**Air pollution control**

Air pollution control, the techniques employed to reduce or eliminate the emission into the [atmosphere](https://www.britannica.com/science/atmosphere) of substances that can harm the [environment](https://www.merriam-webster.com/dictionary/environment) or human health. The control of [air pollution](https://www.britannica.com/science/air-pollution) is one of the principal areas of [pollution control](https://www.britannica.com/technology/pollution-control), along with [wastewater treatment](https://www.britannica.com/technology/wastewater-treatment), [solid-waste management](https://www.britannica.com/technology/solid-waste-management), and [hazardous-waste management](https://www.britannica.com/technology/hazardous-waste-management).

Air is considered to be polluted when it contains certain substances in concentrations high enough and for durations long enough to cause harm or undesirable effects. These include adverse effects on human health, property, and atmospheric visibility. The atmosphere is susceptible to pollution from natural sources as well as from human activities. Some natural phenomena, such as [volcanic eruptions](https://www.britannica.com/science/volcano) and forest fires, may have not only local and regional effects but also long-lasting global ones. Nevertheless, only pollution caused by human activities, such as [industry](https://www.britannica.com/technology/industry) and transportation, is subject to mitigation and control.

Most air contaminants originate from [combustion](https://www.britannica.com/science/combustion) processes. During the Middle Ages the burning of [coal](https://www.britannica.com/science/coal-fossil-fuel) for fuel caused recurrent air pollution problems in London and other large European cities. Beginning in the 19th century, in the wake of the [Industrial Revolution](https://www.britannica.com/event/Industrial-Revolution), increasing use of [fossil fuels](https://www.britannica.com/science/fossil-fuel) intensified the severity and frequency of air pollution episodes. The advent of mobile sources of air pollution—i.e., [gasoline](https://www.britannica.com/technology/gasoline-fuel)-powered highway vehicles—had a tremendous impact on air quality problems in cities. It was not until the middle of the 20th century, however, that meaningful and lasting attempts were made to regulate or limit emissions of air pollutants from stationary and mobile sources and to control air quality on both regional and local scales.

The primary focus of air pollution regulation in industrialized countries has been on protecting ambient, or outdoor, air quality. This involves the control of a small number of specific “criteria” pollutants known to contribute to urban [smog](https://www.britannica.com/science/smog) and chronic [public health](https://www.britannica.com/topic/public-health) problems. The [criteria](https://www.merriam-webster.com/dictionary/criteria) pollutants include fine particulates, [carbon monoxide](https://www.britannica.com/science/carbon-monoxide), [sulfur dioxide](https://www.britannica.com/science/sulfur-dioxide), nitrogen dioxide, [ozone](https://www.britannica.com/science/ozone), and [lead](https://www.britannica.com/science/lead-chemical-element). Since the end of the 20th century, there also has been a recognition of the hazardous effects of trace amounts of many other air pollutants called “[air toxics](https://www.britannica.com/topic/air-toxic).” Most air toxics are organic chemicals, [comprising](https://www.merriam-webster.com/dictionary/comprising) molecules that contain [carbon](https://www.britannica.com/science/carbon-chemical-element), [hydrogen](https://www.britannica.com/science/hydrogen), and other atoms. Specific emission regulations have been [implemented](https://www.merriam-webster.com/dictionary/implemented) against those pollutants. In addition, the long-term and far-reaching effects of the “[greenhouse gases](https://www.britannica.com/science/greenhouse-gas)” on atmospheric chemistry and [climate](https://www.britannica.com/science/climate-meteorology) have been observed, and cooperative international efforts have been undertaken to control those pollutants. The greenhouse gases include [carbon dioxide](https://www.britannica.com/science/carbon-dioxide), [chlorofluorocarbons](https://www.britannica.com/science/chlorofluorocarbon)(CFCs), [methane](https://www.britannica.com/science/methane), [nitrous oxide](https://www.britannica.com/science/nitrous-oxide), and ozone. In 2009 the U.S. Environmental Protection Agency ruled that greenhouse gases posed a threat to human health and could be subject to regulation as air pollutants.

The best way to protect air quality is to reduce the emission of pollutants by changing to cleaner fuels and processes. Pollutants not eliminated in this way must be collected or trapped by appropriate air-cleaning devices as they are generated and before they can escape into the atmosphere. These devices are described below. The emphasis of this article is air pollution control [technology](https://www.britannica.com/technology/technology) as it is designed to remove particulate and gaseous pollutants from the emissions of stationary sources, including power plants and industrial facilities. (The control of air pollution from mobile sources is described in [emission-control system](https://www.britannica.com/technology/emission-control-system).)

