upon the net cost per amount of energy delivered of the replacement fuel compared to the original fuel including transportation, storage, and any other equipment or combustion device changes required to accommodate the replacement fuel.

402 Fuel Switching - Coal to Natural Gas

Description

Coal-fired boilers or process heaters could reduce PM, CO, SO$_2$, and NOx emissions by switching to natural gas. Switching from coal to natural gas may require retrofit of burners. For some types of boilers (e.g., coal-fired stokers) or process heaters, switching to natural gas may be problematic. In addition, switching to natural gas requires that natural gas be available on-site. Gas pipeline extensions may be impractical in some areas. Also, gas supplies may be limited in some areas during winter months, or may be shut off for a period of time as a result of a natural disaster (e.g., earthquakes). Thus, application of fuel switching may be feasible for some types of boilers or process heaters in some locations, and not for other types in other locations (STAPPA/ALAPCO, 1996).

Application

This control is applicable to industrial, commercial, or institutional coal-fired boilers or process heaters.

Control Efficiency

Based on emission factors for coal and natural gas combustion from AP-42 (EPA, 1997b), the following control efficiencies result:

Pollutant	Control Efficiency Range (%)
CO	30 - 98
Total PM	98 - >99
PM10	98 - >99
PM2.5	98 - >99
NOx	30 - 90
SO_2	98 - >99

Control efficiencies will vary depending upon the original and the replacement fuels used in specific cases, as well as any equipment retrofit which influences emissions.

Cost

Costs per ton of pollutant controlled will depend upon the net cost per amount of energy delivered of the replacement fuel compared to the original fuel including transportation, storage, and any other equipment or combustion device changes required to accommodate the replacement fuel.

403 Fuel Switching - Residual Oil to Distillate Oil

Description

Residual oil-fired boilers or process heaters could reduce PM, CO, SO_2, and NO_x emissions by switching to distillate oil with lower sulfur content (STAPPA/ALAPCO, 1996). Switching from a residual oil (e.g., No. 6 or No. 4 oil) to distillate (No. 2) oil usually does not require any equipment modification, particularly as the lower viscosities make lighter oils easier to burn (STAPPA/ALAPCO, 1996).

Application

This control is used on ICI residual oil-fired boilers or process heaters.

Control Efficiency

Based on emission factors for oil combustion from AP-42 (EPA, 1997b), the following control efficiencies result:

Pollutant	Control Efficiency Range (%)
CO	0 - 80
Total PM	60 - >99
PM10	80 - >99
PM2.5	80 - >99
NOx	0 - 70
SO_2	60 - 98

Control efficiencies will vary depending upon the original and the replacement fuels used in specific cases, as well as any equipment retrofit which influences emissions.

Cost

Costs per ton of pollutant controlled will depend upon the net cost per amount of energy delivered of the replacement fuel compared to the original fuel including transportation, storage, and any other equipment or combustion device changes required to accommodate the replacement fuel.

404 Fuel Switching - Oil to Natural Gas

Description

Oil-fired boilers or process heaters could reduce PM, CO, SO_2, and NOx emissions by switching from residual oils (No. 6 or No. 4 oil) or distillate (No. 2 oil) to natural gas. Switching from oil to natural gas may require retrofit of burners.

For some types of boilers or process heaters, switching to natural gas may be problematic. In addition, switching to natural gas requires that natural gas be available on-site. Gas pipeline extensions may be impractical in some areas. Also, gas supplies may be limited in some areas during winter months, or may be shut off for a period of time as a result of a natural disaster (e.g., earthquakes). Thus, application of fuel switching may be feasible for some types of boilers or process heaters in some locations, and not for other types in other locations (STAPPA/ALAPCO, 1996).

Application

This control is applicable to industrial, commercial, or institutional oil-fired boilers or process heaters.

Control Efficiency

Based on emission factors for oil and natural gas combustion from AP-42 (EPA, 1997b), the following control efficiencies result:

Pollutant	Control Efficiency Range (%)
CO	30 - 90
Total PM	90 - >99
PM10	80 - >99
PM2.5	50 - >99
NOx	30 - 80
SO_2	98 - >99

Control efficiencies will vary depending upon the original and the replacement fuels used in specific cases, as well as any equipment retrofit which influences emissions.

Cost
Costs per ton of pollutant controlled will depend upon the net cost per amount of energy delivered of the replacement fuel compared to the original fuel including transportation, storage, and any other equipment or combustion device changes required to accommodate the replacement fuel.

405 Coal Cleaning

Description
Since SO_2 emissions are directly related to the sulfur content of the fuel used in combustion processes, any sulfur removed from the fuel before combustion will not be emitted as SO_2. Most fuel cleaning efforts have been focus on coal, though oil can be desulfurized at the refinery. Usually oil desulfurization is only economic when the raw sulfur levels are very high and there is a requirement to remove sulfur for the purposes of other downstream processes. Most types of fuel cleaning, by virtue of economics of scale, are only worthwhile when done in bulk at the pithead or refinery.

Coal contains sulfur in two different forms, inorganic and organic. Inorganic sulfur, which is combined with iron in the form of pyrite, is removed from coal by physical cleaning. Most physical cleaning processes involve crushing the coal to a point where some of the mineral and coal particles are then separated by techniques usually based on differences in the densities or surface properties of the particles.

Chemical and biological processes to remove the organically bound sulfur from coal are under development and many are still in the experimental stage. Chemical cleaning processes which have been developed are limited by energy usage, reagent requirements, and the management of chemical wastes from the procedures. Biological cleaning involves the use of bacteria or enzymes to consume the sulfur in the coal (Dennis, 1993; Torrens, 1990; EPA, 1981).

Application
Physical coal cleaning is applied to about 40 percent of all the United States coal for utility boilers, and about 70 percent of the bituminous coal mined in the eastern United States. Chemical and biological cleaning processes are still in the development stage (Torrens, 1990).

Control Efficiency
The typical control efficiency range is 10 to 40 percent (Dennis, 1993; Torrens, 1990; WGA, 1988; EPA, 1981). The range of control efficiencies is determined by the efficiency of the physical cleaning process used, as well as the fraction of inorganic sulfur in the coal used. Higher sulfur coals with large pyritic sulfur contents will have larger SO_2 control efficiencies as a result of coal cleaning.

Cost
The cost range for this control is $200 to $500 per ton SO_2 controlled (STAPPA/ALAPCO, 1996). The lower costs per ton controlled are for coals which contain large amounts of pyritic sulfur cleaned by a process which is relatively costly per ton of coal cleaned (Dennis, 1993; EPA, 1981).

431 Electric Boost, Glass Manufacturing

Description Electric boost is the application of an electrical current to the glass mixture to augment the heat generated by the furnace. Electric boost heating is accomplished by resistance heating with a set of electrodes immersed in the molten glass. The NOx reduction is attributed to a decrease in furnace demand (STAPPA/ALAPCO, 1994). It has the added benefit of increasing production capacity (CARB, 1997).

Limitations
   The addition of electric boost can be an expensive method of NOx control due to the high cost of electricity. However, electric boost may be one of the least expensive methods of increasing glass production capacity (STAPPA/ALAPCO, 1994).

Application
   This control is applicable to glass furnaces.

Control Efficiency
   The typical control efficiency range is 10 to 25 percent (STAPPA/ALAPCO, 1994). Control efficiency ranges for specific sources are presented in Appendix A.

Cost
(STAPPA/ALAPCO, 1994)

Application	Cost Effectiveness $/ton (NOx)
Glass Furnaces	2,750 - 10,500

432 Cullet Preheat, Glass Manufacturing

Description
   In the typical glass melting operation, roughly one-third of the energy input is lost in the flue gas. If some of this energy is recovered, less fuel is needed to produce a given quantity of glass, and the normalized NOx emissions (lb NOx/ton glass) are reduced (EPA, 1994b). In cullet preheat, exhaust gases from the furnace, which are typically 600°F to 900°F, are used to heat the cullet before it is introduced into the furnace. This reduces the overall energy requirements with a corresponding reduction in NOx emissions. A variation on this technology uses a conventional or low NOx design burner to preheat the cullet to 900°F to 1100°F (CARB, 1997). Cullet reuse in general has the added benefit of having a lower energy requirement for glass production than producing glass from raw materials (STAPPA/ALAPCO, 1994).

Limitations
   Cullet preheat may require extensive modification to system. Some of the mechanical add-on systems can be complex and expensive.

Application
    This control is applicable to glass furnaces.

Control Efficiency
    The typical control efficiency range for this control is 5 to 25 percent
(STAPPA/ALAPCO, 1994). Control efficiency ranges for specific sources are presented in
Appendix A.

Cost
(STAPPA/ALAPCO, 1994)

Application	Cost Effectiveness $/ton (NOx)
Glass Furnaces	950 - 1,100

450   Inert Gas Blanketing

Description
    Inert gases, primarily nitrogen, may be used to purge the headspace in reactors,
storage tanks, dryers, and other vessels containing organic liquids. The purpose of the
inert blanket is to keep out unwanted air and moisture to prevent unwanted reactions,
such as fire, explosion, condensation, and corrosion. The non-reactive properties of
nitrogen ensure the safety of organic vapors under the blanket.

Application
    The inert gas blanket also acts as a seal, preventing fugitive emissions. Gas
blanketing is used in industries that store flammable liquids or powders and other
chemicals that need to limit oxygen exposure.

Control Efficiency
    The typical control efficiency for this control is 90 to 98 percent (STAPPA/ALAPCO,
1993).

Costs
    Costs not available.

451   Conversion to Variable Vapor Space Tank

Description
    A typical fixed roof tank consists of a cylindrical steel shell with a permanently
affixed roof. When storing volatile liquids, emissions result from breathing and working
losses. Breathing losses are losses due to the expansion of vapors in the tank due to
changes in ambient temperature and pressure. Working losses result from vapors emitted
as a result of filling and emptying operations.

By connecting the vapor space of a fixed roof tank to a variable vapor space tank, evaporative emissions from the storage of volatile liquids, such as petroleum liquids and other volatile organic liquids can be reduced. An integral unit may be mounted atop the fixed roof tank. The unit contains an expandable vapor reservoir to accomodate vapor volume fluctuations attributable to temperature and barometric changes.

