

REDUCE VOC AND HAP EMISSIONS

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Follow this roadmap to understand the abatement technologies available for controlling emissions of volatile organic compounds and hazardous air pollutants and the criteria for choosing among them.

Over the past decade, tremendous scientific, political, social and economic changes have impacted air quality and environmental regulations, prompting a new look at the subject of controlling volatile organic compound (VOC) and hazardous air pollutant (HAP) emissions. Some of the significant changes that influence the selection of solutions for reducing emissions of VOCs and HAPs are:

- The implementation of the Maximum Achievable Control Technology (MACT) provisions of the Clean Air Act. Many of the facilities affected by MACT standards consider the reporting and control of HAP emissions to be the single largest driver toward VOC abatement.
- Increased public interest in the environment through web-based access to right-to-know reports. This continues to prompt many companies to find innovative ways to reduce pollution.
- The emergence of regional air-quality initiatives related to ozone transport and market-based incentive programs such as emission-reduction credit trading programs.
- Highly political or newsworthy issues in air quality management, such as the recent legal battle over EPA's ambient air-quality standard for ozone, the public dialogue over smog and urban sprawl, and the efforts to balance the regulation of stationary and mobile sources.
- The refocusing of environmental policy from a command-and-control format to a more collaborative,

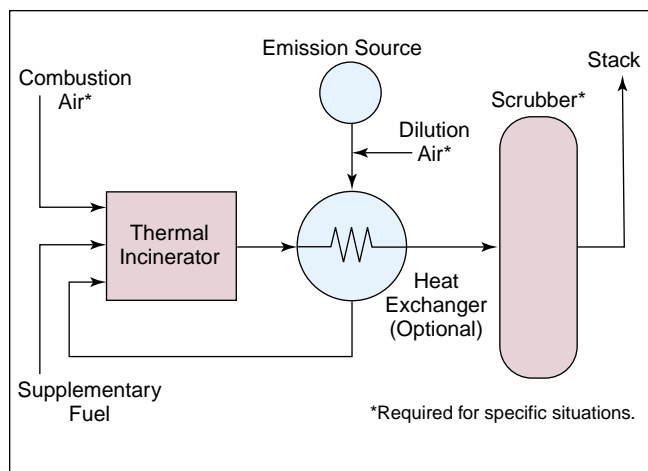
incentive-based approach that promotes pollution prevention over end-of-pipe control.

- The emergence of international agreements to enhance regional environmental cooperation, avoid potential environmental and trade disputes, promote effective enforcement of environmental laws, and explore transboundary air issues.

This article will help chemical engineers evaluate and select VOC and HAP control technologies. It is excerpted from the book "Practical Solutions for Reducing and Controlling Volatile Organic Compounds and Hazardous Air Pollutants" (1), published by AIChE's Center for Waste Reduction Technologies (CWRT). The book includes information that the Du Pont Co. developed based on technical and economic evaluations of VOC and HAP abatement technologies. The book also includes information from EPA's control-technology guidance documents. EPA's National Risk Management Laboratory, Sustainable Technology Division, provided funding for the book.

Thermal oxidation

Thermal oxidation, or thermal incineration, is the process of oxidizing combustible materials by raising their temperature above the autoignition point in the presence of oxygen and maintaining it at a high temperature for sufficient time to complete combustion to carbon dioxide and water. Time, temperature, turbulence (for mixing) and the amount of oxygen affect the rate and efficiency of the combustion process. These



■ Figure 1. A thermal oxidizer may incorporate recuperative or regenerative energy recovery.

factors provide the basic design parameters for VOC and HAP oxidation systems. For safety considerations, the maximum concentration of the VOCs/HAPs in the waste gas must be substantially below the lower explosive limit (LEL) of the specific compound(s) being controlled. As a rule, a safety factor of four (*i.e.*, 25% of the LEL) is used, although some direct-flame oxidizers are able to operate safely above this level. The waste gas may be diluted with ambient air, if necessary, to lower the concentration.

The heart of the thermal incinerator (Figure 1) is a nozzle-stabilized flame maintained by a combination of auxiliary fuel, waste gas compounds, and supplemental air as required. When the waste gas passes through the flame, it is heated from the preheated inlet temperature to the ignition temperature. The ignition temperature varies for different compounds and is usually determined empirically. It is the temperature at which the combustion reaction rate exceeds the rate of heat loss, thereby raising the temperature of the gases. Thus, any organic/air mixture will ignite if its temperature is raised high enough.

The required level of VOC/HAP control that must be achieved in the time that the waste gas spends in the thermal combustion chamber dictates the reactor temperature. The shorter the residence time, the higher the reactor temperature must be. Most thermal oxidizers are designed to provide no more than one second of residence time to the waste gas with typical temperatures of 650°C to 1,100°C (1,200–2,000°F). Once the unit is designed and built, the residence time is not easily changed. The required reaction temperature, therefore, becomes a function of the particular gaseous species and the desired level of control. To ensure 98% destruction of non-halogenated organics, thermal oxidizers generally should be run at 870°C (1,600°F) with a nominal residence time of 0.75 seconds. Destruction of halogenated organics may require an oxidation temperature

closer to 1,100°C (2,000°F) and, most likely, a post-oxidation water or caustic scrubber to remove highly corrosive acid gases (*e.g.*, HCl).

