

**OBJECTIVES****Terminal Learning Objective**

At the end of this chapter, the student will be able to identify techniques for controlling gaseous contaminants.

**Enabling Learning Objectives**

- 2.1 Identify the gas stream characteristics that affect the selection and design of gaseous control systems.
- 2.2 Distinguish among the techniques used to control gaseous contaminants.

## *Control Techniques for Gaseous Contaminants*

This chapter provides an introduction to the types of control technologies that can be used to remove gaseous contaminants from industrial gas streams. The appropriateness of a given technology depends, in part, on the chemical and physical characteristics of the specific gas and vapor phase compounds present in the gas stream. Data concerning some of the chemical compounds are summarized in this chapter. References to data tabulations that report important properties of chemical compounds of potential interest are provided at the end of the chapter.

Several gas stream characteristics must be taken into account in the selection and design of a gaseous control system. These characteristics are introduced briefly in this chapter and are discussed in more detail in subsequent chapters concerning each major control technique.

### *2.1 Gas Stream Characteristics*

#### ***Important Gas Stream Properties***

The selection and design of a gaseous contaminant control system must be based on specific information concerning the gas stream to be treated. The following is a partial list of the gas stream parameters that are often useful:

- Flow rate
- Temperature
- Pressure
- Contaminant concentration
- Contaminant ignition characteristics
- Oxygen concentration

Information concerning the gas flow rate, temperature, and pressure are needed to physically size the collector for the expected process operating conditions. Many gaseous contaminant control systems have a relatively narrow range of operating conditions. In situations where these parameters vary with time, it is important to know, whenever available, the minimum, average, and maximum parameter values. In situations where the gas stream also contains particulate matter, it is important to know the concentration, particle size distribution, and composition of the particulate.

Particulate matter entrained in the gas stream with the gaseous contaminants can have a severe impact on the efficiency and reliability of the collector. Certain types of gaseous contaminant control systems use beds of collecting media (e.g., fixed adsorption beds and catalyst beds) or pre-collector heat exchangers. Particulate matter can accumulate in these systems and disrupt proper gas flow. The impact of particulate matter is especially severe if it is relatively large (> 3 micrometers) or sticky. If the gaseous contaminant control system is vulnerable to particulate matter-related problems, a pre-collector might be needed.

### ***Explosion Limits***

Information concerning the oxygen concentration and ignitability of the gases and vapors is needed to determine the allowable contaminant concentrations. A number of potentially explosive gases and vapors are collected in gaseous contaminant control systems, including:

- Organic compounds
- Carbon monoxide
- Ammonia
- Hydrogen (sometimes present with organic compounds)
- Hydrogen sulfide

One of the main factors that must be considered in designing a gaseous contaminant control system is the concentration range at which one or more of the contaminants can be ignited. Potentially explosive conditions must be anticipated and conscientiously avoided in the design of the control system.

The explosive range is bounded by two limits: the lower explosive limit (LEL) and the upper explosive limit (UEL). At contaminant concentrations below the LEL, there is insufficient contaminant (fuel) for an explosion. At contaminant concentrations above the UEL, there is insufficient oxygen for the oxidation of the compounds present. Theoretically, a gaseous control system could be designed for any contaminant concentrations below the LEL or above the UEL. However, almost all systems (with the exception of flares) are designed for concentrations below the LEL. Because of the uncertainties in the LEL values and the monitors used for real-time measurement, gaseous contaminant systems are usually designed for concentrations less than 25% of the LEL, providing some margin of protection from fires and explosions in the control system.

Example data concerning the LELs and UELs for specific contaminants are provided in Table 2-1. These data are usually expressed in terms of volume

percent. For example, the LEL for benzene is 1.2% by volume, which is equivalent to 12,000 ppm. If the gas stream concentration cannot exceed 25% of the LEL, the maximum benzene concentration should be 25% of 12,000 ppm, or 3000 ppm. The 25% LEL safety limit usually restricts the maximum contaminant concentration in the gas stream to be treated to less than 10,000 ppm.

Table 2-1. LEL and UEL at room temperature and ambient oxygen concentration. <sup>1</sup>		
Compound	Lower Explosive Limit, Percent by Volume*	Upper Explosive Limit, Percent by Volume*
Acetone	2.5	12.8
Acrylonitrile	3.0	17.0
Ammonia	15.0	28.0
Benzene	1.2	7.8
Carbon Disulfide	1.3	50.0
Ethyl Alcohol	3.3	19.0
Formaldehyde	7.0	73.0
Gasoline	1.4	7.6
Hydrogen	2.0	80.0
Methylene Chloride	13.0	23.0
Octane	1.0	6.5
Propane	2.1	9.5
Styrene	0.9	6.8
Toluene	1.1	7.1
Xylenes	0.9	7.0

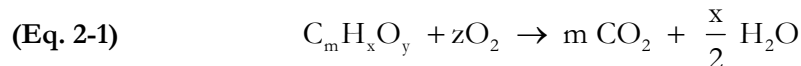
\*Note: to convert from percent by volume to ppm, multiply by 10,000 (2% by volume is equivalent to 20,000 ppm).

