Two different approaches:

- Pollution Prevention at the source – the better alternative
- Treatment of fumes as they are formed – the classical approach

Table 7.C.2 Treatment Technologies for Gaseous Air Pollutants

<table>
<thead>
<tr>
<th>Technology</th>
<th>Pollutants</th>
<th>Description and comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adsorption</td>
<td>H₂SO₄, HCl, VOCs</td>
<td>A spray scrubber or packed column maintains high gas-liquid contact area; especially effective for water-soluble species that can be converted to nonhazardous form in water</td>
</tr>
<tr>
<td>Adsorption</td>
<td>VOCs</td>
<td>Contact is promoted between gas and granular sorbent material, such as activated carbon, so that pollutant molecules adhere to surfaces; offers the method of choice for controlling nonpolar organics; can be effective when low trace levels of contamination (ppb–ppm) must be achieved; effective in processing large air volumes with dilute contaminants</td>
</tr>
<tr>
<td>Incineration</td>
<td>VOCs</td>
<td>Waste gases are burned to convert H₂ to H₂O, C to CO₂; commonly applied for low to medium levels of contamination with pure hydrocarbons or oxygenated organics</td>
</tr>
<tr>
<td>Catalytic redox</td>
<td>NOₓ, CO, VOCs</td>
<td>Solid catalyst is used to increase rate of reaction and convert elements to less hazardous forms; common application is the three-way catalyst used in motor vehicles</td>
</tr>
<tr>
<td>Condensation</td>
<td>VOCs</td>
<td>Phase change from gas to liquid is caused either by cooling or by increasing pressure; requires high gas-phase concentration of species with significant recovery value and high boiling point; cannot achieve very low gas-phase concentrations, so sometimes used as pretreatment technique</td>
</tr>
<tr>
<td>Membrane recovery</td>
<td>VOCs</td>
<td>Organic vapors are separated from air by flowing gas past membranes that are more permeable to organics than to air; advanced, newly emerging technology</td>
</tr>
</tbody>
</table>

Illustrative examples rather than an exhaustive list. (Nazaroff & Alvarez-Cohen, Table 7.C.2, page 444)
Example of steps taken to minimize air pollution from gasoline internal combustion engines.
A three-way catalytic converter performs three simultaneous tasks:

1. Oxidation of carbon monoxide (CO) to carbon dioxide
   \[ 2 \text{CO} + \text{O}_2 \rightarrow 2 \text{CO}_2 \]

2. Oxidation of unburned hydrocarbons (HC) to carbon dioxide and water
   \[ C_xH_y + [(2x+y)/2]O_2 \rightarrow x \text{CO}_2 + y \text{H}_2\text{O} \]

3. Reduction of nitrogen oxides to nitrogen and oxygen
   \[ 2\text{NO}_x \rightarrow \text{N}_2 + x \text{O}_2 \]

In other words: Choose your pollutant!

Techniques to remove particles from an air stream

<table>
<thead>
<tr>
<th>Device</th>
<th>Particle size</th>
<th>Collection mechanism and application</th>
</tr>
</thead>
<tbody>
<tr>
<td>Settling chamber</td>
<td>&gt; 20 ( \mu )m</td>
<td>Separates particles from a gas stream by gravity; used to treat very dirty air streams that contain very coarse particles</td>
</tr>
<tr>
<td>Cyclone</td>
<td>&gt; 1 ( \mu )m</td>
<td>Separates particles by inertia in a vortex flow; common pretreatment process ahead of electrostatic precipitator or fabric filter</td>
</tr>
<tr>
<td>Scrubber</td>
<td>&gt; 1 ( \mu )m</td>
<td>Wet collector; induces collisions between particles and water droplets to remove particles from gas stream by inertia; may be used for combined collection of particles and water-soluble gases</td>
</tr>
<tr>
<td>Electrostatic precipitator</td>
<td>All</td>
<td>Creates electrostatic charge on particles so they can be removed by an electric field; high-efficiency device that is used to treat stack gases in industrial processes</td>
</tr>
<tr>
<td>Filter</td>
<td>All</td>
<td>Air flow is forced through matrix of fibers, capturing particles by a combination of Brownian motion, physical straining, interception, and impaction; high efficiency possible; applied for treating waste gases and for removing particles from air before use</td>
</tr>
</tbody>
</table>

(Nazaroff & Alvarez-Cohen, Table 7.C.1, page 443)
Cyclone separators have been used in the United States for about 100 years, and are still one of the most widely used of all industrial gas-cleaning devices. The main reasons for the wide-spread use of cyclones are that they are inexpensive to purchase, they have no moving parts, and they can be constructed to withstand harsh operating conditions.

Cyclone Design

Typically, a particulate-laden gas enters tangentially near the top of the cyclone, as shown schematically in the left figure. The gas flow is forced into a downward spiral simply because of the cyclone’s shape and the tangential entry.

Another type of cyclone (a vane-axial cyclone — see right figure) employs an axial inlet with fixed turning vanes to achieve a spiraling flow.