The two most common types of variable vapor space tanks are lifter roof tanks and flexible diaphragm tanks. Lifter roof tanks have a telescoping roof that fits loosely around the outside of the main tank wall. The space between the roof and the wall is closed by either a wet seal, which is a trough filled with liquid, or a dry seal, which uses a flexible coated fabric. Flexible diaphragm tanks use flexible membranes to provide expandable volume. They may separate either gasholder units or integral units mounted atop fixed roof tanks.

Variable vapor space tank losses occur during tank filling when vapor is displaced by liquid. Loss of vapor begins when the vapor storage capacity of the tank is exceeded (EPA, 1995).

Application
This control is applicable to storage tanks for petroleum product and other volatile organic liquids.

Control Efficiency
The typical control efficiency range for this control is 10 to > 99 percent. Control efficiencies vary according to the available vapor space and working and breathing losses generated by the storage tank(s).

Cost
Costs are highly variable, depending upon the scale of the system, the compounds involved, and the nature of the existing storage system.

452 Conversion to Floating Roof Tank

Description
A typical fixed roof tank consists of a cylindrical steel shell with a permanently affixed roof. When storing volatile liquids, emissions result from so-called breathing and working losses. Breathing losses are losses due to the expansion of vapors in the tank due to changes in ambient temperature and pressure. Working losses result from vapors emitted as a result of filling and emptying operations.

Conversion to an internal floating-roof tank will reduce emissions from the storage of volatile liquids such as petroleum and other volatile organics. Conversion includes adding a cover that floats on the liquid surface (contact roof) or one that rests on pontoons several inches above the liquid surface (noncontact roof) inside the tank. The internal roof includes seals or wipers, which slide against the tank wall as the roof moves up and down.

Application
A control applied to fixed-roof storage tanks for petroleum product and other volatile organic liquids.

Control Efficiency

The typical control efficiency range is 60 to 99 percent (EPA, 1995). The control efficiency of this method depends on the type of roof and seals installed and the type of organic liquid stored. Generally, reductions of 93 to 97 percent are achieved in the storage of petroleum product. Data for cyclohexane indicate control efficiencies between 85 and 96 percent (EPA, 1992d).

Cost

The cost of this control ranges between $380 and $530 per to VOC controlled (STAPPA/ALAPCO, 1993). Lower vapor pressure volatile organic liquids (VOLs) are at the higher end of the cost range, while storage of lower vapor pressure VOLs are at the lower end of the range (STAPPA/ALAPCO, 1993).

453   Conversion to Pressurized Tank

Description

Pressurized tanks are generally used for storing high vapor pressure organic liquids and gases. Pressurized tanks are equipped with a pressure/vacuum vent that is set to prevent venting loss from boiling and breathing loss from diurnal temperature and barometric changes. Two classes of pressurized tanks are in general use: low pressure [2.5 to 15 pounds per square inch (psi)] and high pressure (higher than 15 psi).

Application

Conversion of a fixed or floating roof storage tank to a pressurized tank is economically viable only if the pressure setting is high enough.

Control Efficiency

The typical control efficiency range for this control is 95 to >99 percent. Converting from storage of liquids from a fixed or floating roof storage tank to a pressurized tank will virtually eliminate fugitive emissions in high pressure tanks, assuming proper design and maintenance. In low pressure tanks, working losses can occur with atmospheric venting of the tank during filling operations.

Costs

Pressure tanks are a costly method of control. Costs depend on storage material properties and are highly variable.

454   Submerged/Bottom Filling

Description

A storage tank or container may be filled in several different ways. In splash filling, a volatile organic liquid is introduced into a tank above the liquid level. Submerged and bottom filling reduces vapors generated during product loading into tanks or other containers. In the submerged fill pipe method, the fill pipe extends almost to the bottom of the cargo tank. In the bottom loading method, a permanent fill pipe is attached to the cargo tank bottom.

During submerged or bottom filling, the liquid is introduced into the tank with the transfer line outlet below the liquid surface. This minimizes droplet entrainment, evaporation, and turbulence, resulting in much lower vapor generation than encountered during splash loading.

Application

Submerged filling is used in petroleum product and other organic liquid transfer into tanks, containers, and marine vessels.

Control Efficiency

The typical control efficiency can run up to 60 percent (AWMA, 1992).

Cost

The cost of this control ranges between a savings of $200 and a cost of $100 per ton VOC controled (Pechan, 1988).

455 Underground Tank

Description

A pressure-vacuum vent on a tank or other storage container prevents air inflow and vapor escape until some preset vacuum or pressure develops.

Application

Generally, this control is installed on tanks at gasoline service stations to control vapor emissions resulting from diurnal temperature or barometric pressure changes or Stage I gasoline loading pressure equalization (STAPPA/ALAPCO, 1993).

Control Efficiency

The typical control efficiency range for this control is 98 to >99 percent (STAPPA/ALAPCO, 1993). Emissions may occur through seepage through the valve, which may occur during high pressure differential periods (STAPPA/ALAPCO, 1993).

Cost

Costs for this control run between $10 and $20 per ton VOC controlled, which does not include savings associated with recovery of stored VOC (STAPPA/ALAPCO, 1993).

456 White Paint

Description

The paint color of a fixed roof tank will affect the amount of radiant heat absorbed by an aboveground tank, which will in turn affect the amount of breathing loss emissions (losses of VOC due to vapor expansion and contraction).

A tank with a white roof and shell will have the lowest tank paint absorptance factor (absorb the least amount of heat) and will result in lower VOC breathing emissions than other color tanks.

Application

Painting a dull aluminum or gray tank with white paint will reduce heat absorption which will reduce VOC emissions due to breathing loss for fixed roof tanks. Working loss emissions (due to vapor expansion from filling) are not affected by paint color. Floating roof tanks are not affected by paint color.

Control Efficiency

The typical control efficiency of this control ranges from 0 to 30 percent. Compared to aluminum and gray-colored fixed roof tanks, a white tank will have up to 30 percent less VOC emissions due to breathing loss (EPA, 1995).

457 Process Change

For SOx Control

Description

Process changes are modifications to methods, materials, and/or equipment intended to reduce emissions of air pollutants.

Application

For SO_2 control, process changes include (Buonicore, 1992; EPA, 1981):

Fuel Combustion
- Inspect, maintain, and update combustion system for more efficient operation.

Industrial Emissions
- Capture fugitive emissions for which capture systems do not exist.
- Change to lower emission roasting, smelting, converting, and refining equipment and processes.
- Reduce sulfur content of materials used, or modify processes to not require sulfur-containing compounds.
- Change to low-sulfur fuels for process, kiln, and boiler heating.

Control Efficiency

The control efficiency range is 10 to 90 percent.

Cost

The costs of process changes vary widely depending upon the nature and scope of the change.

For VOC Control

Description

Process changes are changes to production practices, materials, and plant or equipment design to reduce air emissions.

Application

Process changes include (EPA, 1992b):

Input Material Changes
- Substitute materials to lower VOC/HAP or aqueous solutions for paints, printing inks, adhesives, resins, etc.
- Halt use of heavy metal pigments.
- Use raw materials free of trace quantities of hazardous or toxic impurities.

Technology Changes
- Capture and duct process and fugitive emissions to a production combustion device, such as a boiler.
- Use mechanical and aqueous stripping/cleaning devices to avoid solvent use.
- Use high volume-low pressure nozzles for applying coatings.
- Change to powder-coating system.

Improve Operating Practices
- Institute inspection and maintenance programs to stop fugitive emission leaks.
- Train production personnel.
- Improve material handling practices.
- Cover solvent tanks.
- Improve control of operating conditions.

Control Efficiency

The typical control efficiency range is 10 to >99 percent. Potential emission reductions can only be evaluated on a case-by-case basis.

Cost

Costs will vary on a case-by-case basis.

600 Low NOx Burners, Process Heaters, Gas

601 Low NOx Burners, Process Heaters, Residual Oil

602 Low NOx Burners, Utility Boiler, Coal

603 Low NOx Burners, Utility Boiler, Oil or Gas

604 Low NOx Burners, Cement Kiln, Mid-kiln Firing

Description

Low NOx burners (LNB) are designed to delay and control the mixing of fuel and air in the main combustion zone. Lower combustion temperatures and reducing zones are created by LNB which lower thermal and fuel NOx. LNB have been applied to both tangentially- and wall-fired boilers in new and retrofit applications. LNB can be combined

with operational modifications and FGR, lean premix, air staging, fuel staging, or a combination of treatment controls to further reduce NOx emissions (EPA, 1994a).

Low NOx burners can be divided into two different general technologies -- "delayed combustion" and "internal staged." Delayed combustion is designed to delay fuel/air mixing in the primary combustion zone by reducing flame turbulence. This provides for an initial, fuel-rich combustion of lower flame temperatures. The long flame duration inhibits the formation of thermal NOx, while the fuel-rich condition of the primary combustion inhibits the formation of fuel NOx. Internally staged LNB creates stratified, dual combustion zones consisting of a fuel-rich zone and a fuel-lean zone. The fuel-rich zone inhibits the formation of fuel NOx, and the fuel-lean zone provides for complete combustion at a lower temperature (EPA, 1994a).

Some of the different LNB technologies include, but are not limited to, Staged Air, Stage Fuel, Controlled Flow/Split Flame™, Dual-Register Burner -- Axial Control Flow™, Controlled Combustion Venturi™, Low NOx Cel Burner™ and Tertiary Staged Venturi (EPA, 1993d; EPA, 1994a).

Limitations

Retrofit equipment must have compatible and adequate ancillary equipment, such as pulverizers and combustion control systems, to minimize CO and unburned carbon emissions and to optimize the performance of the LNB. LNB operation with residual fuel oil becomes primarily limited by opacity levels which increase when burners are operated in staged combustion mode at low excess air levels. Fouling is promoted in many low NOx burner designs because the burner register relies on mechanical devices, such as bluff bodies and/or spinner vane assemblies located near the atomizer tip, to either stabilize the flame or stage air introduction into the root of the flame. The retrofitting of some types of low NOx burners may require derating of equipment, as some of these burners have long flame lengths which may impinge on parts of the boiler or heater when operating at full rating. The typical configuration of cyclone furnaces prevents the successful application of standard LNB technology (Zinc, 1997).

