Selecting the Best Air Pollution Control Strategy

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Marc Karell, P.E., CEM

CED engineering.com
PDH FOR THE PROFESSIONAL

Continuing Education and Development, Inc.
22 Stonewall Court
Woodcliff Lake, NJ 07677

P: (877) 322-5800
info@cedengineering.com

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THE ISSUE

Despite progress over the last 40 years, air pollution is a major public health issue in the U.S. Over a third of the nation lives in ozone nonattainment areas. The National Ambient Air Quality Standard for ozone is about to be lowered, causing more areas to be nonattainment. Ultrafine particulate matter ("$PM_{2.5}$") has been implicated in a number of public health issues, such as asthma. Therefore, the Obama Administration and USEPA Administrator Lisa Jackson have openly called for making air pollution, as well as all environmental, rules more stringent. Perhaps more important, neighborhood environmental groups have gotten more knowledgable and savvy, and know how to use the system to block proposed plans to make changes or expansions at existing plants or to block construction of new plants. Minimizing air emissions will be a priority at many facilities nationwide.

The "best" way to reduce emissions of air pollutants is to optimize your process, so as less air pollutants are produced. Optimizing your process includes:

- Using less raw materials to make product,
- Combusting less fuel for the same amount of product,
- Minimizing waste generation and/or reuse byproducts or waste generated, and
- Capturing potential pollutants as part of process.

In the literature, these efforts are often called "Pollution Prevention" or "P2". The USEPA openly encourages companies to implement P2 programs.

Some examples include regular maintenance (tune-up) of combustion equipment so that excess fuel does not need to be combusted to achieve the same amount of heat/steam production; improvement of chemical reaction parameters (i.e., temperature, mixing, etc.) to minimize the need of excess raw materials and generation of waste byproducts; capture and reuse of solvents, components, etc., where possible.

In addition to reducing air and other environmental impacts, process optimization also potentially saves the company much in the way of regular cost, such as purchase of raw materials, purchase of fuels, maintenance, etc. Therefore, it is also obvious that companies actively research optimization options extensively, implement optimization strategies that make sense, and often have staff devoted to this.

But at a certain point, a facility will have implemented all feasible optimization strategies. It is likely that to comply with applicable air quality regulations some type of "end of pipe" control device removing contaminants that are formed must be installed and operated. What site- or process-specific factors are critical to selecting the technology type? How does one decide on the most appropriate technology to install (advantages

and disadvantages)? What are the key design features that need to be addressed for each candidate technology type applied to the source of emissions? These are the issues to be covered in this course. This course is designed for engineers with responsibility for air quality compliance.

AIR POLLUTION CONTROL BASIC MODE OF OPERATION

Air pollution control ("APC") equipment is the non-process or "end-of-pipe" solution to reduce air emissions. It treats the exhaust after the process has created the air pollutants and before exiting into the atmosphere in such a way to prevent them from entering the atmosphere. APC equipment may:

- Capture and destroy the pollutants in question,
- Convert pollutants to less toxic compounds,
- Remove pollutants from the air and transfer them to another media,
- Concentrate pollutants.

To begin to assess which air pollution control equipment is best for a given operation, the following determinations need to be made:

- Nature or chemistry of the pollutant(s) to be controlled,
- Rate or concentration of pollutant going through APC,
- Presence of other compounds in the exhaust,
- Cost,
- Disposal of potential waste products.

Therefore, the environmental engineer needs to fully understand which pollutants are being emitted and their emission rates leaving the process and entering potential APC equipment, including how rates may change over time (i.e., do they peak at a certain segment of the operations cycle and trail off later?). Other courses examine how to measure and estimate air emissions.

With this information, the environmental engineer should first check all applicable air quality regulations as well as current air permit limits to determine whether any compound's emission rate during the process must be reduced and, if so, by how much. Evaluating any proposed legislation which may impact the facility in the future is a good thing, as well. In addition, if APC equipment is necessary, must it be operated continually or not?