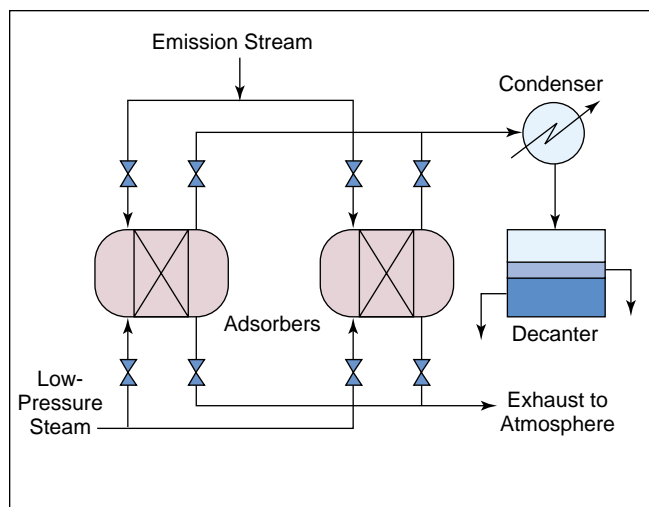
There are three types of thermal oxidation systems: direct flame, recuperative and regenerative. They are differentiated by the equipment used for heat recovery. A direct-flame thermal oxidizer, also known as an afterburner, consists of a combustion chamber and does not include any heat recovery. A recuperative oxidizer includes a waste-

Pollution Prevention

An alternative to the end-of-pipe pollution control techniques discussed here is pollution prevention. Pollution prevention initiatives may be categorized as recovery, product design changes, technology or process modifications, input or material changes, in-process recycling and reuse, and good operating practices (*e.g.*, waste segregation, preventive maintenance, training and awareness programs, and production scheduling).

More and more facilities are affirming the benefits of pollution prevention and volume reduction: reduced capital investment for end-of-pipe control, lower waste-disposal costs, and lower annual operating and maintenance costs. However, pollution prevention still faces some barriers to wider use by engineers, designers and planners. Corporate values about environmental protection influence the process through which abatement strategies are selected and the availability of capital for environmental projects. Also, companies may be unwilling to accept the risks of innovative strategies to prevent or abate pollution; these risks include unknown operating and maintenance costs, scale-up problems, unacceptable process changes and unknown long-term reliability. Finally, companies may be restricted in applying pollution prevention strategies as a result of traditional command-and-control regulations that impede technological innovation and traditional regulators who may be reluctant to approve these innovations.

Pollution prevention is the fundamental concept behind nearly all emerging trends in environmental rulemaking and regulatory compliance. International efforts to reduce VOC and HAP emissions advocate pollution prevention, energy efficiency, integrated environmental-management systems, and sustainable development. Since there is a direct link between a nation's prosperity and its level of environmental action, most countries with heavily urbanized areas are attempting to allocate resources for programs to reduce VOCs, HAPs and other smog precursors. In addition, socioeconomic conditions (*e.g.*, energy costs and geography) and cultural values may accelerate the transition to pollution prevention and energy efficiency.



■ Figure 3. In a dual-bed adsorption system, one bed is adsorbing VOCs/HAPs while the other bed is being regenerated.

“breakthrough”) and needs to be regenerated, the incoming VOC- or HAP-laden stream is routed to an alternate bed. Bed regeneration is typically done by heating or applying a vacuum to desorb the adsorbed gases; the bed is then cooled and dried, usually by blowing air through it with a fan, and the vapors are routed to a recovery system such as a condenser, decanter or distillation tower. The regenerated bed is returned to adsorber service, while the now-saturated other bed is purged of VOCs/HAPs. The regeneration process may be repeated numerous times; however, the adsorbent must eventually be replaced because of a gradual decrease in adsorptive capacity.

Common industrial adsorption systems often use activated carbon, zeolite and polymeric adsorbents. Activated carbon, which is neither fully hydrophobic nor hydrophilic, has an affinity for both polar and non-polar molecules. Because of this, humidity has a noticeable effect on activated carbon. Polymers and hydrophobic zeolite are generally much less sensitive to humidity, and much less susceptible to fire, crumbling or powdering. Therefore, they do not need to be replaced as often. However, activated carbon has a lower initial cost.

There are three methods of bed regeneration: thermal swing, vacuum, and pressure swing. The traditional carbon adsorber system uses steam to desorb VOCs/HAPs from the activated carbon surface; other heat sources have been tried successfully, including microwaves, embedded heaters and heated nitrogen. To enhance solvent recovery and eliminate contamination of the VOC/HAP by steam, vacuum regeneration may be used. In pressure swing adsorption, twin adsorber beds alternately adsorb and desorb VOCs/HAPs; the heat of adsorption is conserved and subsequently used to desorb the VOCs/HAPs from the bed.

For adsorption systems that are well designed and operated, continuous VOC and HAP removal efficiencies

greater than 95% can be achieved for a variety of solvents. Adsorption is applicable to continuous or intermittent streams and is capable of handling a range of concentrations. Adsorbents are useful for recovering high-value solvents, but are not recommended for certain situations. First, high VOC/HAP concentrations may result in excessive temperature rise in the bed due to the large heat of adsorption. If flammable vapors are present, insurance requirements may limit inlet concentrations of VOCs and HAPs to less than 25% of the LEL. However, vent streams with high VOC/HAP concentrations can be diluted with air or inert gases. Second, very-high-molecular-weight compounds ($MW \geq 130$) that are characterized by low volatility (boiling point $> 400^\circ\text{F}$ or 204°C) are strongly adsorbed on carbon, making it difficult to remove them during regeneration. Conversely, low-molecular-weight compounds ($MW < 45$) do not adsorb readily on carbon. Third, properly operated adsorption systems can be very effective when handling homogeneous waste gas streams, but are less so with a stream containing a mixture of low- and high-molecular-weight hydrocarbons. The lighter organic compounds tend to be displaced on the adsorbent surface by the heavier (higher boiling) components, greatly reducing system efficiency. Finally, gas stream humidity levels above 50% can affect working adsorber capacity at adsorbate concentrations below 1,000 ppmv. Relative humidity may be reduced by adding drier dilution air to the waste gas stream or by heating the gas with a heat exchanger.