Application

This control is applicable to industrial, commercial and utility boilers, cement kilns and process heaters

Control Efficiency

The typical control efficiency range for this control is 20 to 60 percent (STAPPA/ALAPCO, 1994). Actual control efficiencies are application and fuel specific. Control efficiency ranges for specific sources are presented in Appendix A.

Cost

(STAPPA/ALAPCO, 1994)

Application	Fuel Type	Cost Effectiveness $/ton (NOx)
Utility Boiler	Coal	150 - 400
	Oil or Gas	400 - 8,000
Process Heater	Oil, Residual/Distillate	800 - 1,950
	Natural Gas	1,000 - 2,750
Industrial and Commercial Boilers	Coal	800 - 1,050
	Oil, Residual/Distillate	550 - 7,200
	Natural Gas	850 - 12,250

605 Dry Low NOx Combustor, Gas Turbine

Description

Dry low NOx combustor is term given to several different technologies with lean premix combustion affording the greatest NOx reduction potential. Lean premixed combustors prepare a lean air/fuel mixture prior to introduction into the main combustor to provide a uniform mixture ratio as well as a thermal sink. These conditions provide a cooler peak flame temperature and a reduction in the formation of thermal NOx (STAPPA/ALAPCO, 1994).

Limitations

Dry low NOx combustors retrofits may require modifications to the main combustor section. As this technology controls thermal NOx, the control efficiency for oil-fired turbines are less than that of gas-fire turbines (STAPPA/ALAPCO, 1994).

Application

This control is applicable to gas-fired gas turbines.

Control Efficiency

The typical control efficiency range for this control is 60 to 90 percent (STAPPA/ALAPCO, 1994; CARB, 1997). Actual control efficiencies are engine specific. Control efficiency ranges for specific sources are presented in Appendix A.

Cost

Fuel	Cost Effectiveness $/ton (NOx)
Gas	140 - 1,600

606 Staged Combustion

607 Staged Combustion, Cement Kiln

Description

Staged combustion is a method of dividing the combustion process into two combustors. The primary combustor is typically a rich-fuel, high temperature zone. Final combustion occurs in the fuel-lean, low temperature, secondary combustor. This technology is applicable to cement kilns as the process materials counter flow with the temperature gradient (STAPPA/ALAPCO, 1994).

Limitations

Retrofitting existing systems may be complex and restrained by system design.

Application

This control is applicable to cement kilns.

Control Efficiency

The typical control efficiency range is 20 to 60 percent (STAPPA/ALAPCO, 1994). Control efficiency ranges for specific sources are presented in Appendix A.

Cost

Application	Fuel Type	Cost Effectiveness $/ton (NOx)
Cement Kiln		N/D

608 Flue Gas Recirculation

609 Flue Gas Recirculation, Industrial & Commercial Boiler, Coal

610 Flue Gas Recirculation, Industrial & Commercial Boiler, Oil

611 Flue Gas Recirculation, Industrial & Commercial Boiler, Gas

612 Flue Gas Recirculation, Process Heaters, Oil

613 Flue Gas Recirculation, Process Heaters, Gas

614 Flue Gas Recirculation, Utility Boiler, Coal

615 Flue Gas Recirculation, Utility Boiler, Oil or Gas

Description

FGR is a flame-quenching strategy in which the cooled flue gas is recirculated back to the combustion zone. This recirculated flue gas acts as a thermal sink and diluent to reduce peak flame temperatures and oxygen concentrations in the combustion zone. This technology controls the formation of thermal NOx and is ineffective for fuel NOx. Therefore, FGR is most effective in reducing emissions from boilers firing natural gas or low nitrogen fuel (EPA, 1994a). However, FGR can be used with coal-fired, stoker boilers by replacing the combustion air flowing through the grate. This reduces excess air levels in the boiler without overheating the grate (STAPPA/ALAPCO, 1994).

Limitations

Flame stability problems can occur if high natural gas flow rates are coupled with a recirculated flue gas concentration greater than 15 percent (STAPPA/ALAPCO, 1994). Retrofitting existing furnaces can be expensive as FGR requires new ductwork, recirculation fans, flue gas/combustion air mixer, and control devices (EPA, 1994a).

Application

Utility boilers, process heaters, and industrial and commercial boilers.

Control Efficiency

The typical control efficiency range is 15 to 70 percent (STAPPA/ALAPCO, 1994; EPA, 1994a). Control efficiency ranges for specific sources are presented in Appendix A.

Cost

(STAPPA/ALAPCO, 1994)

Application	Fuel Type	Cost Effectiveness $/ton (NOx)
Utility Boiler	Coal	N/D
	Oil or Gas	250 - 6,550
Process Heater	Oil, Residual/Distillate	500 - 2,300
	Natural Gas	700 - 1,700
Industrial and Commercial Boilers	Coal	N/D
	Oil, Residual/Distillate	1,850 - 23,850
	Natural Gas	1,500 - 12,150

616 Low Excess Air, Steel Reheat Furnace

617 Low Excess Air, Industrial & Commercial Boiler, Coal

618 Low Excess Air, Industrial & Commercial Boiler, Oil

619 Low Excess Air, Industrial & Commercial Boiler, Gas

620 Low Excess Air, Process Heaters, Oil

621 Low Excess Air, Process Heaters, Gas

622 Low Excess Air, Utility Boiler, Coal

623 Low Excess Air, Utility Boiler, Coil or Gas

Description

Low excess air (LEA) is one of the more basic control techniques of NOx reduction. LEA was first used to increase the thermal efficiency of boilers and reduce stack gas opacity. Relatively easy to install in boilers, LEA has become standard practice (EPA, 1992a).

For relatively complete combustion to occur, some excess air is required. With LEA, less oxygen is supplied to the burner than usual. As a result, a reducing atmosphere forms in the combustion zone. This reduces the equilibrium concentration of oxygen atoms and thus less thermal NOx is formed. In the starved-air flame zone, more of the fuel-bound

nitrogen is converted into molecular nitrogen, lowering the formation of fuel NOx. LEA involves operating at the lowest level of excess air possible without jeopardizing good combustion and allows for maximum combustion efficiency. LEA can be used in all combustion sources and with all fuels. LEA works well in combination with other combustion control technologies (CARB, 1997).

Limitations

A decrease in excess air can increase hydrocarbon and CO emissions. At very low excess air, combustion instabilities can occur. The reducing atmosphere created by LEA can increase the rate of corrosion within the furnace (STAPPA/ALAPCO, 1994). Slagging or high CO levels may result in coal fired boilers with long periods of LEA (EPA, 1994a). In older heaters, draft type influences the excess air level attainable by affecting the degree of fuel/air mixing in the burner. Variations in fuel composition (such as a fuel combination of gas and oil) may affect the ability of an LEA system to continuously maintain oxygen levels (EPA, 1993d).

Application

This control is applicable in industrial, commercial and utility boilers and process heaters.

Control Efficiency

The typical control efficiency range for this control is 5 to 35 percent (STAPPA/ALAPCO, 1994). Actual control efficiencies are application and fuel specific. Control efficiency ranges for specific sources are presented in Appendix A.

Cost
(STAPPA/ALAPCO, 1994)

Application	Fuel Type	Cost Effectiveness $/ton (NOx)
Utility Boiler	Coal	N/D
	Oil or Gas	N/D
Process Heater	Oil, Residual/Distillate	N/D
	Natural Gas	N/D
Industrial and Commercial Boilers	Coal	N/D
	Oil, Residual/Distillate	N/D
	Natural Gas	N/D
Steel Reheat Furnace		700 - 1,200

624 Over Fire Air, Industrial & Commercial Boiler, Coal

625 Over Fire Air, Industrial & Commercial Boiler, Gas or Oil

626 Over Fire Air, Utility Boiler, Oil or Gas

627 Over Fire Air, Utility Boiler, Coal

Description

OFA is a control technology that reduces the amount of air introduced at the burner. Additional air is injected through over fire ports near the exit of the fire box. By affecting a rich-burn condition within the primary combustion event, the formation of fuel NOx is reduced. Additionally, as the peak flame temperature within the primary combustion event is cooler than stoichiometric combustion and the entire combustion event occurs over a large area of the furnace, the formation of thermal NOx is also reduce (STAPPA/ALAPCO, 1994; CARB, 1997).

Limitations

Installation of retrofit equipment in support of OFA can be complex and costly. This may make furnace replacement a more attractive control option compared to retrofitting existing equipment. Poorly controlled OFA can cause increased emissions of CO and hydrocarbons. There is an increased potential of corrosion of furnace components due to the reduced environment caused by the OFA control (STAPPA/ALAPCO, 1994).

Application

This control is applicable to utility boilers and ICI boilers.

Control Efficiency

The control efficiency range for this control is 15 to 45 percent (STAPPA/ALAPCO, 1994). Control efficiency ranges for specific sources are presented in Appendix A.

Cost
(STAPPA/ALAPCO, 1994)

Application	Fuel Type	Cost Effectiveness $/ton (NOx)
Utility Boiler	Coal	200 - 4,750
	Oil or Gas	400 - 4,450
ICI Boilers	Coal	650 - 1,550
	Oil, Residual/Distillate	N/D
	Natural Gas	N/D

628 Low Emission Combustion, Lean Burn Dual Fuels

629 Low Emission Combustion, Rich Burn Gas

630 Low Emission Combustion, Lean Burn Gas

Description

   Low emission combustion (LEC) is a control technique of combusting a very fuel-lean mixture in an internal combustion engine. The ignition and stable combustion of a very fuel-lean mixture is difficult to achieve and requires extensive modification to the both ancillary equipment and internal components. These include modifications to combustion chamber design (pistons and cylinder head), the ignition system, and intake and exhaust systems. In smaller displacement engines, air/fuel mixing can be accomplished through combustion chamber design. However, larger displacement engines require the installation of a precombustion chamber to promote mixing and combustion stability (STAPPA/ALAPCO, 1994; EPA, 1993b).

Limitations

   LEC requires extensive modification to both add-on and internal components. There is a potential for a reduction of load acceptance capacity. This would have an impact on engines that are subjected to cyclical loading. This control technology is not applicable to compression ignition engines.