Then after the list of compounds whose emission rates must be reduced and their degree of control are determined, the environmental engineer must select the type of APC equipment likely to meet the required reductions. APC equipment that cannot capture, remove, or otherwise control a certain compound must be removed from consideration. APC equipment that can control the compound but not sufficiently based on regulatory requirements or the air permit must be removed from consideration, too.

For sources where more than one compound must be controlled or a very large reduction in emissions is required, it is possible that more than one APC device must be utilized.

APC CONTROL SELECTION CONSIDERATIONS

The effectiveness of APC equipment is generally measured in "control efficiency", the percentage of the inlet mass rate of the compound in question not found in the exhaust to the atmosphere after treatment by the equipment. The control efficiency performance can vary for a type of APC, however, based on how it operates and the inlet rate of the compound in question.

It is important to understand regulatory requirements in order to select the proper APC equipment. While APC performance is measured in percent reduction of the compound in the inlet stream, most air permits contain limits on a mass rate (i.e., pounds per hour or tons per year). Therefore, an understanding of what the worst-case uncontrolled mass rate and the required mass rate are is critical. Can the APC equipment in consideration deliver the necessary mass reductions of the subject pollutant?

Minimum APC equipment performance requirements are written into several prominent air quality regulations. Such performance is summarized by acronyms. First, comes Reasonably Available Control Technology (RACT). This is the least stringent control strategy. It is generally based on a "reasonable" technology that many with similar processes are successfully using. Some RACT rules allow the facility to exempt itself from different APC equipment if the cost is considered excessive. If such an exemption is preferred, the environmental engineer must determine the true cost of the equipment, including its capital cost, amortized cost, and operating costs for the lifetime of the equipment. Then it must determine total emissions that it will control over its lifetime, and use these to determine cost per ton of compound controlled. If this rate exceeds a certain published factor, then the cost of the APC equipment is considered not "reasonable" and does not have to be considered.

Next comes Maximum Achievable Control Technology (MACT), used in many federal (NESHAP) hazardous air pollutant regulations. This is a standard where an applicable facility must meet a control efficiency standard based on the average of the top 12% of facilities for the same process. Cost is not supposed to be a factor in determining whether a strategy meets the MACT criteria.

Next in stringency comes Best Available Control Technology (BACT), used in the Prevention of Significant Deterioration program. It is an assessment that a facility must make to determine which technology is "best." The USEPA requires a Top-Down Analysis. The environmental engineer must first create a list of all APC equipment that are technically feasible for the compound(s) in question and list them in order of effectiveness for the process in question from most effective (greatest potential control efficiency) to least effective. Then the engineer must take the most stringent listed APC

and perform an assessment of its economic, environmental, and energy impacts. The economic impact is similar to the one performed for RACT, except for BACT the cost threshold (in dollars per ton controlled) that allows an APC to be stricken from consideration is much higher than for RACT. As a rule requiring more stringent compound control, it would take a very high cost to exempt a technically-feasible APC. The environmental evaluation is a technical evaluation of environmental impacts, including unintentional ones. Does the operation of the APC equipment to remove the compound convert it into another compound that may be more dangerous (toxic)? Does its operation cause the contamination or other adverse impacts of another source (i.e., major increase in generation of a toxic solid waste or wastewater)? If such an environmental impact is considered as serious or worse than not operating the APC, then that candidate APC can be stricken from consideration. Finally, the engineer must perform an energy evaluation. Will the operation of the candidate APC cause a huge energy penalty, with its resultant high fuel usage and combustion emissions? In its wish to conserve energy usage, the USEPA takes a major energy demand into consideration to potentially exclude an APC from consideration for BACT.

Finally, comes Lowest Achievable Emission Rate (LAER), required for control of compounds from major new or modified sources in a non-attainment area. Like with BACT, the environmental engineer must develop a list of technically-feasible APC equipment from most stringent. The most stringent APC is LAER, unless the cost is so overwhelmingly expensive, and/or environmental and energy impacts are so large and able to cause hardship.

The environmental engineer must know what the agency requirements will be for the source in question so that the right approach can be taken and APC equipment selected.