Volume concentrators

Volume concentrators are designed specifically for the control of low-concentration VOC or HAP gas streams. These devices raise the concentration of VOC/HAP vapor to allow more economical treatment of the concentrated compound in the exhaust gas.

The most common volume concentrator is a rotary carousel system. In this unit, one sector of the carousel is being used for adsorption while another sector is being regenerated (or desorbed) with hot gas. As the carousel turns, each section alternately adsorbs VOC and HAP from the waste gas and is then regenerated. The adsorbent can be a zeolite, a mixture of zeolite and activated carbon, a mixture of zeolite and polymer adsorbents, or activated carbon or polymer adsorbent beds followed by zeolite beds downstream.

A concentration ratio of well above 1,000:1 can often be obtained in a volume concentrator. (Permissible concentration ratios may be limited by flammability considerations.) Of course, the flowrate of the regeneration gas is correspondingly lowered. This higher-concentration/lower-flowrate regeneration gas can then be treated in various ways, including thermal oxidation, catalytic oxidation or fixed-bed adsorption.

Fluidized-bed concentrators have also been developed. They are designed for concurrent adsorption and desorp-

VOC Control

tion in separate sections of the unit. VOC/HAP-laden gas enters one end and adsorbent enters the other end via a carrier gas. The VOC/HAP is stripped off the adsorbent using steam, hot nitrogen or hot ambient air.

Volume concentrators can achieve 90% to 98% removal efficiency, depending on the number of rotors in series and the inlet VOC/HAP concentration. Concentrators produce savings in the size and cost of downstream control equipment. When an existing end-of-pipe treatment system is operating at its volumetric capacity, a concentrator can be used to extend the capacity of the system by pre-concentrating the incoming waste gas stream. However, a volume concentrator coupled with another control device results in a more complex system, which may affect utility and maintenance requirements. Also, other approaches, such as source reduction, may be more economical for reducing the volume of waste gas.

Absorption

Absorption, or scrubbing, is often used to separate gaseous streams containing high concentrations of organics, especially water-soluble compounds such as methanol, ethanol, isopropanol, butanol, acetone and formaldehyde. It is widely used to abate VOC/HAP emissions during natural gas purification and coke byproduct recovery. However, it is more commonly used for controlling inorganic gases, such as HCl, than for VOCs/HAPs.

The use of absorption as the primary control technique for organic vapors is subject to several limiting factors. One factor is the availability of a suitable solvent. The VOC/HAP must be soluble in the absorbing liquid. Some common solvents that may be useful for VOCs/HAPs include water, mineral oils or other nonvolatile petroleum oils. Another factor is the availability of vapor/liquid equilibrium data for the specific organic/solvent system in question. Such data are necessary for the design of absorber systems; however, they are not readily available for uncommon organic compounds.

Another consideration in the use of absorption is the treatment or disposal of the material removed from the absorber. In most cases, the scrubbing liquid containing the VOC/HAP is regenerated by stripping, where the VOC/HAP is desorbed from the absorbent liquid, typically at elevated temperatures and/or under vacuum. The VOC/HAP is then recovered as a liquid in a condenser. The stripping process may create water disposal problems that may require a wastewater treatment system to handle the contaminants.

Condensation

Separation via condensation can be achieved by increasing the system pressure at a given temperature (compression condensation) or by lowering the temperature at a constant pressure (refrigerated condensation). Most commercial condensers are refrigerated condensers.

In a two-component system where one of the compo-

nents is non-condensable (*e.g.*, air), condensation occurs at the dew point (saturation) when the partial pressure of the volatile compound is equal to its vapor pressure. For more-volatile compounds (*i.e.*, compounds with lower boiling points), a larger amount of the compound remains as vapor at a given temperature; hence, to remove or recover the compound, a lower temperature would be required for saturation and condensation. In such cases, refrigeration can be used to obtain the lower temperatures needed to achieve acceptable removal efficiencies.

The basic equipment in a refrigerated condenser system includes a condenser, refrigeration unit(s) and auxiliary equipment (*e.g.*, precooler, recovery/storage tank, pump/blower and piping). For applications requiring low temperatures (below about -30°F or -34°C), multistage refrigeration systems are frequently used. Alternatively, cryogenic condensation using liquid nitrogen is emerging as a safe and effective control system.

Condensers are widely used as raw-material and/or product-recovery devices. They may be used to recover VOCs/HAPs upstream of other control devices, or they may be used alone for controlling vent streams containing high VOC/HAP concentrations. They can handle both intermittent and continuous flowrates. They are especially well-suited for low-flow (< 100 scfm), high-concentration ($> 2,500$ ppmv) vents from storage tanks, reactors and solvent unloading operations.