A gas stream having contaminants with a large explosive range requires extreme caution in control system design and operation. For example, hydrogen, which is used as a feedstock or is an intermediate reaction product, has an especially large explosive concentration range.

The LEL and UEL concentrations for specific compounds can be found in Material Data Safety Sheets (MSDS) or other reference books. However, these data and the values listed in Table 2-1 should *not* be taken as absolutely correct. Some of the data were measured at temperatures, pressures, and oxygen concentrations different from the specific application of current interest. Furthermore, the evaluation of references used in the LEL and UEL tables shows that some of the measurements were conducted from the 1920s through the 1950s, using analytical methods that have long since been abandoned. Unfortunately, there is no easy way to identify data based on out-of-date test methods other than by conducting an exhaustive reference review.

The caveats discussed above with respect to tabulated data also apply to the empirical equations used to estimate LEL and UEL concentrations. These equations only provide a useful approximation of LEL and UEL concentrations.

Equipment design based on a maximum of 25% of the LEL provides a safety factor to account for the uncertainties in the actual values. One of the estimation techniques is the Jones method, summarized in Equations 2-1 through 2-3.



(Eq. 2-2) 
$$LEL, \% = \frac{0.55(100)}{(4.76m + 1.19x + 1 - 2.38y)}$$

(Eq. 2-3) 
$$UEL, \% = \frac{3.50(100)}{(4.76m + 1.19x + 1 - 2.38y)}$$

Industrial processes often generate gas streams having more than one potentially ignitable gas or vapor contaminant. Therefore, it is necessary to estimate the LEL and UEL for the gas mixture. Because of the number of site-specific variables involved, one of the best approaches is to have a qualified laboratory measure the LEL and UEL for the exact range of conditions anticipated. If that is not possible, it is sometimes assumed that all of the contaminants have a LEL at a level equivalent to the lowest LEL value of any contaminant present, as is illustrated in Problem 2-1.

**Problem 2-1**

A gas stream contains acetone at 1000 ppm, benzene at 2000 ppm, and toluene at 500 ppm. Is this mixture at a level equivalent to 25% of the LEL for the overall gas stream?

**Solution:**

The following LEL limits are taken from Table 2-1.

Acetone, LEL = 25,000 ppm

Benzene, LEL = 12,000 ppm

Toluene, LEL = 11,000 ppm

The lowest LEL limit is 11,000 ppm (toluene).

25% of 11,000 ppm = 2750 ppm

The total contaminant concentration:

1000 ppm + 2000 ppm + 500 ppm = 3500 ppm

Answer: No. The total concentration exceeds the 25% LEL value.

An alternative, less conservative approach for determining the concentration limits for gas mixtures in air is provided by the Le Chatelier equations (2-4, 2-5).

These are simply weighted averages of the LELs and UELs of each of the combustible constituents in the gas stream.

$$\text{(Eq. 2-4)} \quad \text{LEL}_{\text{mixture, \%}} = \frac{1}{\sum \frac{y_i}{\text{LEL}_i}}$$

$$\text{(Eq. 2-5)} \quad \text{UEL}_{\text{mixture, \%}} = \frac{1}{\sum \frac{y_i}{\text{UEL}_i}}$$

Where:  $y_i$  = concentration of component  $i$  on a combustible-only basis

Problem 2-2 illustrates the use of the Le Chatelier approach and clarifies the definition of  $y_i$ .

**Problem 2-2**

Using the same gas stream mixture discussed in Problem 2-1, estimate the LEL for the gas mixture using Equation 2-4.

**Solution:**

The following LEL limits apply for the compounds, assuming that the LELs in Table 2-1 have been verified by reference review or independent laboratory study.

Acetone, LEL = 25,000 ppm

Benzene, LEL = 12,000 ppm

Toluene, LEL = 11,000 ppm

$$\text{LEL}_{\text{Mixture}} = \frac{1}{\left[ \left( \frac{\left( \frac{1000}{3500} \right)}{\left( \frac{25,000}{1,000,000} \right)} \right) + \left( \frac{\left( \frac{2000}{3500} \right)}{\left( \frac{12,000}{1,000,000} \right)} \right) + \left( \frac{\left( \frac{500}{3500} \right)}{\left( \frac{11,000}{1,000,000} \right)} \right) \right]}$$

The values of  $y_i$ , the numerator terms within the summation, represent the concentration of component  $i$  divided by the sum of the concentrations of all combustible components.

$$\text{LEL}_{\text{Mixture}} = \frac{1}{11.43 + 47.62 + 12.99} = 0.014$$

$$25\% \text{ of the LEL} = 0.25 (14,000) = 3500 \text{ ppm}$$

Using this approach, the gas mixture concentration is just equal to the 25% of LEL safety limit.