Application

   This control is applicable to spark ignition, reciprocating internal combustion engines.

Control Efficiency

   The typical control efficiency range for this control is 60 to 90 percent (STAPPA/ALAPCO, 1994; CARB, 1997). Control efficiency ranges for specific sources are presented in Appendix A.

Cost Effectiveness

(STAPPA/ALAPCO, 1994)

Application	Cost Effectiveness $/ton (NOx)
Rich-Burn	1,300 - 5,450
Lean-Burn	1,100 - 4,850
Dual-Fuels	3,200 - 14,050

631 Ignition Timing Retard, Rich Burn Gas

632 Ignition Timing Retard, Lean Burn Gas

633 Ignition Timing Retard, Lean Burn Diesel

634 Ignition Timing Retard, Lean Burn Dual Fuels

Description

Ignition timing retard is the delay of igniting the air/fuel mixture until later in the power stroke in an internal combustion engine. When the ignition is delayed until the piston is in its downward motion and the combustion chamber volume is increasing, the subsequent combustion occurs at lower operating pressures, combustion temperature, and residence time. The retard of ignition timing can be adjusted in the field and require little or no modifications (EPA, 1993b).

For compression ignition engines, the ignition retard is accomplished by retarding the injection of fuel into the combustion chamber. Injection can be adjusted in the field. The addition of an electronic injection timer may be required for some applications (EPA, 1993b).

Limitations

Excessive ignition retard can lead to misfiring and increased exhaust temperatures. This can severely shorten the serviceable life of exhaust components such as exhaust valves and turbocharger impellers. Excessive ignition retard can adversely affect the engine's responses to load changes. For compression ignition engines, excessive retard can product the emission of both black smoke and white smoke at start-up. For both ignition systems, fuel consumption may increase (EPA, 1993b).

Application

This control is applicable to spark ignition and compression ignition reciprocating internal combustion engines.

Control Efficiency

The typical control efficiency range is 0 to 40 percent (STAPPA/ALAPCO, 1994). Actual control efficiencies are engine specific. Control efficiency ranges for specific sources are presented in Appendix A.

Cost

(STAPPA/ALAPCO, 1994)

Application	Cost Effectiveness $/ton (NOx)
Rich-Burn	300 - 1,250
Lean-Burn	400 - 5,350
Diesel	300 - 1,250
Dual-Fuels	300 - 1,550

635 Air-Fuel Ratio Adjustment, Internal Combustion Engines

Description

For rich-burn engines, the air-to-fuel ratio is lowered to reduce NOx emissions. This provides for a decrease in peak flame temperatures and produces a reducing atmosphere. This is similar to low excess air technique used in furnace applications (STAPPA/ALAPCO, 1994).

For lean-burn engines, the air to fuel ratio is increased to reduce NOx emissions. This extra air acts as a combustion gas diluent and produces a decrease in peak flame temperatures (STAPPA/ALAPCO, 1994).

Limitations

There is the potential for an increase in CO and hydrocarbon emissions at very low air-to-fuel ratios in a rich-burn engine. Engine derate and combustion instabilities are possible for both lean-burn and rich-burn engines using air to fuel ratio adjustments. An automatic air to fuel ratio controller is required for variable loads.

Application

This control is applicable to rich-burn and lean-burn, spark ignition, reciprocating internal combustion engines.

Control Efficiency

The typical control efficiency range for this control is 5 to 40 percent (STAPPA/ALAPCO, 1994). Control efficiency ranges for specific sources are presented in Appendix A.

Cost

(STAPPA/ALAPCO, 1994)

Application	Cost Effectiveness $/ton (NOx)
Rich-Burn	300 - 1,000
Lean-Burn	500 - 5,100

636 Prestratified Charged Combustion

Description   ·

Prestratified Charge Combustion is a technology for injecting additional air into the intake manifold prior to the air/fuel charge. The additional air enters the combustion chamber before the main air/fuel charge and remains a distinct layer, or stratifies. Upon compression, the stratified charge nearest the spark plug is fuel-rich were the rest of the charge is fuel-lean. This permits a small, fuel-rich initial ignition zone while maintaining an overall fuel-lean condition. Prestratified charge combustion provides for lower combustion temperatures and stable combustion of air/fuel mixtures approaching the lower limits of flammability (EPA, 1993a).

Prestratified charge retrofit kits are available for most carbureted, spark-ignition, four stroke engines (EPA, 1993a).

Limitations

Prestratified charged combustion is only applicable to carbureted, spark-ignition, four-stroke engines. There is a potential of an increase in CO and hydrocarbon emissions. Load reduction potentials could be as high as 20 percent (EPA, 1993a).

Application

This control is applicable to spark ignition reciprocating internal combustion engines.

Control Efficiency

The typical control efficiency range is 80 to 90 percent (STAPPA/ALAPCO, 1994). Actual control efficiencies are engine specific. Control efficiency ranges for specific sources are presented in Appendix A.

Cost

(STAPPA/ALAPCO, 1994)

Application	Cost Effectiveness $/ton (NOx)
Rich-Burn	300 - 3,250

637 Burner Out of Service, Utility Boiler, Coal

638 Burner Out of Service, Utility Boiler, Oil or Gas

639 Burner Out of Service, Utility Boiler, Industrial & Commercial Boiler, Coal, Oil or Gas

Description

Burner out of service (BOOS) is a variation of staged combustion technology. BOOS consists of removing individual burners from service by stopping the fuel flow. The air flow is maintained through the idle burners to create a staged-combustion atmosphere. The balance of fuel is redirected to lower burners, creating fuel-rich conditions in those burners. Typically, the top row of burners are removed from service, keeping the air register open thus simulating OFA (EPA, 1994a).

Limitations

Applicability is usually limited to larger boilers and boilers with multiple burners. BOOS combustion NOx controls suppress both thermal and fuel NOx formation by reducing the peak flame temperature and by delaying the mixing of fuel with combustion air. This can result in a decrease in boiler efficiency. For coal fired boilers, an increase in CO emissions and unburned carbon levels as well as changes in the thermal profile and heat transfer characteristics of the boiler, may result. If improperly implemented, stack opacity and CO levels may increase. Implementing changes to BOOS may reduce the operating flexibility of a boiler, particularly during load fluctuations. BOOS in natural gas and oil fired boilers often degrade to some extent, the performance of the boiler. Poor air/fuel mixing may occur with combustion products causing high CO emissions or high excess air operation thus a trade off must be made between low NOx emissions and high boiler efficiency (EPA, 1994a).

Application

This control is applicable to industrial, commercia,l and utility boilers.

Control Efficiency

The typical control efficiency range for this control is 10 to 35 percent (STAPPA/ALAPCO, 1994). Actual control efficiencies are application and fuel specific. Control efficiency ranges for specific sources are presented in Appendix A.

Cost Effectiveness

Application	Fuel Type	Cost Effectiveness $/ton (NOx)
Utility Boiler	Coal	N/D
	Oil/Gas	100 - 1,000
Industrial and Commercial Boilers	Coal	N/D
	Oil, Residual/Distillate	450 - 1,350
	Natural Gas	700 - 1,150

640 Natural Gas Reburn, Industrial & Commercial Boiler, Coal

641 Natural Gas Reburn, Industrial & Commercial Boiler, Oil or Gas

642 Natural Gas Reburn, Utility Boiler, Coal

Description

Reburn is a combustion hardware modification in which the NOx produced in the main combustion zone is reduced downstream in a second combustion zone. This is accomplished by withholding up to 40 percent of the heat input above the top row of burners to create a reburn zone. The reburn fuel is injected with either air or flue gas to create a fuel-rich zone where the NOx formed in the main combustion zone is reduced to nitrogen and water vapor. The fuel-rich combustion gases leaving the reburn zone are completely combusted by injecting OFA above the reburn zone. Any unburned fuel leaving the reburn zone is burned to completion in the burnout zone where OFA is introduced. OFA ports are designed for adjustable air velocities to optimize mixing and complete burnout of the fuel before it exits the unit (EPA, 1994a).

Reburning can be applicable to cyclone furnaces that are not easily adapted to other NOx reduction techniques such as LNB, LEA or OFA. Reburn technology can be combined with LNB to further reduce NOx (EPA, 1994a).

Limitations

The performance of reburn can be adversely affected by stoichiometry, residence time in the reburn zone, reburn fuel carrier gas, temperature and oxygen level in the burnout zone, FGR rate, furnace size and geometry. Reburning is not expected to be used on natural gas fired units since other techniques such as FGR, BOOS, and OFA are effective and do not need extensive modifications (EPA, 1994a).

Application

This control is applicable in industrial, commercial, and utility boilers.

Control Efficiency

The typical control efficiency range for this control is 15 to 60 percent ((STAPPA/ALAPCO, 1994). Actual control efficiencies are application and fuel specific. Control efficiency ranges for specific sources are presented in Appendix A.

Cost Effectiveness

(STAPPA/ALAPCO, 1994)

Application	Fuel Type	Cost Effectiveness $/ton (NOx)
Utility Boiler	Coal	400 - 2,450
Industrial and Commercial Boilers	Coal	N/D
	Oil, Residual/Distillate	N/D

643 Oxygen Firing, Glass Furnace

Description

Oxygen firing is the substitution of nitrogen of combustion air with oxygen to a level exceeding 90 percent. If the combustion fuel is low nitrogen-fuel, the resulting combustion gas is relatively free of NOx. Another benefit is improved furnace efficiency through a reduction of flue gas volume (STAPPA/ALAPCO, 1994).

Limitations

Oxygen firing requires extensive modification to system. Although a net decrease in capital costs can occur if the furnace is retrofitted during a complete rebuild, it is off-set by higher operating costs (CARB, 1997).

Application

This control is applicable to glass furnaces.

Control Efficiency

The typical control efficiency range is 80 to 90 percent (STAPPA/ALAPCO, 1994). Control efficiency ranges for specific sources are presented in Appendix A.