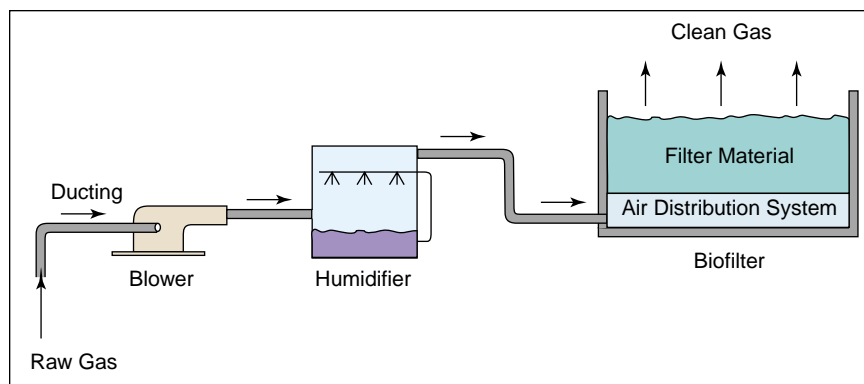
Condensers can be used to remove non-halogenated and halogenated VOCs/HAPs without the need for expensive auxiliary equipment. If the vent stream contains water vapor or if the VOC/HAP has a high freezing point (*e.g.*, benzene), ice or frozen hydrocarbons may form on the condenser tubes or plates. This will reduce the heat transfer efficiency and thus reduce the removal efficiency, as well as increase the pressure drop across the condenser. In such cases, a precooler may be used to remove the moisture before the vent stream enters the condenser.

Depending on the type of condenser used, disposal of the spent coolant can be a problem.

Flares

A flare system begins with a collection header and knock-out drum to remove water or condensed hydrocarbons. The knock-out drum is typically either a horizontal or vertical vessel located at or close to the base of the flare or a vertical unit inside the base of the flare stack. Liquids must be removed from the vent stream because they can extinguish the flame or cause irregular combustion and smoking; the flaring of liquids can also generate a spray of burning chemicals that could reach the ground and create a safety hazard.

Vent streams are also typically routed through a flame arrestor to prevent possible flame flashback, which occurs when the vent-stream flowrate to the flare is too low and the flame front drops down into the flare stack. Purge gases



■ Figure 4. Adequate moisture is critical to the proper functioning of a biofiltration system.

(*e.g.*, nitrogen, carbon dioxide or natural gas) also help to prevent flashback.

The vent stream enters the base of the flame, where it is heated by fuel and pilot burners at the flare tip. Pilot burners positioned around the outer perimeter of the flare tip ensure reliable ignition of the vent stream. The vent stream flows into the combustion zone, where it is oxidized.

Flares are generally categorized in two ways: by the height of the flare tip (*i.e.*, ground-level or elevated), and by the method of enhancing mixing at the flare tip (*i.e.*, steam-assisted, air-assisted, pressure-assisted or unassisted).

Flares can be used to control almost any VOC/HAP stream and can typically handle large fluctuations in VOC/HAP concentration, flowrate, heating value and inert species content. Flaring is appropriate for continuous, batch and variable-flow vent-stream applications, but flares are primarily used as safety devices. Most chemical plants and petroleum refineries have flare systems designed to relieve emergency process upsets that require the release of large volumes of gas. These large-diameter flares are designed to handle emergency releases but also can be used to control vent streams from various process operations. Gases flared from refineries, petroleum production and chemical plants are composed largely of low-molecular-weight VOCs/HAPs and have high heating value.

Flares have few controls, resulting in lower maintenance costs than other VOC/HAP control devices. On the other hand, they can produce undesirable noise, smoke, heat radiation and light. Furthermore, they cannot be used to treat waste streams containing halogenated compounds.

Biofiltration

The key component of a biofiltration system (Figure 4) is a biofilter, which consists of a bed made of natural materials (*e.g.*, compost, soil or bark) that is kept wet by sprayers that continuously supply water to maintain high humidity. An adequate moisture level is very important to the proper functioning and efficiency of a biofilter because the degradation processes are exothermic and tend to dry

the filter beds. Typically, the organic pollutants in the waste gas dissolve in water droplets and then are converted by microorganisms in the bio-layer. The type of microorganism used depends on the type of VOC/HAP. Most microorganisms require neutral pH conditions.

The natural materials used as the filter substrate supply the nutrients necessary to support the growth and survival of the microorganisms. Decomposition of cells also leads to the release of nutrients. The substrate particle size is selected to provide a large absorbing surface and minimum

flow resistance. Additives such as bark, polystyrene or activated carbon may be included to enhance performance and minimize pressure drop.

The most suitable type of biofilter for chemical plant emissions is a closed, fixed-bed design (similar to a carbon adsorber, where the organic media takes the place of the activated carbon). Water spray nozzles are used to supply moisture. Some designs include pre-humidification of the waste gas stream. Temperature and humidity can be more effectively controlled in this closed design than in an open system, and effluent monitoring is easier.

Compounds of low molecular weight that are water-soluble and contain oxygen atoms are good candidates for biofiltration. Aldehydes, ketones, alcohols, ethers, esters and organic acids degrade rapidly in biofilters, but halogenated hydrocarbons and polyaromatic hydrocarbons do not. Removal efficiencies greater than 90% have been demonstrated for easily degradable compounds.

Degradation of sulfur-, nitrogen- or halogen-containing compounds leads to formation of acids that lower the pH of the aqueous layer in biofilters. Alkaline compounds such as lime are added to the filter material to control pH; however, after a period of time there is an accumulation of salts that clog the bed. Bed lifetime is limited to two to five years. Occasional washing of the bed can extend its life in some cases.

Because of the uncertainties involved in the biological process, pilot testing is necessary for most potential applications. Pilot testing provides scale-up parameters required to obtain the desired overall removal efficiency and the filter-bed volume needed to achieve the desired level of VOC/HAP destruction.