The removal of obvious sources of ignition from the system does not provide a satisfactory solution to the potential contaminant explosion problem. If portions of the gas stream are above the LEL, even on an intermittent basis, there is a significant risk of serious fires or explosions, because the energy requirement to ignite the gas mixture is extremely small. A number of subtle conditions can create sources of ignition in the system, including:

- Static electricity due to movement of the gas stream through the equipment
- Static electricity due to particle impaction with metal components in the ductwork
- Sparks due to metal-to-metal contact
- Hot surfaces
- Electrically powered instruments mounted in the gas stream

It is usually assumed that a gas stream in the explosive range will eventually ignite because of the difficulty in avoiding all sources of ignition on a long-term basis.

#### *Monitoring Contaminant Concentrations*

There are a variety of fixed and portable instruments available for directly measuring LEL levels in an existing gas stream. These instruments are particularly useful for the detection of short-term, intermittent conditions that increase the concentration of contaminants to levels approaching the LEL. If the concentration of contaminants exceeds the 25% LEL level, the control system and associated process equipment can be de-energized, and the problem can be corrected safely. The LEL readings can be in error when one or more of the following conditions exist:

- Oxygen levels are either lower or higher than the 21% level at which the instruments were calibrated.
- The presence of acid gases may have damaged the sensor.
- The gas stream pressure is either significantly higher or lower than atmospheric pressure.
- The gas stream contains combustible particles and/or fibers.

The oxygen levels are important because the instruments use combustion air in the sample stream to measure the concentration of LEL. When oxygen concentrations are low, the instrument is not able to detect increased contaminant concentrations. The measurement of LEL is also in error at oxygen levels above 21%, because oxygen-rich environments are inherently more ignitable.

The presence of corrosive gases and vapors in the gas stream can damage the sensor in the LEL meter and bias the measurement results. Common corrosive gases and vapors include sulfuric acid, hydrogen chloride, and hydrogen fluoride.

The performance of the LEL monitor at high and low absolute pressures should be checked with the instrument manufacturer. The response of the meter is subject to change due to the gas pressure in the sensing cell.

LEL monitors are not designed to measure the concentration and ignitability of particulate matter and fibers. Common ignitable particulate matter and fibers include but are not limited to the following:

- Coal dust
- Wood sander dust
- Flour and related grain dusts
- Metal dusts such as aluminum
- Carbonaceous dusts
- Organic fibers

The ignitability of these materials is strongly dependent on the particle size distribution, because small particles provide a high surface area for oxidation reactions.

## *2.2 Gaseous Contaminant Control Techniques*

Six major control technologies are used commercially for the capture and/or destruction of gaseous contaminants.

- Adsorption onto solid surfaces
- Absorption into liquids
- Biological oxidation
- Chemical oxidation
- Chemical reduction
- Condensation of vapors

This section provides a general introduction to the uses and limitations of these gaseous control technologies.

### ***Adsorption***

Adsorption involves transferring the contaminant from the gas to the surface of a solid adsorbent. The adsorbent can be in a wide variety of physical forms, such as pellets in a thick bed, small beads in a fluidized bed, or fibers pressed onto a flat surface. Adsorption only results in phase transfer—i.e., the chemical nature of the contaminant is not altered. In nonregenerative adsorption, the adsorbent containing the contaminant is normally disposed of by landfilling. In regenerative adsorption, the contaminant is subsequently desorbed so that the adsorbent may be used in multiple cycles. The desorbed contaminant, normally present in significantly higher concentration, may be recycled or further treated using a destruction process.

There are two types of adsorption mechanisms: physical and chemical. The basic difference is in how strongly the contaminant molecule is held to the adsorbent surface.

In physical adsorption, intermolecular cohesion weakly holds the contaminant molecule to the adsorbent surface. Physical adsorption may be reversed by the application of heat or by reducing the pressure surrounding the adsorbing material. In chemical adsorption, a chemical reaction occurs between the adsorbent and the contaminant, and this process is not easily reversed.

### ***General Applicability***

Physical adsorption systems are used extensively for the capture and recovery of organic solvents used in printing operations, surface coating operations, and a variety of chemical manufacturing applications.

One of the main factors determining the suitability of physical adsorption for the capture of an organic compound is how strongly the adhesive forces hold the molecule to the surface of the adsorbent. A very general and imperfect indicator of that adhesion force is the molecular weight of the compound. Most organic compounds with molecular weights between approximately 50 and 200 are collected with high efficiency. Methane, with a molecular weight of 16, has almost negligible adhesion to most adsorbents and therefore cannot be controlled by adsorption. Compounds with molecular weights greater than 200 can be collected with very high efficiency, but the adhesion forces are often too large to overcome in normal regeneration systems. In fact, the presence of the high-molecular-weight trace contaminants in gas streams containing other organic compounds otherwise suitable for adsorption is one of the major limits to the applicability of physical adsorption.