TYPICAL APC EQUIPMENT

Incineration or Oxidation

Incineration is commonly used to control both volatile organic compound (VOCs) and inorganic gases, such as hydrogen sulfide. Thermal incineration involves having the exhaust travel into a high temperature chamber, causing the compounds to destabilize and break down to their elemental components, followed by their oxidation. Therefore, this technology is often referred to as thermal oxidation. VOCs will be oxidized by high temperature to carbon dioxide and water. Inorganic gases will be oxidized to simpler inorganic substances; for example, hydrogen sulfide is oxidized to sulfur dioxide.

These units are sometimes also called afterburners. Control efficiencies for thermal incinerators of over 99% can be achieved for VOCs and inorganic gases. Often the literature refers to this as "destruction efficiency", as the compound is permanently destroyed. Incinerators are used in many processes to control exhausts laden with VOCs, such as pharmaceutical and chemical manufacturing, coating operations, and printing. Incinerators are effective in controlling exhausts with low concentrations of

VOCs.

The two key factors in the design of a thermal incinerator for enhanced performance of destroying and oxidizing the subject compounds is sufficient high temperatures in the chamber and sufficient residence time in the combustion zone. Although the ideal chamber temperature may differ based on the compound being treated, generally incinerators are programmed to maintain a temperature of 1,200 to 1,500°F. Temperatures significantly above this represent a waste of fuel combusted to reach the necessary range. In addition, at a certain point (generally, above 1,600°F), the system begins to form nitrogen oxides (NO_x), a regulated pollutant, from the breakdown and oxidation of nitrogen in the fuel and in the air. Maintaining a temperature below 1,200°F may cause the exhaust components to not combust completely. And in fact, in such conditions, not only will VOC or other gases move through the system uncontrolled, but products of incomplete combustion (PICs) could form. Many of these compounds are toxic, making the exhaust potentially more toxic than the original vapors being combusted. Odorous exhaust coming out the stack or a slight black smoke may indicate the formation of PICs. Therefore, many regulatory agencies in issued air permits set forth a minimum absolute or average temperature that must be maintained in the incinerator chamber at all times during operation, and require thermocouples in the combustion chamber and appropriate recording devices to ensure compliance and have documentation.

The residence time, or the average time the exhaust travels through the combustion chamber is critical, as well. Residence time is the ratio of the capacity of a chamber to hold a substance divided by the rate of flow into and out of the chamber. A chamber not designed properly for the worst case maximum quantity of compound to be destroyed will allow compound to be exposed for too short a period at the necessary temperature and not be destroyed. Typically, an average residence time of 0.5 seconds is sufficient to meet a 99% destruction efficiency at a temperature range of 1,200°F to 1,500°F. When an environmental engineer determines that the destruction efficiency is below this and the temperature monitor is properly calibrated and shows that the right temperature is maintained, then a likely reason is that too much VOC is entering the incinerator given the size of the chamber. An expanded chamber or reduced flow rate would raise the residence time. A knowledge of worst case maximum contaminant inlet is critical to designing the combustion chamber to meet the minimum residence time necessary to meet a high destruction efficiency.

While incinerators are highly effective, their operation comes at a great energy cost. Fuel must be burned to create sufficient heat in the combustion chamber. While energy released when VOCs and other compounds in the exhaust are combusted can compensate for this somewhat, this effect is negligible for typical dilute VOC streams. And for very highly concentrated VOC exhausts, there is a chance that a lower explosivity limit may be approached. To reduce fuel use, the incinerator/oxidation unit can be modified by adding a catalyst in the unit. The catalyst slows down the compounds in the combustion unit to raise its residence time sufficiently to allow a lower temperature in the combustion unit, yet still maintain a high destruction efficiency.

Typically, catalytic oxidizers can operate at a sustained temperature of 800°F to 1,100°F. The hold up by the catalyst is sufficient to necessitate less heat for the breakdown. Commercially available catalysts are made of a variety of materials. Many are plastics; some contain metals, such as platinum and nickel.