## Control Of [Particulates](https://www.britannica.com/science/particulate)

Airborne particles can be removed from a polluted airstream by a variety of physical processes. Common types of equipment for collecting fine particulates include cyclones, scrubbers, electrostatic precipitators, and baghouse filters. Once collected, particulates adhere to each other, forming agglomerates that can readily be removed from the equipment and disposed of, usually in a [landfill](https://www.britannica.com/technology/sanitary-landfill).

Because each air pollution control project is unique, it is usually not possible to decide in advance what the best type of particle-collection device (or combination of devices) will be; control systems must be designed on a case-by-case basis. Important particulate characteristics that influence the selection of collection devices include [corrosivity](https://www.britannica.com/science/corrosion), reactivity, shape, density, and especially size and size distribution (the range of different particle sizes in the airstream). Other design factors include airstream characteristics (e.g., [pressure](https://www.britannica.com/science/pressure), [temperature](https://www.britannica.com/science/temperature), and [viscosity](https://www.britannica.com/science/viscosity)), flow rate, removal [efficiency](https://www.merriam-webster.com/dictionary/efficiency) requirements, and allowable resistance to airflow. In general, cyclone collectors are often used to control industrial dust emissions and as pre-cleaners for other kinds of collection devices. Wet scrubbers are usually applied in the control of flammable or explosive dusts or mists from such sources as industrial and chemical processing facilities and [hazardous-waste incinerators](https://www.britannica.com/technology/hazardous-waste-management); they can handle hot airstreams and sticky particles. [Electrostatic precipitators](https://www.britannica.com/technology/electrostatic-precipitator) and fabric-filter baghouses are often used at power plants.

## [Cyclones](https://www.britannica.com/technology/cyclone-technology)

A cyclone removes particulates by causing the dirty airstream to flow in a spiral path inside a cylindrical chamber. Dirty air enters the chamber from a tangential direction at the outer wall of the device, forming a vortex as it swirls within the chamber. The larger particulates, because of their greater inertia, move outward and are forced against the chamber wall. Slowed by friction with the wall surface, they then slide down the wall into a conical dust hopper at the bottom of the cyclone. The cleaned air swirls upward in a narrower spiral through an inner cylinder and emerges from an outlet at the top. Accumulated particulate dust is periodically removed from the hopper for disposal.

Cyclones are best at removing relatively coarse particulates. They can routinely achieve [efficiencies](https://www.merriam-webster.com/dictionary/efficiencies) of 90 percent for particles larger than about 20 micrometres (μm; 20 millionths of a metre). By themselves, however, cyclones are not sufficient to meet stringent air quality standards. They are typically used as pre-cleaners and are followed by more efficient air-cleaning equipment such as electrostatic precipitators and baghouses (described below).

## Scrubbers

Devices called [wet scrubbers](https://www.britannica.com/technology/wet-scrubber) trap suspended particles by direct contact with a spray of water or other liquid. In effect, a scrubber washes the particulates out of the dirty airstream as they collide with and are entrained by the countless tiny droplets in the spray. Several configurations of wet scrubbers are in use. In a spray-tower scrubber, an upward-flowing airstream is washed by water sprayed downward from a series of nozzles. The water is recirculated after it is sufficiently cleaned to prevent clogging of the nozzles. Spray-tower scrubbers can remove 90 percent of particulates larger than about 8 μm.

In **orifice scrubbers** and wet-impingement scrubbers, the air-and-droplet mixture collides with a solid surface. Collision with a surface atomizes the droplets, reducing droplet size and thereby increasing total surface contact area. These devices have the advantage of lower water-recirculation rates, and they offer removal efficiencies of about 90 percent for particles larger than 2 μm.

**Venturi scrubbers** are the most efficient of the wet collectors, achieving efficiencies of more than 98 percent for particles larger than 0.5 μm in diameter. Scrubber efficiency depends on the relative velocity between the droplets and the particulates. Venturi scrubbers achieve high relative velocities by injecting water into the throat of a [venturi channel](https://www.britannica.com/technology/venturi-tube)—a constriction in the flow path—through which particulate-laden air is passing at high speed.

## [Electrostatic precipitators](https://www.britannica.com/technology/electrostatic-precipitator)

[Electrostatic precipitation](https://www.britannica.com/technology/electrostatic-precipitator) is a commonly used method for removing fine particulates from airstreams. In an [electrostatic precipitator](https://www.britannica.com/technology/electrostatic-precipitator), particles suspended in the airstream are given an [electric charge](https://www.britannica.com/science/electric-charge) as they enter the unit and are then removed by the influence of an [electric field](https://www.britannica.com/science/electric-field). The precipitation unit [comprises](https://www.merriam-webster.com/dictionary/comprises) baffles for distributing airflow, discharge and collection [electrodes](https://www.britannica.com/science/electrode), a dust clean-out system, and collection hoppers. A high voltage of [direct current](https://www.britannica.com/science/direct-current) (DC), as much as 100,000 [volts](https://www.britannica.com/science/volt-unit-of-measurement), is applied to the discharge electrodes to charge the particles, which then are attracted to oppositely charged collection electrodes, on which they become trapped.