In addition to molecular weight, other parameters, such as boiling point and empirical adsorption correlation coefficients,<sup>2</sup> may be used to evaluate the applicability of physical adsorption to the problem of interest. Overall, physical adsorption is a viable technology for the control of a diverse range of organic compounds. The development of new types of adsorbents and improved properties of existing adsorbents is partly responsible for the increasing applicability of the physical adsorption systems.

Chemical adsorption may provide high-efficiency control of a variety of acid gases, including hydrogen sulfide, hydrogen chloride, and hydrogen fluoride. In

addition, there are now increasing applications for the control of vapor-phase mercury using chemical adsorption systems.

#### *Concentration Dependence*

The efficiency of both physical and chemical adsorption systems increases with high contaminant concentrations, due to the larger concentration driving force which causes transfer of the contaminant from the bulk gas to the surface of the adsorbent. Adsorption may also be used at low contaminant concentrations (e.g., 1 to 100 ppm levels), although larger quantities of adsorbent are needed to ensure efficient collection. Thus, adsorption control systems are applicable to concentrations ranging from trace levels associated with some odor sources to levels approaching 25% of the lower explosive limit (i.e., organic compounds and hydrogen sulfide). Some adsorption systems also operate on gasoline recovery systems at concentrations well above the UEL levels.

#### *Temperature Dependence*

Essentially all adsorption processes work best when the gas temperature is low and the adsorption capacity is high. In physical adsorption, the gas temperature is usually maintained at levels less than approximately 120°F. As new adsorbents are developed, the operating range will probably increase above this level. If the inlet gas temperatures are higher than 120°F on a continuous or short-term peak basis, pre-cooling is often needed. Chemical adsorption can be conducted at higher temperatures due to the increased strength of the chemical bond formed. Many chemical adsorption processes operate in the 100°F to 400°F range.

#### *Multiple Contaminant Limitations*

Physical adsorption systems used for the recovery and reuse of solvents are usually limited to gas streams with one to three organic compounds. The cost of separation of more than three compounds following regeneration is often prohibitive. Systems that are not designed for the recovery of solvents are not limited by the number of organic compounds in the contaminated gas stream, but the presence of trace quantities of high molecular weight compounds must be avoided.

#### *Particulate Matter Limitations*

Most physical adsorption systems are sensitive to particulate matter in the contaminated gas stream. Deposition of particulate matter in the adsorbent bed restricts access of the organics to a portion of adsorbent surface. Pretreatment is often required when particulate matter concentrations are high on either an intermittent or continuous basis.

#### *Absorption and Biofiltration*

Gaseous contaminants that are soluble in aqueous liquids can be removed by absorption, which involves the transfer of contaminant from the gas to a liquid phase. This is one of the main mechanisms used for the removal of acid gas compounds (e.g., sulfur dioxide, hydrogen chloride, and hydrogen fluoride) and water-soluble organic compounds (e.g., alcohols, aldehydes, and organic acids).

The contaminant is absorbed from the gas stream as it comes into contact with the liquid, and the rate of absorption increases as the efficiency of contact between the liquid and gas streams increases. Therefore, factors such as turbulent mixing between the two streams and large gas-liquid interfacial area promote absorption. Like adsorption processes, absorption may be operated in either a regenerable or once-through mode. When regeneration is used, the recovered contaminant may be recycled, may be landfilled when a solid product is formed, or may be destroyed by an oxidation process.

Once the contaminant enters the liquid phase, it can simply dissolve, or it can react irreversibly with other chemicals added to the liquid. The behavior distinguishes the two fundamentally different types of absorption processes. Simple dissolution systems, which are limited by the solubility of the contaminant in the liquid at the prevailing temperature of the liquid, are often used for the removal of soluble organic compounds.

Less soluble compounds, such as SO<sub>2</sub>, may be captured by absorption when a compound such as Ca(OH)<sub>2</sub>, with which SO<sub>2</sub> reacts irreversibly, is added to the liquid. Such systems are limited primarily by the amount of reactant available in the liquid phase to react with the contaminant as it diffuses into the liquid.

Biological treatment systems are termed either *biological oxidation* or *biofiltration* systems. Regardless of the term, the fundamental processes involved are the collection of contaminants on the surface of a media that contains viable microorganisms. The contaminant is metabolized by the organism and carbon dioxide and water vapor are produced. Accordingly, biofiltration can be classified as a special type of absorption system using irreversible processes to control the gaseous contaminant.

### *General Applicability*

The general applicability of simple dissolution-type absorbers is indicated by solubility relationships such as Henry's Law. This law states that the amount of contaminant that can be dissolved into a liquid is proportional to the concentration (or partial pressure) of the contaminant in the gas. Henry's Law is often valid for the low concentrations normally encountered in pollution situations, but cannot be used at high contaminant concentration. One of the most common forms of Henry's Law is given in Equation 2-6.