Cost Effectiveness

Application	Cost Effectiveness $/ton (NOx)
Glass Furnaces	2,300 - 4,650

644 Radiant Burners, Process Heaters, Gas

645 Radiant Burners, Industrial & Commercial Boilers, Gas

Description

This technology involves the passing of premixed air and gaseous fuel through porous ceramic fiber tips which glow, with no flame, at 1800 °F. At the low combustion temperature, very little thermal NOx is generated. Furthermore, fuel/air premixing allows the use of very low excess air levels which also help lower NOx emissions (STAPPA/ALAPCO, 1994).

Limitations

This technology cannot be installed on units utilizing liquid or solid fuels. Technology is suitable for small and medium sized boilers. Radiant burners are available for new installations of process heaters but are not considered practical in most cases for retrofit installation. Problems associated with radiant burners include fouling, fragility, and limited capacities (EPA, 1993d).

Application

This control is application for industrial, commercial and utility boilers, and process heaters.

Control Efficiency

The typical control efficiency range for this control is 70 to 90 percent (STAPPA/ALAPCO, 1994). Actual control efficiencies are application and fuel specific. Control efficiency ranges for specific sources are presented in Appendix A.

Cost

(STAPPA/ALAPCO, 1994)

Application	Cost Effectiveness $/ton (NOx)
Process Heater	2,400 - 2,800
Industrial and Commercial Boilers	3,800 - 6,250

646   Water/Steam Injection, Oil, Industrial & Commercial Boiler

647   Water/Steam Injection, Gas, Industrial & Commercial Boiler

648   Water/Steam Injection, Gas, Gas Turbine

649   Water/Steam Injection, Distillate Oil, Gas Turbine

Description

Water or steam injected into the combustion zone creates a thermal sink which lowers the flame temperature. Additionally, the injection of water or steam provides an inert diluent of the oxygen concentration. The effects of water or steam injection provide a reduction in combustion flame temperature and available excess oxygen lowers the flame temperature, hence, the formation of thermal NOx is reduced (STAPPA/ALAPCO, 1994).

Some of the required equipment are injection nozzles, pumps, metering valves, control units and piping. For gas turbines, a water treatment unit is required (STAPPA/ALAPCO, 1994).

Limitations

For industrial and commercial boilers, the cost of purchasing water may be prohibitive. Excessive water injection can increase the formation of CO due to low flame temperature. Also, there is potential of unacceptable thermal efficiency losses. Since water or steam injection controls thermal NOx, this application is most appropriate for either distillate oil or natural gas (STAPPA/ALAPCO, 1994).

The same limitations encountered by industrial and commercial boilers are applicable to gas turbines. In addition, the injected water or steam used in gas turbines must be treated to remove impurities (dissolved solids and minerals) to prevent the deposition of minerals on the rotating turbine components. The process of water treatment, beyond the increase of associated capital and annual costs, would produce wastewater with elevated concentrations of minerals or metals. This could necessitate the management of the wastewater as hazardous waste (STAPPA/ALAPCO, 1994). An

increase of water injection can increase dynamic pressure oscillations in the turbine combustor. Some gas turbines may experience increased erosion and wear in the hot section of the turbine (EPA, 1993a).

The design of the gas turbine limits the amount of water or steam that can be injected. Aeroderived gas turbines can tolerate higher rates of water injection than industrial gas turbines without significant increases in noise and wear (CARB, 1997).

Application
This control is used in industrial and commercial boilers and gas turbines.

Control Efficiency
The typical control efficiency range is from 15 to 95 percent (STAPPA/ALAPCO, 1994). The control efficiencies are a function of the fuel type, the amount of injected water or steam, and application. Theoretical maximum control efficiencies require over one pound of water per pound of fuel. At these rates, the thermal efficiency of the boiler would decrease to unacceptable levels (STAPPA/ALAPCO, 1994). Control efficiency ranges for specific sources are presented in Appendix A.

Cost
Industrial and Commercial Boilers (STAPPA/ALAPCO, 1994)

Application	Fuel Type	Cost Effectiveness $/ton (NOx)
Industrial and Commercial Boilers	Oil	1,200 - 9,000
	Natural Gas	700 - 8,600
Gas Turbines	Oil	400 - 2,000
	Natural Gas	550 - 2,350

Descriptions for Combinations of NOx Controls

Although there are descriptions for individual pieces of equipment, generally no descriptions are presented for control equipment combinations since the individual pieces are typically oriented in series with each other. The following control combination descriptions are presented because cost data are available for these particular combinations.

700 Low NOx Burners + Flue Gas Recirculation, Steel Furnace

Cost

(STAPPA/ALAPCO, 1994)

Application	Cost Effectiveness $/ton (NOx)
Steel Furnaces	150 - 500

701 Low NOx Burner + Over Fire Air, Utility Boiler, Coal

702 Low NOx Burner + Over Fire Air, Utility Boiler, Oil or Gas

Cost

(STAPPA/ALAPCO, 1994)

Application	Fuel Type	Cost Effectiveness $/ton (NOx)
Utility Boiler	Coal	200 - 4,150
	Oil or Gas	450 - 9,750

704 Low NOx Burner + Selective Non-Catalytic Reduction, Annealing Furnace

Cost

(STAPPA/ALAPCO, 1994)

Application	Cost Effectiveness $/ton (NOx)
Steel Furnace	550 - 700

705 Low NOx Burners + Over Fire Air + Selective Catalytic Reduction, Utility Boiler, Coal

Cost

(EPA, 1997a)

Application	Fuel Type	Cost Effectiveness $/ton (NOx)
Utility Boiler	Coal	1,700 - 1,950
	Oil	1,700 - 1,950
	Gas	1,500 - 2,150

706 Water/Steam Injection + Selective Catalytic Reduction, Gas Turbine

Cost

(EPA, 1997a)

Application	Fuel Type	Cost Effectiveness $/ton (NOx)
Gas Turbine	Oil	5,400
	Gas	5,600 - 6,000

707 Air/Fuel Adjustment + Ignition Timing Retard, Rich Burn Gas

Cost

(EPA, 1997a)

Application	Cost Effectiveness $/ton (NOx)
Rich-Burn/ Lean-Burn	550

708 Selective Non-Catalytic Reduction + Selective Catalytic Reduction, Utility Boiler, Gas/Oil

709 Selective Non-Catalytic Reduction + Selective Catalytic Reduction, Utility Boiler, Coal

Cost

(EPA, 1997a)

Application	Fuel Type	Cost Effectiveness $/ton (NOx)
Utility Boiler	Coal	1,000 - 1,650
	Oil or Gas	1,300 - 2,000

Control Efficiency Ranges for Combinations of PM Control

The control efficiency range of the equipment combinations for control of particulate were determined by professional judgment, as data for control combinations are sparse. In all cases, the following methodology was applied: (1) the low end of the combination control efficiency range is at least as high as the highest of either of the individual pieces of equipment typical low efficiency and (2) the high end of the combination control efficiency range is, at a minimum, as high as the highest of either of the individual pieces of equipment typical high efficiency.

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APPENDIX C: AIR TOXICS CLASSIFICATION

APPENDIX C: AIR TOXICS CLASSIFICATION

Appendix C provides guidance in characterizing air toxics as one or more of the four basic types:

- *VOT* - these are carbon-containing toxics that are typically encountered in a gaseous state;

- *POT* - these are carbon-containing toxics that are typically encountered as a solid or liquid aerosol or attached to other PM;

- *PIT* - these are toxics that do not contain a carbon atom and that exist as an aerosol or attached to other PM; and

- *GIT* - these toxics do not contain a carbon atom and exist as a gas.

Pollutants listed as HAPs under Section 112 of the Clean Air Act and air toxics listed in California's AB2588 program are identified in the Regulatory Program columns. For each air toxic, the pollutant type is indicated by a "1" in the appropriate VOT, POT, PIT, or GIT column. In some cases, a secondary type is indicated with a "2", if the pollutant is known to exist as both types within air pollutant streams. For example, many combustion products, such as dioxins, furans, and PAHs, are known to exist both in the vapor state (i.e., a VOT), as well as being bound to particulate matter (i.e., a POT).

Appendix C: Toxics List and Associated Pollutant Types

Chemical Abstracts Service Number	Pollutant[a]	Regulatory Program[b]		Pollutant Type[c]			
		CAAA	AB2588	VOT	POT	PIT	GIT
75-07-0	Acetaldehyde	x	x	1			
60-35-5	Acetamide	x	x	1			
67-64-1	Acetone	x		1			
75-05-8	Acetonitrile	x	x	1			
98-86-2	Acetophenone	x	x	1			
53-96-3	2-Acetylaminofluorene	x	x		1		
107-02-8	Acrolein	x	x	1			
79-06-1	Acrylamide	x	x	1			
79-10-7	Acrylic acid	x	x	1			
107-13-1	Acrylonitrile	x	x	1			
107-05-1	Allyl chloride	x	x	1			
7429-90-5	Aluminum	x				1	
1344-28-1	Aluminum oxide (fibrous forms)	x				1	

Chemical Abstracts Service Number	Pollutant[a]	Regulatory Program[b]		Pollutant Type[c]			
		CAAA	AB2588	VOT	POT	PIT	GIT
7783-20-2	2-Aminoanthraquinone	x			1		
92-67-1	4-Aminobiphenyl	x	x	1			
61-82-5	Amitrole	x		1			
7664-41-7	Ammonia	x					1
6484-52-2	Ammonium nitrate	x				1	
7783-20-2	Ammonium sulfate	x				1	
62-53-3	Aniline	x	x	1			
90-04-0	o-Anisidine	x	x	1			
120-12-7	Anthracene	x		2	1		
7440-36-0	Antimony	x				1	
n/a	Antimony Compounds	x	x			1	
1327-33-9	Antimony trioxide	x				1	
7440-38-2	Arsenic	x				1	
n/a	Arsenic Compounds (inorganic including Arsine)	x	x			1	2

Chemical Abstracts Service Number	Pollutant[a]	Regulatory Program[b]		Pollutant Type[c]			
		CAAA	AB2588	VOT	POT	PIT	GIT
n/a	Arsenic Compounds (other than inorganic)	x			1		
7784-42-1	Arsine	x					1
1332-21-4	Asbestos	x	x			1	
7740-39-3	Barium	x				1	
10294-40-3	Barium chromate	x				1	
56-55-3	Benz[a]anthracene	x		2			
71-43-2	Benzene (including benzene from gasoline)	x	x	1			
92-87-5	Benzidine	x	x	1			
n/a	Benzidine-based Dyes	x			1		
205-99-2	Benzo[b]fluoranthene	x		2	1		
205-82-3	Benzo[j]fluoranthene	x		2	1		
207-08-9	Benzo[k]fluoranthene	x		2	1		
271-89-6	Benzofuran	x		2	1		
50-32-8	Benzo[a]pyrene	x		2	1		