The benefits of catalytic oxidation compared to thermal oxidation are lower fuel costs and lower emissions from the byproducts of fuel combustion. A disadvantage of a catalytic unit is the potentially higher capital cost of the catalyst, although this may be compensated for (in some cases) by a smaller combustion unit. In addition, catalysts involve greater maintenance and will need to be replaced during the life of the total unit, an additional cost. One other factor is critical in deciding between thermal and catalytic incinerators. To use a catalyst the exhaust must be essentially free of foreign substances which could stick to and poison the catalyst, such as particulates and others. So besides knowing the concentrations of the contaminants one wants to remove from the exhaust stream, determining the presence and quantities of these other substances are crucial, too. Finally, spent catalyst must be removed. In some cases (particularly for those containing metals), catalysts must be treated like a hazardous waste and this adds additional costs.

Another consideration in the design of a thermal or catalytic incinerator is the treatment of waste heat. The entire exhaust stream, potentially many cubic feet per minute is heated to an elevated temperature, and the hot exhaust moves through the combustion chamber and out toward the stack. This is a tremendous waste of heat. Most thermal units these days are designed to exchange the heat of the post-treated stream with the inlet exhaust to preheat it, representing a huge savings in fuel usage to heat the stream to the necessary temperature. A problem with incinerators is that the heated stream, while losing heat as it heads to the stack, passes a critical range of temperatures that is warmer than ambient, yet not hot enough to support destruction of compounds. When the exhaust stream moves through these areas, partially destroyed compounds have the right conditions to re-form larger compounds. Two groups of such compounds are called dioxins and furans. Each are very toxic to human health at low ambient concentrations. Measureable quantities of each have been found downwind of many incinerators, and research has shown this is how they develop. By enabling a rapid heat exchange, a unit not only saves fuel in heating the exhaust, but pushes the post-treated exhaust much quicker through the ideal temperature zone to form dioxins and furans, reducing their concentration.

One final factor to be considered in selecting and designing thermal or catalytic oxidation is the presence of compounds containing halogens (mainly chlorine and fluorine) in the exhaust stream, even if those compounds are not the subject of the emission reduction project. Gaseous compounds containing halogens are often derived from the degradation of plastics. In the combustion process, the compound breaks down, the halogen is freed and usually combines with a hydrogen to form HCl or HF, also known as hydrochloric acid and hydrofluoric acid. In this situation, the exhaust can become noticeably more acidic, potentially damaging your exhaust pipes and stacks and causing distress in the emissions profile. While your incinerator has properly

reduced its target compound, it has formed acid gases, which may have a greater adverse impact than the compounds you destroyed. Therefore, it is important to know before making a decision on APC equipment the content of halogens.

Adsorption

Adsorption occurs when a solid surface attracts and retains compounds with which they come into contact. Both solids and gases (the adsorbate) can be attracted to the solid's surface (adsorbent). Typically, adsorption is a physical process, the adsorbate is attracted by molecular forces onto the adsorbent solid, is adsorbed onto the surface without being converted chemically or dissolving in it.

Adsorption can effectively remove a contaminant from an exhaust based on the nature and degree of attraction between the solid surface and the gaseous component. Some adsorbents are more capable of attracting compounds than others; some adsorbates have a greater tendency to be adsorbed than other gases. Another critical factor in practical terms is the relative area that a solid can adsorb material relative to the flow rate of exhaust passing through; it must have a large surface area for a given mass. Without this, the adsorbent gets "filled up" fairly quickly and must be desorbed or replaced.

To control air pollutants the most common adsorbent is activated carbon, and, in fact, the technology is called carbon adsorption. Activated carbon has a large surface area and, more important, a porous structure and a large exposed surface to allow compounds access to the surface and find a free area to bind to. Activated carbon is commonly used in other systems to adsorb compounds, too, such as aquariums to adsorb liquid contaminants. For APC equipment, carbon adsorption is most commonly used to remove VOCs from an exhaust stream. As with catalytic incineration (above), particulate matter can bind, block, and disturb the activated carbon surface. Therefore, particulate matter should be pre-treated and removed from an exhaust stream before a carbon adsorption system treats the exhaust or not used at all. Note that carbon adsorption is not appropriate for all VOCs.