**(Eq. 2-6)** 
$$y^* = Hx$$

Where:

- $y^*$  = Mole fraction of contaminant in the gas phase in equilibrium with the liquid
- $H$  = Henry's Law constant, mole fraction contaminant in gas/mole fraction contaminant in liquid
- $x$  = Mole fraction of contaminant in the liquid phase

Equation 2-6 is the equation of a straight line that passes through the origin with a slope of  $H$ . If more than one contaminant is interacting with a liquid, Henry's Law is applied to each compound individually.

The general applicability of absorbers using irreversible chemical reactions is limited by the ability to capture and retain the contaminant in solution for a sufficient time to complete the necessary reactions. It is also important to maintain the proper concentrations of components in the liquid to ensure that these components do not exceed their solubility limits and precipitate in spray nozzles or other wetted portions of the absorption vessel.

The primary factor affecting the applicability of a biological oxidation system is the contaminants' compatibility with the microorganisms. Most organic compounds present at moderate-to-low concentrations can be controlled. However, there are a few organics that are toxic to the microorganisms and, therefore, cannot be effectively treated. In addition, some gas stream contaminants may affect the pH levels, thereby reducing the microorganism population.

The suitability of biological oxidation can be determined in consultation with the system suppliers. A reasonably complete summary of the contaminants present in the gas stream and their concentrations will be needed in order to evaluate the feasibility of this type of control system.

#### *Concentration Dependence*

Essentially all absorbers operate at their highest removal efficiency when the contaminant concentrations are high because this maximizes the driving force for mass transfer into the liquid phase. When the contaminant concentration is low (i.e., less than 100 ppm), the absorber must be designed with special attention to ensure highly effective gas-liquid contact to maximize mass transfer conditions. Biological systems are generally designed for moderate-to-low concentrations.

#### *Gas Temperature Dependence*

Absorption processes operate best when the gas and liquid temperatures are low because gas solubility increases with decreasing temperature. In most cases, the cooling provided by evaporating a portion of the absorption liquid sufficiently reduces gas temperature to levels appropriate for absorption. When the gas temperatures are very hot, a pre-cooler, such as a spray chamber or an evaporative cooling vessel, can be used upstream of the absorber.

Biological systems must operate at temperatures that are reasonable for the microorganism population, normally less than 110°F. If the inlet gas stream is higher, cooling with water sprays or a similar technique is needed to protect the microorganisms. An additional advantage of cooling water sprays is that the increased relative humidity of the gas stream reduces the likelihood that the biofiltration bed will dry out.

#### *Multiple Contaminant Removal*

Absorption processes are often effective for the removal of multiple contaminants, although a sophisticated separation process is required if each contaminant needs to be recovered individually. However, in many absorption processes, the collected contaminants are subsequently destroyed or otherwise discarded.

Many biological systems can handle a wide range of organic compounds present at low concentration. However, the removal efficiencies for each of these contaminants might vary slightly due to the differences in their capture in the support media and their metabolism by the microorganisms.

#### *Particulate Matter Limitations*

The vulnerability of an absorption process to particulate matter depends on the type of absorption equipment used for gas-liquid contact. Many absorption processes are well-suited for removal of particulate matter with aerodynamic diameters greater than approximately 3 micrometers. In many cases, this will not impair the removal efficiency for gaseous materials. However, the accumulation of particulate matter on packed beds or at the outlet of spray nozzles may have an adverse effect on gas-liquid contact. The presence of particulate matter in the liquid stream could also add to the wastewater treatment requirements. For these reasons, knowledge of the concentration and other characteristics of particulate matter in the contaminated gas stream is important. In some cases, it may be necessary to install a separate particulate control device upstream of the gas absorption process.

The microorganisms used in biological systems are maintained on media that form a bed. Particulate matter that impacts on the inlet of the bed can partially or completely block access to the microorganism and reduce the overall contaminant removal efficiency. For this reason, gas streams with high particulate matter concentrations often use a particulate matter pretreatment system.

#### *Oxidation*

Oxidization can be used to *destroy* a wide variety of organic contaminants. Oxidation processes may be divided into three main categories:

- Thermal oxidizers
- Catalytic oxidizers
- Flares

Thermal oxidizers and catalytic oxidizers are used for sources such as surface coaters, gasoline storage and distribution terminals, and organic chemical plants. Flares are used primarily to treat emergency vent gases in organic chemical plants and petroleum refineries. The majority of thermal and catalytic oxidizers operate with inlet contaminant concentrations less than 25% of the LEL. Flares can be used for sources that are well below the LEL or well above the UEL.

All chemical oxidation systems destroy organic compounds in the contaminated gas stream. Accordingly, they are used when economic recovery of the compounds is impractical.