Chemical Abstracts Service Number	Pollutant[a]	Regulatory Program[b]		Pollutant Type[c]			
		CAAA	AB2588	VOT	POT	PIT	GIT
98-07-7	Benzotrichloride (benzoic trichloride)	x	x	1			
98-88-4	Benzoyl chloride	x		1			
94-36-0	Benzoyl peroxide	x			1		
100-44-7	Benzyl chloride	x	x	1			
7440-41-7	Beryllium	x				1	
n/a	Beryllium Compounds	x	x			1	
92-52-4	Biphenyl	x	x	1			
542-88-1	Bis(chloromethyl) ether	x	x	1			
103-23-1	Bis (2-ethylhexyl) adipate	x			1		
117-81-7	Bis (2-ethylhexyl) phthalate	x	x		1		
7726-95-6	Bromine	x					1
n/a	Bromine Compounds	x				1	2
75-25-2	Bromoform	x	x	1			
106-99-0	1,3-Butadiene	x	x	1			
141-32-2	Butyl acrylate	x		1			

Chemical Abstracts Service Number	Pollutant[a]	Regulatory Program[b]		Pollutant Type[c]			
		CAAA	AB2588	VOT	POT	PIT	GIT
71-36-3	n–Butyl alcohol	x		1			
7-89-22	sec–Butyl alcohol	x		1			
75-65-0	tert–Butyl alcohol	x		1			
85-68-7	Butyl benzyl phthalate	x			1		
7440-43-9	Cadmium	x				1	
n/a	Cadmium Compounds	x	x			1	
13765-19-0	Calcium chromate	x				1	
156-62-7	Calcium cyanamide	x	x		1		
105-60-2	Caprolactam		x		1		
2425-06-1	Captafol	x			1		
133-06-2	Captan	x	x		1		
63-25-2	Carbaryl	x	x		1		
n/a	Carbon Black Extracts	x			1		
75-15-0	Carbon disulfide	x	x	1			
56-23-5	Carbon tetrachloride	x	x	1			

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Chemical Abstracts Service Number	Pollutant[a]	Regulatory Program[b]		Pollutant Type[c]			
		CAAA	AB2588	VOT	POT	PIT	GIT
463-58-1	Carbonyl sulfide	x	x	1			
n/a	Carrageenan	x			1		
120-80-9	Catechol	x	x	1			
n/a	Ceramic fibers	x				1	
133-90-4	Chloramben	x	x		1		
57-74-9	Chlordane	x	x		1		
76-13-1	Chlorinated fluorocarbon	x		1			
108171-26-2	Chlorinated paraffins (average chain length, C12; approx. 60% chlorine by weight)	x		1	2		
7782-50-5	Chlorine	x	x				1
10049-04-4	Chlorine dioxine	x					1
79-11-8	Chloroacetic acid	x	x		1		
532-27-4	2-Chloroacetophenone	x	x	1			
56-75-7	Chloramphenicol	x			1		
108-90-7	Chlorobenzene	x	x	1			

Chemical Abstracts Service Number	Pollutant[a]	Regulatory Program[b]		Pollutant Type[c]			
		CAAA	AB2588	VOT	POT	PIT	GIT
n/av	Chlorobenzenes	x		1			
510-15-6	Chlorobenzilate (Ethyl-4,4'-dichlorobenzilate)	x	x		1		
13909-09-6	1-(2-Chloroethyl)-3-(4-methylcyclohexyl)-1-nitrosourea	x			1		
67-66-3	Chloroform	x	x	1			
107-30-2	Chloromethyl methyl ether (technical grade)	x	x	1			
n/a	Chlorophenols	x		1	2		
95-83-0	4-Choro-o-phenylenediamine	x			1		
76-06-2	Chloropicrin	x		1			
126-99-8	Chloroprene	x	x	1			
95-69-2	p-Chloro-o-toluidene	x		1			
7440-47-3	Chromium	x				1	
n/a	Chromium Compounds (other than hexavalent)	x	x			1	

Chemical Abstracts Service Number	Pollutant[a]	Regulatory Program[b]		Pollutant Type[c]			
		CAAA	AB2588	VOT	POT	PIT	GIT
18540-29-9	Chromium (hexavalent) (and compounds)	x				1	
1333-82-0	Chromium trioxide	x				1	
218-01-9	Chrysene	x		2	1		
7440-48-4	Cobalt	x				1	
n/a	Cobalt Compounds	x	x			1	
n/a	Coke Oven Emissions	x	x	1	2		
7440-50-8	Copper	x				1	
n/a	Copper Compounds	x				1	
120-71-8	p-Cresidine	x		1			
1319-77-3	Cresol/Cresylic acid (mixed isomers)	x	x	1			
108-39-4	m-Cresol	x	x	1			
95-48-7	o-Cresol	x	x	1			
106-44-5	p-Cresol	x	x	1			
n/a	Creosotes	x			1		

Chemical Abstracts Service Number	Pollutant[a]	Regulatory Program[b]		Pollutant Type[c]			
		CAAA	AB2588	VOT	POT	PIT	GIT
98-82-8	Cumene	x	x	1			
80-15-9	Cumene hydroperoxide	x		1			
135-20-6	Cupferron	x			1		
n/a	Cyanide Compounds[d]	x	x			1	2
110-82-7	Cyclohexane	x		1			
66-81-9	Cycloheximide	x			1		
1163-19-5	Decabromodiphenyl oxide	x			1		
n/a	Dialkylnitrosamines	x		1			
615-05-4	2,4-Diaminoanisole	x		1			
n/a	Diaminotoluenes (mixed isomers)	x		2	1		
334-88-3	Diazomethane	x	x	1			
226-36-8	Dibenz[a,h]acridine	x		2	1		
224-42-0	Dibenz[a,j]acridine	x		2	1		
53-70-3	Dibenz[a,h]anthracene	x		2	1		
224-42-0	7H-Dibenzo[c,g]carbazole	x			1		

Chemical Abstracts Service Number	Pollutant[a]	Regulatory Program[b]		Pollutant Type[c]			
		CAAA	AB2588	VOT	POT	PIT	GIT
132-64-9	Dibenzofuran	x	x	2	1		
n/a	Dibenzofurans (chlorinated)	x		2	1		
192-65-4	Dibenzo[a,e]pyrene	x		2	1		
189-64-0	Dibenzo[a,h]pyrene	x		2	1		
189-55-9	Dibenzo[a,i]pyrene	x		2	1		
191-30-0	Dibenzo[a,l]pyrene	x		2	1		
96-12-8	1,2-Dibromo-3-chloropropane	x	x	1			
84-74-2	Dibutyl phthalate	x	x		1		
95-50-1	1,2-Dichlorobenzene	x		1			
541-73-1	1,3-Dichlorobenzene	x		1			
106-46-7	1,4-Dichlorobenzene (p-Dichlorobenzene)	x	x	1			
25321-22-6	Dichlorobenzenes (mixed isomers)	x		1			
91-94-1	3,3'-Dichlorobenzidine	x			1		
72-55-9	1,1-dichloro-2,2-bis (p-chlorophenyl) ethylene	x	x		1		

Chemical Abstracts Service Number	Pollutant[a]	Regulatory Program[b]		Pollutant Type[c]			
		CAAA	AB2588	VOT	POT	PIT	GIT
111-44-4	Dichloroethyl ether [Bis(2-chloroethyl)ether]	x	x	1			
120-83-2	2,4-Dichlorophenol	x		1			
94-75-7	Dichlorophenoxyacetic acid (including salts and esters)	x	x		1		
542-75-6	1,3-Dichloropropene	x	x	1			
62-73-7	Dichlorvos	x	x	1			
115-32-2	Dicofol	x			1		
n/a	Diesel Engine Exhaust	x		2	1		
n/a	Diesel Fuel (marine)	x		1			
111-42-2	Diethanolamine	x	x	1			
111-46-6	Diethylene glycol	x		1			
111-96-6	Diethylene glycol dimethyl ether	x		1			
112-34-5	Diethylene glycol monobutyl ether	x		1			
111-90-0	Diethylene glycol monoethyl ether	x		1			
111-77-3	Diethylene glycol monomethyl ether	x		1			

Chemical Abstracts Service Number	Pollutant[a]	Regulatory Program[b]		Pollutant Type[c]			
		CAAA	AB2588	VOT	POT	PIT	GIT
64-67-5	Diethyl sulfate	x	x	1			
119-90-4	3,3'-Dimethoxybenzidine	x	x		1		
60-11-7	4-Dimethylaminoazobenzene	x	x		1		
121-69-7	N,N-Dimethylaniline	x	x	1			
57-97-6	7,12-Dimethylbenz[a]anthracene	x		2	1		
119-93-7	3,3'-Dimethylbenzidine (o-Tolidine)	x	x		1		
79-44-7	Dimethylcarbamoyl chloride	x	x	1			
68-12-2	N,N-Dimethylformamide	x	x	1			
57-14-7	1,1-Dimethylhydrazine	x	x	1			
131-11-3	Dimethyl phthalate	x	x	1			
77-78-1	Dimethyl sulfate	x	x	1			
534-52-1	4,6-Dinitro-o-cresol (including salts)	x	x	1			
51-28-5	2,4-Dinitrophenol	x	x	1			
42397-64-8	1,6-Dinitropyrene	x			1		
42397-65-9	1,8-Dinitropyrene	x			1		