In order to select carbon adsorption as the APC for removal of a particular VOC, it is critical to first determine whether or not the subject VOC adsorbs significantly onto activated carbon. If the compound has low or no adsorbtivity, then carbon adsorption should be removed as a candidate for technical applicability reasons. Most manufacturers of activated carbon or carbon adsorption equipment has a list of common VOCs and their relative adsorbtivity. Although there are exceptions, most ringed VOC compounds, such as xylene, toluene, naphthalene, and benzene, adsorb well onto activated carbon, while chained and halogenated VOC, such as hexane, methane, acetone, methylene chloride, chloroethane, do not adsorb onto activated carbon well. The environmental engineer should not select carbon adsorption if compounds such as these need to be controlled.

Sizing the carbon adsorption unit is dependent on the long term inlet of compounds that

will adsorb onto the carbon. Many units operate some type of measurement device downstream to determine if pollutant is being captured or is breaking through, an indication that all of the effective sites on the activated carbon are taken by captured compound.

Therefore, typically a carbon adsorption system used to control an exhaust stream is composed of two units, one to treat the exhaust and a second system to simultaneously regenerate the unit full of captured compound; remove the adsorbate from the spent adsorbent. When the first unit fills up, then the exhaust can be switched to the regenerated unit, so no time is lost and the exhaust is continually treated. Heat, such as that contained in steam, can remove the VOCs from the physical bonds of the activated carbon. Many VOCs removed are not soluble in water; therefore, when the condensed steam is recovered, it would form a separate layer from the VOC. If the captured VOC is one particular compound, it can therefore be recovered in a fairly pure concentration, and potentially could even be reused if allowed.

One other consideration for a carbon adsorption system design is that adsorption is a slightly exothermic process. If the solvent-laden exhaust stream is fairly concentrated, there may be concerns about heat buildup and damage in the system.

In summary, carbon adsorption is an effective and relatively inexpensive means to control certain VOCs and other compounds from chemical plants, paint spray booths, wastewater treatment facilities, and gasoline terminals. The environmental engineer must fully understand the composition of the exhaust, as certain compounds adsorb poorly onto activated carbon, and particulate matter can damage such a unit. If the compounds in question do adsorb onto activated carbon, then the technology can work well to remove them from the exhaust and enable the environmental engineer to capture it in fairly pure form for disposal or even reuse. Carbon adsorption is effective for both high and low concentration streams; however, one must be careful for the former that breakthrough of contaminant does not occur or regeneration occur more frequently.

Absorption

Absorption is a different process from adsorption. While adsorption is the physical binding of the contaminant on to a solid surface, absorption involves the transfer of the compound from the gaseous stream to a liquid medium. Absorption is also referred to as scrubbing and the equipment used are called scrubbers because the process involves scrubbing out the compounds from the exhaust by the liquid scrubbant.

A key for the effectiveness of absorption is that the contaminant must be soluble in the scrubbant. Water is the most common scrubbant, and will be the focus of this discussion. Therefore, absorption cannot be used to remove VOCs from an exhaust stream that are insoluble or has low solubility in water. Common industrial VOCs, such as ethanol, methanol, butanol, and ketones, can be successfully removed from an exhaust stream by a scrubber. But scrubbing would be ineffective for most VOCs as

most are not water soluble. Common industrial VOCs that cannot be removed by absorption include toluene, benzene, methylene chloride, and ethylebenzene. Absorption can be effective in removing from an exhaust stream certain non-VOC gases, such as sulfur dioxide and hydrogen sulfide. Finally, scrubbing can be effective in removing particulate matter from an exhaust stream.

Once the environmental engineer has determined that the contaminants in question can be removed by a scrubber, efforts must be taken to design an effective unit. The consideration in a scrubber design is to optimize the contact between the gas and the water to allow the greatest degree of gas dissolving in the water. Scrubbers can operate to control over 99% of the contaminants entering the unit.