In a typical unit the collection electrodes [comprise](https://www.merriam-webster.com/dictionary/comprise) a group of large rectangular metal plates suspended vertically and parallel to each other inside a boxlike structure. There are often hundreds of plates having a combined surface area of tens of thousands of square metres. Rows of discharge electrode wires hang between the collection plates. The wires are given a negative electric charge, whereas the plates are grounded and thus become positively charged.

Particles that stick to the collection plates are removed periodically when the plates are shaken, or “rapped.” Rapping is a mechanical technique for separating the trapped particles from the plates, which typically become covered with a 6-mm (0.2-inch) layer of dust. Rappers are either of the impulse (single-blow) or vibrating type. The dislodged particles are collected in a hopper at the bottom of the unit and removed for disposal. An electrostatic precipitator can remove particulates as small as 1 μm with an efficiency exceeding 99 percent. The effectiveness of electrostatic precipitators in removing fly ash from the combustion gases of fossil-fuel furnaces accounts for their high frequency of use at power stations.

## [Baghouse filters](https://www.britannica.com/technology/baghouse-filter)

One of the most efficient devices for removing suspended particulates is an assembly of fabric-filter bags, commonly called a baghouse. A typical baghouse comprises an array of long, narrow bags—each about 25 cm (10 inches) in diameter—that are suspended upside down in a large enclosure. Dust-laden air is blown upward through the bottom of the enclosure by fans. Particulates are trapped inside the filter bags, while the clean air passes through the fabric and exits at the top of the baghouse.

A fabric-filter dust collector can remove very nearly 100 percent of particles as small as 1 μm and a significant fraction of particles as small as 0.01 μm. Fabric filters, however, offer relatively high resistance to airflow, which leads to substantial energy usage for the fan system. In addition, in order to prolong the useful life of the filter fabric, the air to be cleaned must be cooled (usually below 300 °C [570 °F]) before it is passed through the unit; cooling coils needed for this purpose add to the energy usage. (Certain filter fabrics—e.g., those made of ceramic or mineral materials—can operate at higher temperatures.) Several compartments of filter bags are often used at a single baghouse installation. This arrangement allows individual compartments to be cleaned while others remain in service.

The bags are cleaned by removing the excess layer of surface dust. This is done in several different ways: by mechanically shaking them; by temporarily reversing the flow of air and causing them to collapse; or by sending a short burst of air down through the bag, causing it to briefly expand. After the dust is removed from the filters, it falls into a hopper below and can be collected for disposal or further use. Care must be taken not to remove too much of the built-up surface dust, or “dust cake,” when cleaning the filters. In most filter types the filter itself is only a substrate that allows for the formation of a layer of dust cake, which then captures the majority of the particulates. Filters with an applied membrane coating such as [polytetrafluoroethylene](https://www.britannica.com/science/polytetrafluoroethylene) (Teflon) do not require the use of dust cake to operate at their highest efficiency.

**Control of Gases**

Gaseous criteria pollutants, as well as [volatile organic compounds](https://www.britannica.com/science/volatile-organic-compound)(VOCs) and other gaseous [air toxics](https://www.britannica.com/topic/air-toxic), are controlled by means of three basic techniques: [absorption](https://www.britannica.com/science/absorption-physics), [adsorption](https://www.britannica.com/science/adsorption), and incineration (or [combustion](https://www.britannica.com/science/combustion)). These techniques can be employed singly or in combination. They are effective against the major greenhouse gases as well. In addition, a fourth technique, known as [carbon sequestration](https://www.britannica.com/technology/carbon-sequestration), is in development as a means of controlling carbon dioxide levels.

## [Absorption](https://www.britannica.com/science/absorption-physics)

In the [context](https://www.merriam-webster.com/dictionary/context) of air pollution control, [absorption](https://www.britannica.com/science/absorption-physics) involves the transfer of a gaseous pollutant from the air into a contacting liquid, such as water. The liquid must be able either to serve as a [solvent](https://www.britannica.com/science/solvent-chemistry) for the pollutant or to capture it by means of a [chemical reaction](https://www.britannica.com/science/chemical-reaction).