Chemical Abstracts Service Number	Pollutant[a]	Regulatory Program[b]		Pollutant Type[c]			
		CAAA	AB2588	VOT	POT	PIT	GIT
121-14-2	2,4-Dinitrotoluene	x	x	1			
606-20-2	2,6-Dinitrotoluene	x		1			
25321-14-6	Dinitrotoluenes (mixed isomers)	x		1			
123-91-1	1,4-Dioxane (1,4-Diethyleneoxide)	x	x	1			
n/a	Dioxins	x					
630-93-3	Diphenylhydantoin	x			1		
122-66-7	1,2-Diphenylhydrazine	x	x	2	1		
25265-71-8	Dipropylene glycol	x		1			
34590-94-8	Dipropylene glycol monomethyl ether	x		1			
1937-37-7	Direct Black 38 (benzidine-based dye)	x			1		
2602-46-2	Direct Blue 6 (benzidine-based dye)	x			1		
16071-86-6	Direct Brown 95 (technical grade) (benzidine-based dye)	x			1		
n/a	Environmental Tobacco Smoke	x		2	1		
106-89-8	Epichlorohydrin (l-Chloro-2,3-epoxypropane)	x	x	1			

Chemical Abstracts Service Number	Pollutant[a]	Regulatory Program[b]		Pollutant Type[c]			
		CAAA	AB2588	VOT	POT	PIT	GIT
106-88-7	1,2-Epoxybutane	x	x	1			
n/a	Epoxy Resins	x		1	2		
12510-42-8	Erionite	x			1		
140-88-5	Ethyl acrylate	x	x	1			
100-41-4	Ethylbenzene	x	x	1			
51-79-6	Ethyl carbamate (Urethane)	x	x	1			
75-00-3	Ethyl chloride (Chloroethane)	x	x	1			
74-85-1	Ethylene	x		1			
106-93-4	Ethylene dibromide (1,2-Dibromoethane)	x	x	1			
107-06-2	Ethylene dichloride (1,2-Dichloroethane)	x	x	1			
107-21-1	Ethylene glycol	x	x	1			
629-14-1	Ethylene glycol diethyl ether	x		1			
110-71-4	Ethylene glycol dimethyl ether	x		1			
111-76-2	Ethylene glycol monobutyl ether	x		1			
110-80-5	Ethylene glycol monoethyl ether	x		1			

Chemical Abstracts Service Number	Pollutant[a]	Regulatory Program[b]		Pollutant Type[c]			
		CAAA	AB2588	VOT	POT	PIT	GIT
111-15-9	Ethylene glycol monoethyl ether acetate	x		1			
109-86-4	Ethylene glycol monomethyl ether	x		1			
110-4-96	Ethylene glycol monomethyl ether acetate	x		1			
2807-30-9	Ethylene glycol monopropyl ether	x		1			
151-56-4	Ethyleneimine (Aziridine)	x	x	1			
75-21-8	Ethylene oxide	x	x	1			
96-45-7	Ethylene thiourea	x	x		1		
75-34-3	Ethylidene dichloride (1,1-Dichloroethane)	x	x	1			
50-00-0	Formaldehyde	x	x	1			
n/a	Fluoride Compounds	x				1	
n/a	Fluorocarbons (brominated)	x		1			
n/a	Fluorocarbons (chlorinated)	x		1			
n/a	Gasoline engine exhaust	x		1	2		

Chemical Abstracts Service Number	Pollutant[a]	Regulatory Program[b]		Pollutant Type[c]			
		CAAA	AB2588	VOT	POT	PIT	GIT
n/a	Gasoline engine exhaust (condensates and extracts)	x		2	1		
n/a	Gasoline vapors	x		1			
n/a	Glasswool fibers	x				1	
111-30-8	Glutaraldehyde	x		1			
n/a	Glycol ethers and their acetates[e]	x	x	1			
126-07-8	Griseofulvin	x			1		
76-44-8	Heptachlor	x	x		1		
35822-46-9	1,2,3,4,6,7,8-Heptachlorodibenzo-p-dioxin	x		2	1		
67562-39-4	1,2,3,4,6,7,8-Heptachlorodibenzofuran	x		2	1		
55673-89-7	1,2,3,4,7,8,9-Heptachlorodibenzofuran	x		2	1		
87-68-3	Hexachlorbutadiene	x	x	1			
118-74-1	Hexachlorobenzene	x	x	2	1		
n/a	Hexachlorocyclohexanes (all stereo isomers, including lindane)	x	x	2	1		

Chemical Abstracts Service Number	Pollutant[a]	Regulatory Program[b]		Pollutant Type[c]			
		CAAA	AB2588	VOT	POT	PIT	GIT
77-47-4	Hexachlorocyclopentadiene	x	x	2	1		
39227-28-6	1,2,3,4,7,8-Hexachlorodibenzo-p-dioxin	x		2	1		
57653-85-7	1,2,3,6,7,8-Hexachlorodibenzo-p-dioxin	x		2	1		
19408-74-3	1,2,3,7,8,9-Hexachlorodibenzo-p-dioxin	x		2	1		
70648-26-9	1,2,3,4,7,8-Hexachlorodibenzofuran	x		2	1		
57117-44-9	1,2,3,6,7,8-Hexachlorodibenzofuran	x		2	1		
72918-21-9	1,2,3,7,8,9-Hexachlorodibenzofuran	x		2	1		
60851-34-5	2,3,4,6,7,8-Hexachlorodibenzofuran	x		2	1		
67-72-1	Hexachloroethane	x	x	1			
822-06-0	Hexamethylene-1,6-diisocyanate	x	x	1			
680-31-9	Hexamethylphosphoramide	x	x		1		
110-54-3	Hexane	x	x	1			
302-01-2	Hydrazine	x	x				1
7647-01-0	Hydrochloric acid [Hydrogen chloride (gas only)]	x	x				1

Chemical Abstracts Service Number	Pollutant[a]	Regulatory Program[b]		Pollutant Type[c]			
		CAAA	AB2588	VOT	POT	PIT	GIT
74-90-8	Hydrocyanic acid	x		1			
7664-39-3	Hydrogen fluoride (Hydrofluoric acid)	x	x				1
7783-06-4	Hydrogen sulfide	x					1
123-31-9	Hydroquinone	x	x	1			
193-39-5	Indeno [1,2,3,-cd] pyrene	x			1		
24267-56-9	Iodine-131	x					1
n/a	Isocyanates	x		1			
78-59-1	Isophorone	x	x	1			
67-63-0	Isopropyl alcohol	x		1			
80-05-7	4-4'-Isopropylidenediphenol	x			1		
7439-92-1	Lead	x				1	
301-04-2	Lead acetate	x				1	
7758-97-6	Lead chromate		x			1	
n/a	Lead Compounds		x			1	
n/a	Lead Compounds (inorganic)	x				1	

Chemical Abstracts Service Number	Pollutant[a]	Regulatory Program[b]		Pollutant Type[c]			
		CAAA	AB2588	VOT	POT	PIT	GIT
n/a	Lead Compounds (other than inorganic)	x			1		
7446-27-7	Lead phosphate	x				1	
1335-32-6	Lead subacetate	x			1		
58-89-9	Lindane	x			1		
108-31-6	Maleic anhydride	x	x		1		
7439-96-5	Manganese	x				1	
n/a	Manganese Compounds	x	x			1	
7487-94-7	Mercuric chloride	x				1	2
7439-97-6	Mercury	x	x				1
n/a	Mercury Compounds	x	x	2		2	1
67-56-1	Methanol	x	x	1			
72-43-5	Methoxychlor	x	x		1		
74-83-9	Methyl bromide (Bromomethane)	x	x	1			
74-87-3	Methyl chloride (Chloromethane)	x	x	1			

Chemical Abstracts Service Number	Pollutant[a]	Regulatory Program[b]		Pollutant Type[c]			
		CAAA	AB2588	VOT	POT	PIT	GIT
71-55-6	Methyl chloroform (1,1,1-Trichloroethane)	x	x	1			
56-49-5	3-Methylcholanthrene	x			1		
3697-24-3	5-Methylchrysene	x			1		
101-14-4	4,4'-Methylene bis (2-chloroaniline)	x	x		1		
75-09-2	Methylene chloride (Dichloromethane)	x	x	1			
101-77-9	4,4'-Methylenedianiline (and its dichloride)	x	x	1	2		
101-68-8	4,4'-Methylenediphenyl diisocyanate	x	x		1		
78-93-3	Methyl ethyl ketone (2-Butanone)	x	x	1			
60-34-4	Methyl hydrazine	x	x	1			
74-88-4	Methyl iodide (Iodomethane)	x	x		1		
108-10-1	Methyl isobutyl ketone (Hexone)	x	x	1			
624-83-9	Methyl isocyanate	x	x		1		
593-74-8	Methyl mercury (Dimethylmercury)	x		1	2		
80-62-6	Methyl methacrylate	x	x	1			

Chemical Abstracts Service Number	Pollutant[a]	Regulatory Program[b]		Pollutant Type[c]			
		CAAA	AB2588	VOT	POT	PIT	GIT
1634-04-4	Methyl tert-butyl ether	x	x	1			
443-48-1	Metronidazole	x			1		
90-94-8	Michler's ketone	x		1	2		
n/a	Mineral fibers (fine)	x	x			1	
1313-27-5	Molybdenum trioxide	x				1	
91-20-3	Naphthalene	x	x	1			
7440-02-0	Nickel	x				1	
373-02-4	Nickel acetate	x			1		
3333-39-3	Nickel carbonate	x			1		
13463-39-3	Nickel carbonyl	x		1			
n/a	Nickel Compounds	x	x			1	
12054-48-7	Nickel hydroxide	x				1	
1271-28-9	Nickelocene	x				1	
1313-99-1	Nickel oxide	x				1	

Chemical Abstracts Service Number	Pollutant[a]	Regulatory Program[b]		Pollutant Type[c]			
		CAAA	AB2588	VOT	POT	PIT	GIT
n/a	Nickel refinery dust from the pyrometallurgical process	x				1	
12035-72-2	Nickel subsulfide	x				1	
61-57-4	Niridazole	x			1		
7697-37-2	Nitric acid	x				2	1
139-13-9	Nitrilotriacetic acid	x			1		
98-95-3	Nitrobenzene	x	x	1	2		
92-93-3	4-Nitrobiphenyl	x	x		1		
7496-02-8	6-Nitrochrysene	x			1		
607-57-8	2-Nitrofluorene	x			1		
302-70-5	Nitrogen mustard N-oxide	x		1	2		
100-02-7	4-Nitrophenol	x	x	2	1		
79-46-9	2-Nitropropane	x	x	1			
5522-43-0	1-Nitropyrene	x			1		
924-16-3	N-Nitrosodi-n-butylamine	x			1		