The main type of scrubber design used for this purpose is the packed tower. The dirty exhaust gas enters the tower at the bottom and exits the top. The clean water enters the unit on the top. This countercurrent motion enables maximum contact across the unit. The water is generally atomized to create small droplets, maximizing the quantity of surface area where the gas enters and dissolves into the water. Finally, the packed tower contains material to slow the movement and hold up both the gas and water to allow more opportunities for contact. The packing material is inert, and generally small in size, maximizing its surface area. Most packing material is made of plastic and may be in the shape of rings, saddles, and balls. Some scrubbers contain horizontal plates with strategically placed holes to allow gas and water to pass at limited locations.

One final design type of a scrubber is called a venturi scrubber. These scrubbers are vertical, like the ones discussed above. However, the unit narrows in the center of the unit, such that the gas and the water can only pass through a narrow "throat", raising the intimacy of their contact. Venturi scrubbers are used mainly for particulate control.
Scrubbers can be used to not only remove a gaseous contaminant from the exhaust stream, but also to change its chemistry. For example, an acidic stream can be treated with a scrubber containing water that is made basic to not only dissolve acid gases out of the exhaust stream, but also to neutralize it. Another example is at wastewater treatment plants where compounds that are odorous even at low concentrations, such as hydrogen sulfide and mercaptans, must be removed from gaseous streams. While a scrubber can succeed in removing these compounds, a small quantity can re-volatilize from the spent water to the air again, and be detected by its malodorous characteristics. Therefore, at many wastewater treatment plants, scrubbers of odorous exhaust streams use water with a dilute quantity of hypochlorite which will chemically oxidize these compounds from their reduced forms. Should some compound re-volatilize it will not be in its odorous form. Another form of this approach is using a solid, such as lime, or a lime-water mixture to neutralize sulfur dioxide or other acidic gases. These are normally referred to as "dry" scrubbers. Between a basic scrubbant and dry units, scrubbers are commonly used to control exhaust streams with acid gases, such as hydrogen chloride, sulfuric acid, sulfur dioxide, etc. In fact, scrubbers to control acid gases are often used to pre-treat an exhaust stream before it goes to an incinerator or a particulate control device.
How does one know whether a scrubber is operating properly? It could be prohibitively

expensive to continually measure the percent control or the outlet concentration of the contaminant in question. A scrubber performing well with the scrubbant being in intimate contact with the dirty gas takes energy to operate and ensure the gas and water flow through properly. This is commonly measured as a "pressure drop" across the plate or packing or venturi throat or wherever the contact occurs. Monitors on both sides will show a pressure drop across the area. If the pressure drop is low, then the hold up and contact is poor and the scrubbant is probably not contacting the gaseous flow optimally. Typically, a stack test under normal or high inlet conditions is performed and the pressure drop measured during tests of good emission reductions. Many air permits require the scrubber to maintain a certain range of pressure drops based on the pressure drops measured during the successful runs.

One of the disadvantages of absorption is that because the contaminant has merely be transferred from one state (gaseous) to another (liquid) treatment and disposal of the contaminated water must be planned. While scrubbant water in many cases can be reused and recycled, there is a point where it is so full of contaminants that at least a portion must be removed and treated and fresh water inserted. In some cases, the contaminated water may require pretreatment before discharge to the local municipal wastewater treatment plant, or transportation offsite to a treatment center. The facility may need to recalculate its total discharge offsite to ensure it still meets water discharge permit standards.

Condensation

Condensation is based on the principle of changing the phase of a gaseous contaminant to the liquid phase. Selective condensation of the desired compound can allow collection of liquid droplets in a pure form for handling or reuse. Condensation is most commonly achieved by decreasing the temperature of the stream it is in, although it can also be achieved by increasing the pressure of the system. Condensation is used mainly for removal of VOCs.