#### *General Applicability*

Oxidization is applicable to essentially all organic compounds. The practicality of thermal oxidation depends on the contaminant's concentration and the operating temperature required for complete oxidation. In most thermal oxidizers, the

heating value of the contaminants provides a major fraction of the total energy input necessary for combustion. The required operating temperature is usually 200°F to 300°F above the auto-ignition temperature of the organic compound of concern. If more than one organic compound is present, thermal oxidizers operate at a temperature 200°F to 300°F above the auto-ignition temperature of the most difficult-to-oxidize compounds. Auto-ignition temperatures of many compounds may be found in standard chemistry and physics reference books. Most thermal oxidizers operate at temperatures ranging from 1200°F to more than 1800°F.

The suitability of catalytic oxidation is normally determined in consultation with catalyst suppliers and catalytic oxidizer manufacturers. The necessary operating temperature and the destruction capability for specific compounds will vary, depending on the type of catalyst used. The supplemental fuel requirements depend, in part, on the concentration of organic contaminants and the efficiency of the heat exchanger used ahead of the catalytic oxidizer. Catalytic oxidizers cannot be used on systems that have high concentrations of materials that will poison the catalyst or otherwise interfere with the gas's access to the catalyst's surface (often termed masking).

Flares are used as emergency controls for a wide variety of organic compounds. To improve destruction efficiencies in the short time periods available later at peak gas stream temperatures, flares often include steam injection to improve mixing and to accelerate oxidation reactions.

#### *Concentration Dependence*

Oxidation systems provide high-efficiency destruction of a wide variety of organic compounds, regardless of the inlet concentrations of the contaminants. The supplemental energy requirement(s) needed to maintain the necessary operating temperature decreases as the contaminant concentration increases.

#### *Gas Temperature Dependence*

The contaminated gas stream is almost always preheated prior to entering the oxidizer. For this reason, oxidation systems are effectively independent of the temperature of the contaminated gas stream.

#### *Multiple Contaminant Capability*

All oxidation systems are capable of treating contaminated gas streams containing a large number of compounds.

#### *Particulate Matter Limitations*

Thermal oxidation systems are generally capable of treating contaminated gas streams containing particulate matter. In fact, particulate matter containing organic species may also be destroyed. However, the particulate matter can deposit in the heat exchangers, which reduces the heat exchange efficiency and eventually plugs the system. Catalytic oxidation systems are much more sensitive to particulate matter. In addition to reducing the efficiency and potentially plugging heat exchangers, particulate matter can also accumulate in catalyst beds and destroy the catalyst activity. Accumulated particulate material in heat exchangers and in catalyst beds must be removed on a routine basis to provide

the necessary gas flow rates and to reduce the vulnerability of the system to bed fires caused by the ignition of these materials.

### ***Reduction Systems***

Chemical reduction is used primarily for the destruction of NO<sub>x</sub> compounds emitted from combustion processes. These systems include selective noncatalytic reduction (SNCR) and selective catalytic reduction (SCR). The chemistry is effectively the same in both systems. A chemically reduced form of nitrogen, ammonia or urea, is injected into the gas stream to react with the oxidized nitrogen compounds, NO and NO<sub>2</sub>. These reactions result in the formation of molecular N<sub>2</sub>, the major constituent of clean air.

Ammonia (NH<sub>3</sub>) can be used in either the anhydrous (compressed gas) or aqueous form. Urea [CO(NH<sub>2</sub>)<sub>2</sub>] is available in liquid form. Either of these compounds is fed to the combustion system to mix with the combustion gases at the temperature range required for the reactions to occur. SCR processes normally operate at temperatures in the range of 550°F to 750°F, while a higher temperature range of 1600°F to 2000°F is required for SNCR. In the case of ammonia systems, dilution is also needed for ammonia-air mixtures to remain below the LEL.

### ***General Applicability***

For SNCR, injection must occur at a position where the combustion gases are in the temperature range required for the reduction reactions to occur, generally between 1600°F and 2000°F (870°C to 1100°C). Sufficient space must be available at this position to install the ammonia or urea injection nozzles. This space is not always available on existing boilers and gas turbines installed long before SNCR became commercially available. Injection of ammonia or urea into a portion of the gas stream that is too cold will result in an incomplete reaction and the emission of ammonia or urea (often termed *slip*). Injection into a portion of the gas stream that is too hot will result in oxidation of the ammonia or urea to form additional NO<sub>x</sub>. Due to the gas temperature range limitations, SNCR systems usually have NO<sub>x</sub> destruction efficiencies in the range of 20% to 60%.