Wet scrubbers similar to those [described above](https://www.britannica.com/technology/air-pollution-control#ref286089) for controlling suspended particulates may be used for gas absorption. Gas absorption can also be carried out in **packed scrubbers,** or towers, in which the liquid is present on a wetted surface rather than as droplets suspended in the air. A common type of packed scrubber is the **countercurrent tower**. After entering the bottom of the tower, the polluted airstream flows upward through a wetted column of light, chemically inactive packing material. The liquid absorbent flows downward and is uniformly spread throughout the column packing, thereby increasing the total area of contact between gas and liquid. [Thermoplastic materials](https://www.britannica.com/science/plastic) are most widely used as packing for countercurrent scrubber towers. These devices usually have gas-removal efficiencies of 90–95 percent.

**Cocurrent** and cross-flow packed scrubber designs are also used for gas absorption. In the cocurrent design, both gas and liquid flow in the same direction—vertically downward through the scrubber. Although not as efficient as countercurrent designs, cocurrent devices can work at higher liquid flow rates. The increased flow prevents plugging of the packing when the airstream contains high levels of particulates. Cocurrent designs afford lowered resistance to airflow and allow the cross-sectional area of the tower to be reduced. The cross-flow design, in which gas flows horizontally through the packing and liquid flows vertically downward, can operate with lower airflow resistance when high particulate levels are present.

In general, scrubbers are used at [fertilizer](https://www.britannica.com/topic/fertilizer) production facilities (to remove [ammonia](https://www.britannica.com/science/ammonia) from the airstream), at [glass](https://www.britannica.com/topic/glass-properties-composition-and-industrial-production-234890) production plants (to remove hydrogen fluoride), at chemical plants (to remove water-soluble solvents such as [acetone](https://www.britannica.com/science/acetone) and [methyl alcohol](https://www.britannica.com/science/methanol)), and at rendering plants (to control odours)

## Flue gas desulfurization

[Sulfur dioxide](https://www.britannica.com/science/sulfur-dioxide) in flue gas from fossil-fuel power plants can be controlled by means of an absorption process called flue gas desulfurization (FGD). FGD systems may involve wet scrubbing or dry scrubbing. In **wet FGD systems**, flue gases are brought in contact with an absorbent, which can be either a liquid or a slurry of solid material. The sulfur dioxide dissolves in or reacts with the absorbent and becomes trapped in it. In dry FGD systems, the absorbent is dry pulverized lime or [limestone](https://www.britannica.com/science/limestone); once absorption occurs, the solid particles are removed by means of baghouse filters ([described above](https://www.britannica.com/technology/air-pollution-control#ref286091)). **Dry FGD systems**, compared with wet systems, offer cost and energy savings and easier operation, but they require higher chemical [consumption](https://www.merriam-webster.com/dictionary/consumption) and are limited to flue gases derived from the combustion of low-sulfur [coal](https://www.britannica.com/science/coal-fossil-fuel).

FGD systems are also classified as either regenerable or nonregenerable (throwaway), depending on whether the [sulfur](https://www.britannica.com/science/sulfur) that is removed from the flue gas is recovered or discarded. In the [United States](https://www.britannica.com/place/United-States) most systems in operation are nonregenerable because of their lower capital and operating costs. By contrast, in Japan regenerable systems are used extensively, and in Germany they are required by law. Nonregenerable FGD systems produce a sulfur-containing [sludge](https://www.britannica.com/topic/sludge)residue that requires appropriate disposal. Regenerable FGD systems require additional steps to convert the sulfur dioxide into useful by-products like [sulfuric acid](https://www.britannica.com/science/sulfuric-acid).

Several FGD methods exist, differing mainly in the chemicals used in the process. FGD processes that employ either lime or limestone slurries as the reactants are widely applied. In the limestone scrubbing process, sulfur dioxide reacts with limestone (calcium carbonate) particles in the slurry, forming [calcium](https://www.britannica.com/science/calcium) sulfite and [carbon dioxide](https://www.britannica.com/science/carbon-dioxide). In the lime scrubbing process, sulfur dioxide reacts with slaked lime (calcium hydroxide), forming calcium sulfite and water. Depending on sulfur dioxide concentrations and oxidation conditions, the calcium sulfite can continue to react with water, forming calcium sulfate ([gypsum](https://www.britannica.com/science/gypsum)). Neither calcium sulfite nor calcium sulfate is very soluble in water, and both can be precipitated out as a slurry by gravity settling. The thick slurry, called FGD sludge, creates a significant disposal problem. Flue gas desulfurization helps to reduce ambient sulfur dioxide levels and [mitigate](https://www.merriam-webster.com/dictionary/mitigate) the problem of [acid rain](https://www.britannica.com/science/acid-rain). Nevertheless, in addition to its expense (which is passed on directly to the consumer as higher rates for electricity), millions of tons of FGD sludge are generated each year.