Condensers are fairly inexpensive equipment typically with a tube for the gas surrounded by shells containing flow of the cooling media. Depending on the temperature that needs to be reached, chilled water or refrigerant may be used. A condenser has an ideal exchange area to allow heat energy to be removed from the gaseous stream, allowing it to be cooled and the materials condensed.

Condensation is most effective when the subject compound is found in high concentrations in the exhaust stream. The lower the concentration in the inlet stream, the lower the temperature must be reduced to (with its concurrent energy penalty) to remove a significant quantity of compound. Condensers are sometimes used as a first step to remove VOCs before the stream is further treated by another or more expensive APC device, such as a carbon adsorber. For example, a condenser can remove some targeted high concentration compounds before the exhaust stream is introduced into a scrubber which could then focus (if water soluble) on other compounds of interest. This scenario is beneficial for condensers because relatively speaking its capital costs are

lower than most other APC equipment. And as mentioned above, collected compounds could be pure enough to reuse in the process or have other uses.

NO$_x$ Control

Nitrogen oxides, made up of NO and NO$_2$ (cumulatively called NO$_x$), derives from the oxidation of nitrogen in the fuel or air during high temperature combustion. NO$_x$ is a precursor for ozone, and thus is a target for many air quality regulations. Control of NO$_x$ emissions is a particularly difficult technical challenge as NO$_x$ is neither acidic, like SO$_2$, and can be controlled by an acid scrubber, nor is it significantly soluble in water, nor does it brake down at high temperatures.

Therefore, the first strategy to reduce NO$_x$ emissions is to introduce designs in your boilers and other combustion equipment that would minimize the formation of NO$_x$. There is now a whole generation of "Low NO$_x$ Burners" (LNB) that arrange combustion to minimize temperature spikes, such as staged combustion such that the period of highest temperature occurs with the least amount of fuel and/or combustion air present to minimize conversion of nitrogen in these medium into NO$_x$. LNB can cause a reduction of 40 to 70% of NO$_x$ formation, compared to conventional burners.

However, in many cases of combustion equipment, NO$_x$ must be controlled by an end-of-pipe device to meet permit or regulatory limits. The main control technology to achieve significant NOx reductions involves the chemical reduction of the NO and NO$_2$ compounds. Reduction of NO$_x$ can be achieved using ammonia (NH$_3$) or urea injected in the exhaust to chemically reduce NO$_x$ to molecular nitrogen (N$_2$) and water. Anhydrous ammonia is the most common compound used. Based on the NO$_x$ concentration in the exhaust, if the stoichiometric quantity of ammonia is injected and mixing is adequate, then significant NO$_x$ emissions control can be achieved. While it may seem natural to inject significant excess ammonia into the stream to ensure that the reduction reaction goes to completion (involves as much NO$_x$ as possible), too much injected ammonia will lead to ammonia emissions, also known as ammonia slip. Many systems operate a continuous monitor to measure the NO$_x$ in the exhaust stream and with it a feedback pump to adjust the injection rate of the ammonia accordingly. Many air permits for such reductive systems contain upper limits for ammonia slip. Another consideration in the design of such systems is the necessity for anhydrous ammonia storage tanks and safeguards in its usage. Ammonia used above a certain concentration and quantity may require a formal hazardous materials handling plan.

In many systems, the reduction reaction is aided by the presence of a catalyst downstream of the ammonia injection. Such a system is called Selective Catalytic Reduction (SCR). The catalyst allows the NO$_x$ and ammonia to intimately mix and to react in the catalyst bed. Therefore, besides requiring the right quantity of ammonia present for reaction, the environmental engineer must ensure that the catalyst does not become poisoned by other contaminants (i.e, particulate matter) and that the gas temperature is in the proper range for the reaction to occur, but not to damage the catalyst.

While SCR systems have achieved 70-90% reductions of NO_x emissions from coal-fired furnaces, SCRs have caused emissions of $PM_{2.5}$ and gaseous mercury as byproducts of its operations. Therefore, many regulatory agencies require a scrubber be operated downstream of the SCR system to remove these pollutants.