Chemical Abstracts Service Number	Pollutant[a]	Regulatory Program[b]		Pollutant Type[c]			
		CAAA	AB2588	VOT	POT	PIT	GIT
1116-54-7	N-Nitrosodiethanolamine	x			1		
55-18-5	N-Nitrosodiethylamine	x			1		
62-75-9	N-Nitrosodimethylamine	x	x		1		
1621-64-7	N-Nitrosodi-n-propylamine	x			1		
156-10-5	p-Nitrosodiphenylamine	x			1		
10595-95-6	N-Nitrosomethylethylamine	x			1		
684-93-5	N-Nitroso-N-methylurea	x	x		1		
59-89-2	N-Nitrosomorpholine	x	x		1		
100-75-4	N-Nitrosopiperidine	x			1		
930-55-2	N-Nitrosopyrrolidine	x			1		
56-38-2	Parathion	x	x		1		
40321-76-4	1,2,3,7,8-Pentachlorodibenzo-p-dioxin	x		2	1		
57117-41-6	1,2,3,7,8-Pentachlorodibenzofuran	x		2	1		
57117-31-4	2,3,4,7,8-Pentachlorodibenzofuran	x		2	1		

Chemical Abstracts Service Number	Pollutant[a]	Regulatory Program[b]		Pollutant Type[c]			
		CAAA	AB2588	VOT	POT	PIT	GIT
82-68-8	Pentachloronitrobenzene (Quintobenzene)	x	x		1		
87-86-5	Pentachlorophenol	x	x	2	1		
79-21-0	Peracetic acid	x			1		
50-06-6	Phenobarbital	x			1		
108-95-2	Phenol	x	x	2	1		
106-50-3	p-Phenylenediamine	x	x	1			
90-43-7	2-Phenylphenol	x		2	1		
75-44-5	Phosgene	x	x	1			
7803-51-2	Phosphine	x	x				1
7664-382	Phosphoric acid	x				1	
7723-14-0	Phosphorus	x				1	
n/a	Phosphorus Compounds	x	x			1	
10025-87-3	Phosphorus oxychloride	x				1	1
10026-13-8	Phosphorus pentachloride	x				1	2

Chemical Abstracts Service Number	Pollutant[a]	Regulatory Program[b]		Pollutant Type[c]			
		CAAA	AB2588	VOT	POT	PIT	GIT
1314-56-3	Phosphorus pentoxide	x				1	
7719-12-2	Phosphorus trichloride	x					1
n/a	Phthalic anhydride	x	x	1			
1336-36-3	Polychlorinated biphenyls	x	x	2	1		
n/a	Polychlorinated dibenzo-p-dioxins	x					
n/a	Polychlorinated dibenzofurans	x					
n/a	Polycyclic Aromatic Hydrocarbons	x					
n/a	Polycyclic Aromatic Hydrocarbon Derivatives	x					
n/a	Polycyclic Organic Matter	x	x				
7758-01-2	Potassium bromate		x			1	
57-83-2	Progesterone	x			1		
1120-71-4	1,3-Propane sultone	x	x	1			
57-57-8	beta-Propiolactone	x	x	1			
123-38-6	Propionaldehyde	x	x	1			

Chemical Abstracts Service Number	Pollutant[a]	Regulatory Program[b]		Pollutant Type[c]			
		CAAA	AB2588	VOT	POT	PIT	GIT
114-26-1	Propoxur (Baygon)	x	x		1		
115-07-1	Propylene	x		1			
78-87-5	Propylene dichloride (1,2-Dichloropropane)	x	x	1			
107-98-2	Propylene glycol monomethyl ether	x		1			
108-65-6	Propylene glycol monomethyl ether acetate	x		1			
75-56-9	Propylene oxide	x	x	1			
75-55-8	1,2-Propylenimine (2-Methylaziridine)	x	x	1			
110-86-1	Pyridine	x		1			
91-22-5	Quinoline	x	x		1		
106-51-4	Quinone (p-Benzoquinone)	x	x		1		
n/a	Radionuclides[f] (including radon and its decay products)	x	x				see notes[f]
50-55-5	Reserpine	x			1		
n/a	Residual (heavy) fuel oils	x			1		

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Chemical Abstracts Service Number	Pollutant[a]	Regulatory Program[b]		Pollutant Type[c]			
		CAAA	AB2588	VOT	POT	PIT	GIT
n/a	Rockwool fibers	x				1	
7782-49-2	Selenium	x				1	
n/a	Selenium Compounds	x	x			1	
7446-34-6	Selenium sulfide	x				1	
n/a	Silica, crystalline	x				1	
7440-22-4	Silver	x				1	
n/a	Slagwool fibers	x				1	
10588-01-9	Sodium dichromate	x				1	
1310-73-2	Sodium hydroxide	x				1	
7789-06-2	Strontium chromate	x				1	
100-42-5	Styrene	x	x	1	2		
96-09-3	Styrene oxide	x	x	1	2		
7664-93-9	Sulfuric acid	x				1	2
n/a	Talc containing asbestiform fibers	x				1	
100-21-0	Terephthalic acid	x			1		

Chemical Abstracts Service Number	Pollutant[a]	Regulatory Program[b]		Pollutant Type[c]			
		CAAA	AB2588	VOT	POT	PIT	GIT
1746-01-6	2,3,7,8-Tetrachlorodibenzo-p-dioxin	x	x	2	1		
51207-31-9	2,3,7,8-Tetrachlorodibenzofuran	x		2	1		
79-34-5	1,1,2,2-Tetrachloroethane	x	x	1			
127-18-4	Tetrachloroethylene (Perchloroethylene)	x	x	1			
7440-28-0	Thallium	x				1	
n/a	Thallium Compounds	x				1	
62-55-5	Thioacetamide	x			1		
62-56-6	Thiourea	x			1		
7550-45-0	Titanium tetrachloride	x	x			1	
108-88-3	Toluene	x	x	1			
95-80-7	Toluene-2,4-diamine (2,4-Diaminotoluene)	x	x		1		
n/a	Toluene diisocyanates	x		1			
584-84-9	Toluene-2, 4-diisocyanate	x	x	2	1		
91-08-7	Toluene-2, 6-diisocyanate	x		2	1		

Chemical Abstracts Service Number	Pollutant[a]	Regulatory Program[b]		Pollutant Type[c]			
		CAAA	AB2588	VOT	POT	PIT	GIT
95-53-4	o-Toluidine	x	x	1	2		.
8001-35-2	Toxaphene (polychlorinated camphenes)	x	x		1		
126-73-8	Tributyl phosphate	x			1		
120-82-1	1,2,4-Trichlorobenzene	x	x	2	1		
79-00-5	1,1,2-Trichloroethane (Vinyl trichloride)	x	x	1	1		
79-01-6	Trichloroethylene	x	x	1			
95-95-4	2,4,5-Trichlorophenol	x	x	2	1		
88-06-2	2,4,6-Trichlorophenol	x	x	2	1		
78-40-0	Triethyl phosphine	x		1			
121-44-8	Triethylamine	x	x	1			
112-49-2	Triethylene gylcol dimethyl ether	x		1			
1582-09-8	Trifluralin	x	x		1		
95-63-6	Trimethylbenzene	x		2	1		
540-84-1	2,2,4-Trimethylpentane	x	x	1			
512-56-1	Trimethyl phosphate	x			1		

Chemical Abstracts Service Number	Pollutant[a]	Regulatory Program[b]		Pollutant Type[c]			
		CAAA	AB2588	VOT	POT	PIT	GIT
78-30-8	Triorthocresyl phosphate	x			1		
115-86-6	Triphenyl phosphate	x			1		
101-02-0	Triphenyl phosphite	x			1		
n/a	Vanadium (fume or dust)	x				1	
108-05-4	Vinyl acetate	x	x	1			
593-60-2	Vinyl bromide	x	x	1			
75-01-4	Vinyl chloride	x	x	1			
75-35-4	Vinylidene chloride (1,1-Dichloroethylene)	x	x	1			
n/a	Wood preservatives (containing arsenic and chromate)	x		2	1		
1330-20-7	Xylenes (mixed isomers)	x	x	1			
n/a	Xylenes (mixed xylenes)	x		1			
108-38-3	m-Xylene	x	x	1			
95-47-6	o-Xylene	x	x	1			
106-42-3	p-Xylene	x	x	1			

Chemical Abstracts Service Number	Pollutant[a]	Regulatory Program[b]		Pollutant Type[c]			
		CAAA	AB2588	VOT	POT	PIT	GIT
7440-66-6	Zinc	x				1	
n/a	Zinc Compounds	x				1	·
1314-13-2	Zinc oxide	x				1	

n/a = chemical abstracts number not available.

[a] For all listings above which contain the word "compounds" and for glycol ethers, the following applies: Unless otherwise specified, these listings are defined as including any unique chemical substance that contains the named chemical (i.e., antimony, arsenic, etc.) as part of that chemical's infrastructure.

[b] CAAA = CAA Amendments Title III Section 112 listed as of July 8, 1996; AB2588 = California AB2588 Program.

[c] VOT = volatile organic toxic; POT = particulate organic toxic; PIT = particulate inorganic toxic; GIT = gaseous inorganic toxic; 1 = primary type (form) of the pollutant; "2" signifies that some portion of the pollutant emissions may also be of this type.

[d] X'CN, where X = H' or any other group where a formal dissociation may occur. For example, KCN or Ca(CN)^2.

[e] CAA Glycol ether definition - Includes mono- and di- ethers of ethylene glycol, diethylene glycol, and triethylene glycol
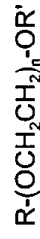
$$R-(OCH_2CH_2)_n-OR'$$

where:

    n = 1, 2, or 3,
    R = alkyl or aryl groups, and
    R' = R, H, or groups which, when removed, yield glycol ethers with the structure: R-(OCH$_2$CH$_2$)$_n$-OH. Polymers are excluded
      from the glycol ether category.

[f] A type of atom which spontaneously undergoes radioactive decay. Although radionuclides are technically of the GIT type, none of the point source controls currently in the database are known to provide significant control of these pollutants.