Membrane technology

In a typical membrane separator, the waste gas stream is fed to an array of membrane modules, where organic solvents preferentially permeate the membrane. The organics in the permeate stream are then condensed and removed as a liquid for recycle or recovery. The purified gas stream is

Table 1. Typical pretreatment considerations.

VOC/HAP Abatement Technology	Typical Pretreatment Considerations
Thermal Oxidation	Dilution Preheating
Catalytic Oxidation	Dilution Particulate Removal Preheating
Adsorption, Volume Concentrators	Cooling Dehumidification Dilution Particulate Removal
Absorption	Cooling Particulate Removal
Condensation	Dehumidification
Flaring	Liquid Knock-out
Biofiltration	Humidification Cooling Particulate Removal
Membrane Separation	Particulate Removal

removed as the residue. Transport through the membrane is induced by maintaining the vapor pressure on the permeate (downstream) side of the membrane lower than the vapor pressure on the feed (upstream) side. In some cases, a vacuum pump is required on the permeate side to maintain this driving force.

A compound permeates the membrane at a rate determined by its permeability in the membrane material and partial-pressure driving force. In some systems, the feed stream is compressed on the feed side of the membrane to provide the pressure drop for the membrane and/or to allow operation of the solvent condenser at a higher temperature. Generally, the permeate is five to 20 times more concentrated in VOC/HAP than the feed stream.

Membrane modules can be of either hollow-fiber or spiral-wound construction. Membrane separation systems may have either one stage or multiple stages as necessary to achieve desired recovery efficiencies. Most membranes are made from synthetic polymers; however, some vendors are considering inorganic materials, such as ceramics, to deal with more rigorous applications. The membranes are thin, multilayer films made by coating a microporous support membrane with a very thin, dense film. The support membrane provides mechanical strength, while the thin film performs the separation. Thinner films promote higher permeation rates. These membranes are then

incorporated into modules that can withstand temperatures up to 60°C (140°F). Membrane life can be as long as three years.

Membrane separations should be considered for low-flow, high-concentration waste gas streams, where condensation or adsorption prove to be either uneconomical or unable to achieve the desired level of recovery efficiency.

Emerging technologies

Researchers and equipment manufacturers currently are evaluating two other VOC/HAP abatement technologies: ultraviolet oxidation (UV) technology and plasma technology. However, these technologies have encountered site-specific constraints (e.g., emission stream characteristics, regulatory concerns, economic considerations) that have limited their commercial availability.

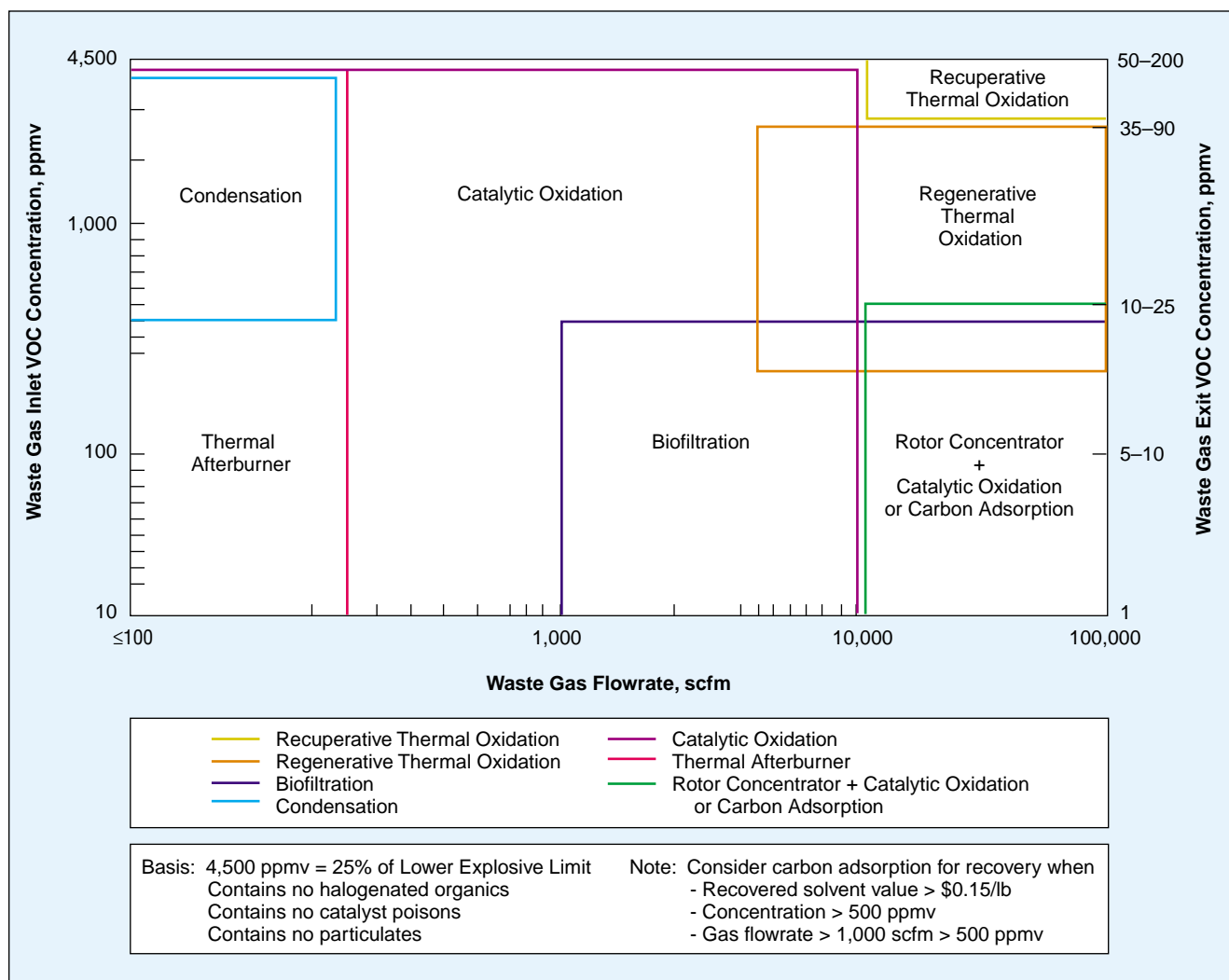
UV oxidation uses oxygen-based oxidants like ozone (O₃), peroxide (H₂O₂), hydroxyl free radicals (OH⁻), and O-radicals to convert VOC/HAP into carbon dioxide and water in the presence of UV light. The UV radiation excites the oxidants, which destroy the VOC/HAP through direct oxidation. In certain applications, a wet scrubber may be used to remove HCl and Cl₂ generated during the oxidation of chlorinated solvents. A carbon adsorber may be used to remove unreacted VOC/HAP from the oxidation process.