Selective non-catalytic reduction (SNCR) is another option to reduce NO_x emissions by injecting ammonia into the exhaust gas, usually at very high temperatures to make up for the lack of a catalyst that would encourage the reduction reaction. SNCR is most efficient within a temperature window of 1,600° to 2,000°F. For SCR, the temperature window is generally between 800° to 1,100°F. A problem with SNCR is that without the catalyst, heat is needed to drive the reaction. But at too high a temperature, the reaction may be driven toward oxidation which would form additional NO_x.

Fabric Filter

The final two common APC equipment described here pertain to control of particulate matter, and focus on fine particulates, $PM_{2.5}$. Links between $PM_{2.5}$ and a number of adverse public health conditions, such as lung disease and asthma, have been substantiated. Future air quality rules will likely focus on APC equipment focused on removal of $PM_{2.5}$.

A fabric filter, also known as a baghouse or a dust collector, is a filter that allows the exhaust gas through but retains the dust or particulate matter. In a simple sense, it is similar to a vacuum cleaner one has at home. It is a relatively simple and inexpensive APC device and can achieve PM control efficiencies of over 99% depending on the design and relative flow going through the system. It is effective for both high and low concentration dusty streams.

These days fabric filter bags are woven tight and made of a variety of materials, such as cotton, synthetics, or fiberglass. The bags have pores to allow gases through, but the pores are small enough to prevent particulates from going through. As particulates build up around the pores it makes it more difficult for later particulate matter to cross over. Effective control is common. However, at a certain point this "cake" of solids can be so thick that it can damage the bag(s) and/or make more difficult the flow of gases. This can be measured by either a decrease in pressure drop across the bag (there is a tear in the bag and the entire exhaust can flow through rendering the system ineffective) or a major increase in pressure drop from normal (gases are held up and are more hard pressed to flow across). Therefore, most fabric filter systems have automated systems to remove the dust cake when it builds up to a certain high pressure drop. Most systems use mechanical shakers to free the dust from the bags with a container on the bottom to catch it. Some use "reverse air". Operation of the bags is stopped and air is pumped in the reverse direction, freeing the dust from the bags. Either way, the environmental engineer must plan for either disposal of the solid dust (depending on the composition, such dust may represent a hazardous waste) or potential reuse if it is a fairly pure product or raw material lost during transfer.

As discussed, baghouses are relatively inexpensive, yet effective means of removing particulate matter from a dirty exhaust stream. Fabric filtration has several concerns. The first one is its relatively high maintenance, involving constant measurement of the pressure drop and the need to shut the system down and replace one or more bags with new ones once a tear is detected. Second is the knowledge of all of the components of the inlet exhaust stream. Exhausts with a large water content and/or with highly acidic or basic gases are problematic as each could damage and tear bags more frequently. Pre-treatment of the exhaust stream in this case is highly recommended. Finally, fabric filtration is not as effective for fine particulates ($PM_{2.5}$) compared to large size particulates. As discussed earlier, control of fine particulates is becoming a higher priority in current and future air quality regulations.

Electrostatic Precipitators

Electrostatic precipitators (ESPs) confer electric charges onto the dust in the exhaust and then remove them from the stream by a collection electrode. The dust particles receive a negative charge as they pass through the ionized field between electrodes. These charged particles are then attracted to a positively-charged electrode and adhere to it. The collected material is removed by vibrating the collecting electrodes usually at a predetermined interval. Unlike with fabric filters, collecting dust from an ESP can be performed without interrupting the control process. Finally ESPs can be assisted in their particulate control functions by the use of water. These are "Wet ESPs", as opposed to conventional or "Dry ESPs".

Like fabric filters, ESPs are effective APCs for particulate matter and relatively inexpensive and simple to operate. Also like fabric filters, ESPs are less effective for fine $PM_{2.5}$. Particulate matter is not controlled by an ESP if it is able to pass through the ionizing electrodes without being made ionic. $PM_{2.5}$ is both smaller and easier to evade ionization and travels at a higher velocity through the ionizing portion of an ESP compared to larger PM, explaining its drop in effectiveness.