## [Adsorption](https://www.britannica.com/science/adsorption)

Gas [adsorption](https://www.britannica.com/science/adsorption), as contrasted with absorption, is a surface phenomenon. The gas molecules are sorbed—attracted to and held—on the surface of a solid. Gas adsorption methods are used for odour control at various types of chemical-manufacturing and food-processing facilities, in the recovery of a number of volatile solvents (e.g., [benzene](https://www.britannica.com/science/benzene)), and in the control of VOCs at industrial facilities.

**Activated carbon** (heated [charcoal](https://www.britannica.com/science/charcoal)) is one of the most common adsorbent materials. It is very porous and has an extremely high ratio of surface area to volume. Activated carbon is particularly useful as an adsorbent for cleaning airstreams that contain VOCs and for solvent recovery and odour control. A properly designed carbon adsorption unit can remove gas with an efficiency exceeding 95 percent.

Adsorption systems are configured either as stationary bed units or as moving bed units. In stationary bed adsorbers, the polluted airstream enters from the top, passes through a layer, or bed, of activated carbon, and exits at the bottom. In moving bed adsorbers, the activated carbon moves slowly down through channels by gravity as the air to be cleaned passes through in a cross-flow current.

[**Incineration**](https://www.britannica.com/technology/incineration)

The process called incineration or [combustion](https://www.britannica.com/science/combustion)—chemically, rapid oxidation—can be used to convert VOCs and other gaseous [hydrocarbon](https://www.britannica.com/science/hydrocarbon) pollutants to [carbon dioxide](https://www.britannica.com/science/carbon-dioxide) and [water](https://www.britannica.com/science/water). Incineration of VOCs and hydrocarbon fumes usually is accomplished in a special incinerator called an afterburner. To achieve complete combustion, the **afterburner** must provide the proper amount of turbulence and burning time, and it must maintain a sufficiently high temperature. Sufficient turbulence, or mixing, is a key factor in combustion because it reduces the required burning time and temperature. A process called **direct flame incineration** can be used when the waste gas is itself a combustible mixture and does not need the addition of air or fuel.

An afterburner typically is made of a steel shell lined with refractory material such as [firebrick](https://www.britannica.com/technology/firebrick). The refractory lining protects the shell and serves as a thermal insulator. Given enough time and high enough temperatures, gaseous organic pollutants can be almost completely oxidized, with incineration efficiency approaching 100 percent. Certain substances, such as [platinum](https://www.britannica.com/science/platinum), can act in a manner that assists the combustion reaction. These substances, called [catalysts](https://www.britannica.com/science/catalyst), allow complete oxidation of the combustible gases at relatively low temperatures.

Afterburners are used to control odours, destroy toxic [compounds](https://www.merriam-webster.com/dictionary/compounds), or reduce the amount of photochemically reactive substances released into the air. They are employed at a variety of industrial facilities where VOC vapours are emitted from combustion processes or solvent evaporation (e.g., [petroleum refineries](https://www.britannica.com/technology/petroleum-refining), paint-drying facilities, and [paper mills](https://www.britannica.com/technology/papermaking)).

## [Carbon sequestration](https://www.britannica.com/technology/carbon-sequestration)

The best way to reduce the levels of [carbon dioxide](https://www.britannica.com/science/carbon-dioxide) in the air is to use energy more efficiently and to reduce the combustion of [fossil fuels](https://www.britannica.com/science/fossil-fuel) by using [alternative energy](https://www.britannica.com/science/renewable-energy) sources (e.g., [nuclear](https://www.britannica.com/science/nuclear-energy), [wind](https://www.britannica.com/science/wind-power), [tidal](https://www.britannica.com/science/tidal-power), and [solar power](https://www.britannica.com/science/solar-energy)). In addition, [carbon sequestration](https://www.britannica.com/technology/carbon-sequestration) can be used to serve the purpose. Carbon sequestration involves the long-term storage of carbon dioxide underground, as well as on the surface of Earth in forests and oceans. Carbon sequestration in forests and oceans relies on natural processes such as forest growth. However, the clearing of forests for agricultural and other purposes (and also the pollution of oceans) diminishes natural carbon sequestration.

 Storing carbon dioxide underground—a technology under development that is also called **geosequestration** or carbon capture and storage—would involve pumping the gas directly into underground geologic “reservoir” layers. This would require the separation of carbon dioxide from power plant flue gases (or some other source)—a costly process.