When the UV frequency range is chosen to match the absorption characteristics of the compound, maximum removal can be achieved. This process is highly energy-efficient for very dilute streams, and no pollutant byproducts are created. However, the use of a water scrubber could require wastewater treatment. UV oxidation has been applied commercially to surface coating operations with waste-gas flowrates between 20,000 and 90,000 scfm.

Table 2. Applicability of VOC/HAP abatement systems.

Abatement Technology	Waste Gas Flowrate (scfm)	VOC/HAP Concentration (ppmv)
Thermal Oxidation	< 10,000 (Thermal Afterburner) 250–100,000 (Recuperative) 2,000–500,000 (Regenerative)	60% of LEL (Thermal Afterburner)* 25% of LEL (Recuperative) 10% of LEL (Regenerative)
Catalytic Oxidation	< 75,000	25% of LEL
Adsorption	No practical limit	100–5,000
Volume Concentrators	> 10,000	< 100
Absorption	< 100,000	> 200
Condensation	< 3,000	> 1,000
Flare	No practical limit	No practical limit
Biofiltration	< 100,000	< 1,000
Membrane Separation	< 500	> 5,000

* Special safety considerations apply when the waste stream concentration is 25% of the lower explosive limit (LEL) or higher.



■ Figure 5. Use this selection map (which is based on lowest net present costs) to choose an appropriate VOC/HAP-abatement technology.

Plasma technology can be divided into corona discharge reactors and electron beam reactors. Plasma is a high-temperature ionized gas that is very reactive. The “hot” plasma can initiate dissociation reactions in VOC/HAP molecules. The decomposition reaction is initiated by free-radical mechanisms. Therefore, it is important to establish optimum conditions (e.g., electron density and residence time) to generate enough free radicals for the reactions to reach completion.

Plasma reactors can be highly selective for the decomposition of halogenated VOC/HAP, since halogen free radicals are highly reactive.

Comparison of abatement technologies

Which VOC/HAP control device is best for your needs? Fortunately, there are only a few main criteria for selecting an appropriate control device. One of those criteria may be a regulation that mandates a specific type of control equipment. However, most regulations impose a level of control (e.g., MACT or BACT) but do not prescribe a specific control device.

The main selection criteria for VOC/HAP abatement technologies are costs, VOC/HAP concentration, vent-gas flowrate and the required control level. In addition, pretreatment of the vent gas may be required for some control devices and could affect project costs.

Pretreatment considerations

Pretreatment refers to the methods and practices used to condition a VOC/HAP-laden stream prior to its entry into an abatement device. While pretreatment considerations rarely are barriers to equipment selection, they are crucial to a thorough evaluation of the environmental and economic impacts and the ultimate operational success of a particular technology.

Table 1 summarizes typical pretreatment considerations for common VOC/HAP abatement technologies. The necessity of pretreatment is often a function of emission stream characteristics; therefore, pretreatment considerations identified in the table are not relevant for all applications.

Table 3. Estimating investment costs for VOC/HAP abatement.

Cost Element	Basis
Engineered Equipment	Vendor estimate
Miscellaneous Engineered Equipment	0%–10% of Engineered Equipment
Equipment Installation	10%–40% of (Engineered Equipment + Miscellaneous Engineered Equipment)
Field-Erected Equipment	Vendor estimate
Equipment Foundations, Supports, Platforms	5%–15% of (Engineered Equipment + Miscellaneous Engineered Equipment + Equipment Installation + Field-erected Equipment)
Installed Equipment	Sum of first five cost elements
Process and Service Piping, Instrumentation, and Electrical	Usually based on a combination of historical values from previous projects and vendor estimates
Architectural and Civil Items (e.g., pipe supports, dikes, trenches, pilings, sanitary sewers, concrete pads)	Contractor estimate
Buildings and Structures (e.g., process buildings, silo supports, control rooms, offices, laboratories, maintenance shops)	5%–15% of (Installed Equipment + Piping/Instrumentation/Electrical)
Dismantlement and Rearrangement (e.g., existing equipment, buildings, piping, asbestos insulation)	0%–10% of (Installed Equipment + Piping/Instrumentation/Electrical + Architectural/Civil + Buildings/Structures)
Freight/Quality Assurance/Procurement	7% of Engineered Equipment
Sales Tax	Varies by state. Some states exempt pollution abatement equipment from sales taxes.
Construction Contractor (e.g., payroll, taxes, benefits, tools and equipment, rentals, overhead, profit)	20% of (Installed Equipment + Piping/Instrumentation/Electrical + Architectural/Civil + Buildings/Structures + Dismantlement/Rearrangement)
Other Identifiable Costs (e.g., fire protection, railcar/track loading spots, waste treatment allowances, substations, cooling towers, demineralized water, site preparation such as roads and walkways)	Project-specific
Direct Costs	Sum of all previous costs
Project Management	15%–22% of Direct Costs
Contracts Administration	2%–5% of Direct Costs
Contingencies	10%–30% of (Direct Costs + Project Management Costs + Contracts Administration)
Total Investment	Sum of all costs