The same chemistry is used in SCR systems, but the presence of the catalyst allows the reactions to occur at significantly lower temperatures, generally 550°F to 750°F. Sufficient space must be available for the moderately large reaction vessel in the area of the boiler where the combustion gases are in the desired temperature range. The unintentional conversion of sulfur dioxide to sulfuric acid and the formation of very sticky ammonium bisulfate and ammonium sulfate deposits in downstream boiler equipment can result in boilers using high sulfur fuels. High particulate matter levels can also create problems in gas flow through the catalyst bed or can mask the catalyst surfaces. Trace components may also tend to poison the catalyst. When properly operated, SCR systems are capable of achieving NO<sub>x</sub> reduction efficiencies ranging from 60% to more than 90%.

### *Concentration Dependence*

SNCR and SCR systems achieve the high reduction efficiencies when the inlet NO<sub>x</sub> levels range from a low of about 100 ppm to a high of 1000 ppm.

### *Gas Temperature Dependence*

For effective reduction, both SNCR and SCR systems must operate in a relatively narrow temperature range as specified above. Furthermore, the spatial distribution of the gas temperatures at the points of reagent injection must be relatively uniform.

### *Multiple Contaminant Capability*

SNCR and SCR systems are effective for the reduction of both NO, which comprises 90% to 95% of the NO<sub>x</sub>, and NO<sub>2</sub>.

### *Particulate Matter Limitations*

SNCR systems are not sensitive to particulate matter concentrations, except in extreme circumstances when solid deposition on the injection nozzles may disrupt proper reagent spray patterns.

In contrast, accumulated particulate matter on the catalyst bed in SCR systems can cause flow alterations and catalyst surface masking.

### *Condensation Systems*

Condensation systems are used exclusively for the recovery of organic compounds present at moderate-to-high concentrations in industrial process effluent gas streams. There are three main categories of condensation systems based on the general operating temperature range:

- Water-based direct and indirect condensers (40°F to 80°F)
- Refrigeration condensers (-50°F to -150°F)
- Cryogenic condensers (-100°F to -320°F)

The most common condensers are those using cooling water in direct contact or indirect contact vessels. Refrigeration and cryogenic systems are used primarily for high-efficiency recovery of high-value contaminants.

### *General Applicability*

The applicability of condensation systems is determined by the concentration and vapor pressure of the contaminant or contaminants being controlled. Condensation systems reduce the gas stream contaminant's partial pressure to a value equivalent to the vapor pressure of the compound at the condenser's operating temperature. Procedures for estimating the vapor pressure are discussed later in this course.

### *Concentration Dependence*

Condensation systems are used primarily for the control of high concentrations of high-value organic contaminants.

*Gas Temperature Dependence*

Condenser systems operate at low temperatures to take advantage of the decrease in vapor pressure with decreasing temperature.

*Multiple Contaminant Capability*

Condensers can be used for the simultaneous removal of multiple organic compounds present in the gas stream. However, the cost of separation and recovery of individual components from the condensed mixture can be high. Consequently, most condenser systems are used when the gas stream contains only a single contaminant or a mixture of compounds that does not require separation (i.e., gasoline).

*Particulate Matter Limitations*

Condensers operate by transferring heat from the gas stream being treated to the cooling media used in the system. Since the accumulation of particulate matter on heat transfer surfaces can reduce the effectiveness of the system, it is sometimes necessary to remove particulate matter prior to the condenser.

*Summary of Control Techniques*

Table 2-2 summarizes the general properties and characteristics of the main control technologies used for the control of gaseous contaminants. Essentially all of the control techniques exhibit maximum control efficiency when the inlet concentration is high. All of the technologies are also sensitive to the gas stream temperature. Absorption, adsorption, biological treatment, and condensation work best at low temperatures, while oxidation and reduction systems operate in narrowly limited high-temperature ranges.

Table 2-2. Summary of the general applicability of gaseous contaminant control techniques.					
Control Technique	General Applicability	Typical Concentration Range	Typical Gas Temperature Range	Applicable for Control of Multiple Contaminants?	Applicable for Control of Gas Streams with Particulate Matter?
<b>Absorption</b>	Acid Gases and Organic Compounds	<1 ppm to >100,000 ppm <sup>l</sup>	<150°F <sup>b</sup>	Yes <sup>g</sup>	Yes
<b>Adsorption</b>	Acid Gases and Organic Compounds	<1 ppm to 25% of LEL <sup>l</sup>	<130°F <sup>b</sup>	Yes <sup>g,h</sup>	Pretreatment Often Required
<b>Biological Treatment</b>	Organic Compounds	<1 ppm to ~1000 ppm	<110°F <sup>c</sup>	Yes	Pretreatment Often Required
<b>Oxidation</b>	Organic Compounds	<1 ppm to 25% of LEL <sup>a</sup>	600°F to 2000°F <sup>d</sup>	Yes	Pretreatment Often Required
<b>Reduction</b>	NO and NO <sub>2</sub>	<100 ppm to 1000 ppm <sup>a</sup>	550°F to 2000°F <sup>e</sup>	Yes <sup>i</sup>	Yes
<b>Condensation</b>	Organic Compounds	> 100 ppm <sup>a</sup>	-320°F to 80°F <sup>f</sup>	Yes <sup>g,h</sup>	Pretreatment Often Required