Flowrate and concentration

Air flow and pollutant loading are the two most important design criteria for VOC/HAP control devices. Table 2 summarizes the full range of flowrates and VOC/HAP concentrations for the control devices.

Figure 5 is an applicability chart for the most popular control technologies. The figure shows the range of flowrate and concentration in which the devices operate most efficiently and cost-effectively. Many of the control devices are technically capable of operating outside the in-

dicated ranges, but operation outside these ranges may not be cost-effective.

Other key properties of control equipment design may also drive the selection of a control device for an application outside its indicated cost-effective range. These properties include the heat content, oxygen content, moisture content, halogen or metals content, temperature and pressure of the vent gas stream, and the molecular weight, vapor pressure, solubility and adsorptive properties of the specific VOC/HAP in the vent gas stream.

As shown in Figure 5, thermal and catalytic oxidizers can be used over a fairly wide range of organic vapor concentrations, provided adequate safety precautions are implemented for VOC/HAP loadings greater than 25% of the LEL. Thermal afterburners can be used for higher-fuel-value streams than other thermal oxidizer systems (up to 60% of the LEL in some cases). Regenerative and recuperative oxidizers perform best at medium to high concentrations, because the heat of combustion of organic gases is sufficient to sustain the temperatures required without the addition of expensive fuel. Catalytic oxidizers can and have been used effectively at low to high VOC/HAP concentrations and low to high flowrates. Thermal afterburners are best suited for low-flow applications, where heat recovery does not pay for itself. Waste streams that have steady and high flowrates over long periods of time can be treated economically with recuperative or regenerative oxidizers.

Adsorption systems operate best at concentrations ranging from 20 ppmv to 10,000 ppmv and flowrates from 1,000 scfm to 50,000 scfm. Concentrations above 10,000 ppmv may lead to

excessive bed temperatures. At higher flowrates, the pressure drop across the bed becomes too high for standard blowers, while at lower flowrates, the required bed volume is large and its cost becomes prohibitive.

Absorption is usually considered only when the VOC/HAP concentration is above 200 to 300 ppmv. Below these levels, the rate of mass transfer of the VOC/HAP to the solvent is low enough to make reasonable designs impractical. There are, however, no practical limits on the gas flowrate that an absorber can handle.

Condensers can process waste gas streams containing high VOC/HAP concentrations (usually above 1,000 ppmv) but relatively low flows (usually below 3,000 scfm). Flowrates above 3,000 scfm may require significantly larger heat-transfer areas.

Flares can be used to control almost any VOC/HAP stream and can handle fluctuations in VOC/HAP concentration, flowrate, heat content and inert gas content.

Biofilters are cost-competitive for flowrates above 1,000 scfm and VOC/HAP concentrations below approximately 300 to 500 ppmv.

Membrane separation systems are suitable for low-flow, high-concentration waste gas streams. As a rule of thumb, membranes are applicable for flowrates below 500 scfm and VOC/HAP concentrations above 5,000 ppmv.

Costs

There are three main economic measures for selecting a cost-effective VOC/HAP control device: net present value (NPV), total investment and total annual operating costs. The total investment in a specific control device includes the equipment costs, installation costs, site preparation and construction costs, and costs for land, working capital and offsite facilities. Total annual operating costs include direct costs (which are proportional to the quantity of exhaust gas processed by the control system), indirect costs (which are independent of the exhaust gas flowrate) and credits for recovered chemicals.

There are many models for estimating NPV, investment and annual operating costs for VOC/HAP abatement systems. They range from simple computer-based spreadsheet functions (e.g., Excel) to EPA cost programs (e.g., COST-AIR) to sophisticated financial-management software. The EPA's computer-based cost programs are publicly available on its website and are simple to use. However, publicly available cost models may underestimate costs because they are based on an average of multiple data sets. Facilities that install sophisticated process control equipment and safety equipment and that use more expensive materials of construction may encounter costs higher than those estimated by the EPA's and other publicly available cost models.