Notes:

- a. Maximum removal efficiency usually occurs at maximum contaminant inlet concentration.
- b. Gas stream precooling is needed in some applications to reduce operating temperatures.
- c. Gas stream precooling and humidification is needed in some applications to reduce operating temperatures and to increase gas stream humidity.
- d. Catalytic systems operate in the 500°F to 1000°F range. Thermal oxidizers and flares operate in the 1200°F to 2000°F range.
- e. SCR systems operate in the 550°F to 750°F range. SNCR systems operate in the 1600°F to 1900°F range.
- f. Cryogenic systems operate in the -100°F to -320°F range. Refrigeration systems operate in the -50°F to -150°F range. Water condensers operate in the 40°F to 80°F range.
- g. Multiple compound separation and recovery can be difficult in some applications.
- h. Generally used for systems having one to three organic compounds in the gas stream.
- i. Used for control of nitric oxide (NO) and nitrogen dioxide (NO<sub>2</sub>).

While these data provide a general indication of the most common operating characteristics, specific systems can be designed to operate at high efficiency outside the ranges described in Table 2-2.

Although APTI 415 is limited to the six major control techniques summarized in this section, it is important to note that a number of additional techniques in commercial service and under development can also be used in specific cases.

## Review Exercises

1. What is the typical concentration limit for ignitable organic compounds in the inlet gas stream to an air pollution control system?
  - a. 10% of the LEL
  - b. 25% of the LEL
  - c. 50% of the LEL
  - d. 100% of the LEL
  
2. What factors influence the actual site-specific LEL value?
  - a. Composition of the gas mixture
  - b. Oxygen concentration
  - c. Gas temperature
  - d. All of the above
  
3. What type of adsorption mechanism is used in regenerative systems for organic compound removal?
  - a. Physical adsorption
  - b. Chemisorption
  - c. Both of the above
  - d. Neither of the above
  
4. Physical adsorption is more effective when the gas temperature is \_\_\_\_\_.
  - a. High
  - b. Low
  - c. Independent of gas temperature
  - d. Near 200 °F
  
5. The capacity of an adsorbent for a gaseous contaminant (grams per 100 grams of adsorbent) increases with \_\_\_\_\_. Select all that apply.
  - a. Reduced gas temperature
  - b. Decreased contaminant concentration
  - c. Decreased gas pressure
  - d. The presence of multiple contaminants

6. In simple dissolution, the mass transfer of a gaseous contaminant to the liquid stream is limited by \_\_\_\_\_. Select all that apply.
- a. Solubility equilibrium
  - b. Availability of reactive alkali
  - c. The degree of gas-liquid contact
  - d. The gas and liquid stream temperatures
7. Thermal oxidizers usually operate at gas temperatures that are \_\_\_\_\_.
- a. Above the auto-ignition temperature of the most difficult-to-oxidize major constituent
  - b. 200°F to 300°F above the auto-ignition temperature of the most difficult to oxidize major constituent
  - c. 400°F to 500°F above the auto-ignition temperature of the most difficult to oxidize major constituent
  - d. Between 550°F and 800°F
8. A catalytic oxidizer used for organic compounds usually operates with a catalyst bed inlet temperature that is \_\_\_\_\_.
- a. Above the auto-ignition temperature of the most difficult-to-oxidize major constituent
  - b. 200°F to 300°F above the auto-ignition temperature of the most difficult-to-oxidize major constituent
  - c. 400°F to 500°F above the auto-ignition temperature of the most difficult-to-oxidize major constituent
  - d. Between 400°F and 800°F

## Review Answers

1. What is the typical concentration limit for ignitable organic compounds in the inlet gas stream to an air pollution control system?
  - b. 25% of the LEL
2. What factors influence the actual site-specific LEL value?
  - d. All of the above
3. What type of adsorption mechanism is used in regenerative systems for organic compound removal?
  - a. Physical adsorption
4. Physical adsorption is more effective when the gas temperature is \_\_\_\_\_.
  - b. Low
5. The capacity of an adsorbent for a gaseous contaminant (grams per 100 grams of adsorbent) increases with \_\_\_\_\_. Select all that apply.
  - a. Reduced gas temperature
6. In simple dissolution, the mass transfer of a gaseous contaminant to the liquid stream is limited by \_\_\_\_\_. Select all that apply.
  - a. Solubility equilibrium
7. Thermal oxidizers usually operate at gas temperatures that are \_\_\_\_\_.
  - b. 200°F to 300°F above the auto-ignition temperature of the most difficult-to-oxidize major constituent
8. A catalytic oxidizer used for organic compounds usually operates with a catalyst bed inlet temperature that is \_\_\_\_\_.
  - d. Between 400°F and 800°F

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