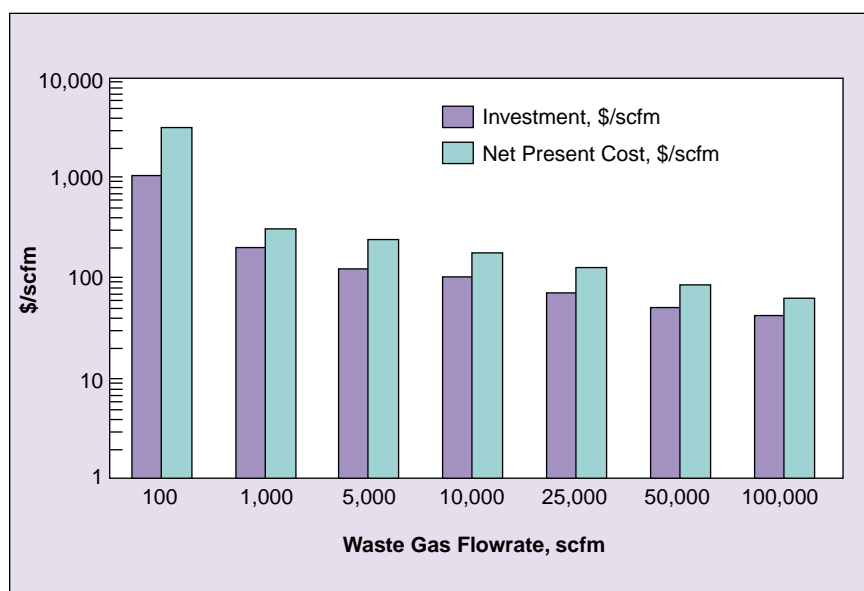
Table 3 presents a model for estimating the total investment costs for VOC/HAP control devices. It is based

Table 4. Annual operating cost factors.

Cost Element	Unit Cost Factor (U.S. Dollars)
Raw Materials	
Activated Carbon (5-yr life)	\$2.80/lb
Platinum Catalyst (5-yr life)	\$4,200/ft ³
Membrane Module (3-yr life)	\$450/m ²
Polymeric Adsorbent (5-yr life)	\$3.00/lb
Zeolite Honeycomb (5-yr life)	\$1,000/unit
Carbon Fiber Wheel (5-yr life)	\$1,000/unit
Compost Bed (3-yr life)	\$10/yd ³
Utilities	
Electricity	\$0.04/kWh
Natural Gas	\$2.50/MMBtu
Cooling Water	\$0.05/Mgal
Filtered Water	\$0.15/Mgal
Steam	\$3.50/Mlb
Nitrogen	\$0.045/lb
Other	
Wastewater Treatment	\$0.35/lb organic
Cost Factors	
Technical Support	\$160,000/yr
Operations Labor	\$430,000/yr for 3-shift coverage
Maintenance	4% of total investment/yr
Taxes and Insurance	0.75% of total investment/yr
General Plant Overhead — Investment-related	0.5% of total investment/yr
General Plant Overhead — Labor-related	24% of (Operating + Maintenance Labor)/yr
Project Liaison Costs (1 yr only)	2% of total investment
Start-up Costs (1 yr only)	10% of total investment
Creep Investment	1.5% of total investment/yr
Working Capital	60 days of cash costs
Cash-Flow Bases	
Depreciation (6-yr accelerated)	20%, 32%, 19%, 12%, 12%, 5%
Income Tax Rate	40%
Discount Rate for Net Present Cost	12%
Capital Recovery	10% borrowing costs, 10-yr life

Rules-of-Thumb for VOC and HAP Abatement

- The minimum capital investment into end-of-pipe equipment is \$40 per scfm.
- The minimum net present cost of end-of-pipe equipment is \$60 per scfm.
- The minimum incentive for volume reduction is \$30 per scfm.
- VOC concentration has little effect on the economics of end-of-pipe treatments for dilute streams.
- The cost to treat streams containing halogenated organics, particulates, or both will be at least double the cost for simple nonhalogenated streams.
- Reducing diluent flow at the source and standardization of equipment design will have the largest impact on minimizing investment in end-of-pipe abatement.



■ Figure 6. Overview of investment and net present costs for end-of-pipe treatment technologies.

models and cost factors from Tables 3 and 4. Figure 6 presents an overview of investment and net present costs for end-of-pipe treatment of VOC and HAP emissions (based on a 12% discount rate and a 10-yr equipment life). The costs shown in Figure 6 assume there are no halogenated organics and no particulates in the stream to be treated; the costs to treat streams containing these compounds would be double the costs in Figure 6.

It is important to note that the costs in Figure 6 do not include the “hidden costs” of installing and operating a VOC/HAP control device, such as permitting costs and compliance costs. Frequently, the installation of a VOC/HAP control device may be a “physical or operational” change that triggers state and/or federal air permitting rules. Preparation

of an air permit application may include a thorough evaluation of alternative control devices, applicable regulations and air dispersion impacts. Furthermore, compliance demonstrations (*e.g.*, stack testing, continuous or parametric monitoring, recordkeeping, reporting and work practices) may be required to ensure that the VOC/HAP control devices are operating correctly.

Reference 1 includes over 30 figures detailing the investment, annual and net present costs for each of the VOC/HAP control devices described in this article over a range of VOC/HAP concentrations and exhaust stream flowrates.

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Literature Cited

1. American Institute of Chemical Engineers, “Practical Solutions for Reducing and Controlling Volatile Organic Compounds and Hazardous Air Pollutants,” AIChE, Center for Waste Reduction Technologies, New York, NY (2001).

For Additional Details

This article is based on the book “Practical Solutions for Reducing Volatile Organic Compounds and Hazardous Air Pollutants,” published by the American Institute of Chemical Engineers’ Center for Waste Reduction Technologies (CWRT). The book includes additional information on VOCs and HAPs, current regulations, regulatory trends, pollution prevention, and modifying and designing plants for VOC/HAP abatement. To order the book (softcover, 150 pages, \$65.00, Publication C-14, ISBN 0-8169-0831-1), call 1-800-AIChemE (1-800-242-4363) or go to AIChE’s online publications catalog at www.aiche.org/pubcat. For information about AIChE’s Center for Waste Reduction Technologies, contact Jo Rogers, CWRT Director, at jorogers@aiiche.org or (212) 591-7727.

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