Centrifugal force and inertia cause the particles to move outward, collide with the outer wall, and then slide downward to the bottom of the device. Near the bottom of the cyclone, the gas reverses its downward spiral and moves upward in a smaller inner spiral. The cleaned gas exits from the top through a "vortex-finder" tube, and the particles exit from the bottom of the cyclone through a pipe sealed by a spring-loaded flapper valve or rotary valve.
Advantages of cyclones:

- Low capital cost (few parts, easy to assemble)
- Ability to operate at high temperatures (all metal parts)
- Low maintenance requirements (no moving parts).

Disadvantages of cyclones:

- Low collection efficiencies (especially for very small particles)
  → cyclones used almost exclusively for particles > 5 \( \mu \)m.
- High operating costs (power required to overcome large pressure drop).

Cyclones by themselves are generally not adequate to meet stringent air pollution regulations, but they serve an important purpose. Their low capital cost and their maintenance-free operation make them ideal for use as pre-cleaners for more expensive final control devices such as baghouses or electrostatic precipitators. In addition to use for pollution control, cyclones are used extensively in process industries. For example, they are used for recovering and recycling certain catalysts in petroleum refineries, for recovering freeze-dried coffee in food processing plants, and for capturing saw dust in a lumber shop.

Cyclones have often been regarded as low-efficiency collectors. However, efficiency varies greatly with particle size and cyclone design. Advanced design work has greatly improved cyclone performance. Some cyclone manufacturers advertise cyclones that have efficiencies greater than 98% for particles larger than 5 microns, and others that routinely achieve efficiencies of 90% for particles larger than 15 – 20 microns.

In general, operating costs increase with efficiency (higher efficiency requires higher inflow pressure), and three categories of cyclones are available: high efficiency, conventional, and high throughput.

Typical efficiency curves for these three types of cyclones are presented in the figure.
Standard Cyclone Dimensions

Extensive work has been done to determine in what manner dimensions of cyclones affect performance. In some classic work that is still used today, Shepherd and Lapple (1939, 1940) determined "optimal" dimensions for cyclones. Subsequent investigators reported similar work, and the so-called "standard" cyclones were born.

All dimensions are related to the body diameter of the cyclone so that the results can be applied generally.

The table on the next slide summarizes the dimensions of standard cyclones of the three types mentioned in the previous figure. The side figure illustrates the various dimensions used in the table.

<table>
<thead>
<tr>
<th>Cyclone Type</th>
<th>High Efficiency</th>
<th>Conventional</th>
<th>High Throughput</th>
</tr>
</thead>
<tbody>
<tr>
<td>Body Diameter, D/D</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Height of Inlet, H/D</td>
<td>0.5</td>
<td>0.44</td>
<td>0.5</td>
</tr>
<tr>
<td>Width of Inlet, W/D</td>
<td>0.2</td>
<td>0.21</td>
<td>0.25</td>
</tr>
<tr>
<td>Diameter of Gas Exit, De/D</td>
<td>0.5</td>
<td>0.4</td>
<td>0.5</td>
</tr>
<tr>
<td>Length of Vortex Finder, S/D</td>
<td>0.5</td>
<td>0.625</td>
<td>0.6</td>
</tr>
<tr>
<td>Length of Body, Lb/D</td>
<td>1.5</td>
<td>1.4</td>
<td>2.0</td>
</tr>
<tr>
<td>Length of Cone, Lc/D</td>
<td>2.5</td>
<td>2.5</td>
<td>2.0</td>
</tr>
<tr>
<td>Diameter of Dust Outlet, Dd/D</td>
<td>0.375</td>
<td>0.4</td>
<td>0.25</td>
</tr>
</tbody>
</table>

SOURCES: Columns (1) and (5) = Stairmand, 1951; columns (2), (4) and (6) = Swift, 1969; column (3) and sketch = Lapple, 1951.
Cyclone Theory

Collection Efficiency

A very simple model can be used to determine the effects of both cyclone design and operation on collection efficiency.

In this model, gas spins through a number $N$ of revolutions in the outer vortex. The value of $N$ can be approximated as the sum of revolutions inside the body and inside the cone:

$$ N = \frac{1}{H} \left( L_b + \frac{L_c}{2} \right) $$

where

- $N$ = number of turns inside the device (no units)
- $H$ = height of inlet duct (m or ft)
- $L_b$ = length of cyclone body (m or ft)
- $L_c$ = length (vertical) of cyclone cone (m or ft).

To be collected, particles must strike the wall within the amount of time that the gas travels in the outer vortex. The gas *residence time* in the outer vortex is

$$ \Delta t = \frac{\text{path length}}{\text{speed}} = \pi \frac{D N}{V_i} $$

where

- $\Delta t$ = time spent by gas during spiraling descent (sec)
- $D$ = cyclone body diameter (m or ft)
- $V_i$ = gas inlet velocity (m/s or ft/s) = $Q/WH$
- $Q$ = volumetric inflow (m$^3$/s or ft$^3$/s)
- $H$ = height of inlet (m or ft)
- $W$ = width of inlet (m or ft).

The maximum radial distance traveled by any particle is the width of the inlet duct $W$. The centrifugal force quickly accelerates the particle to its terminal velocity in the outward (radial) direction, with the opposing drag force equaling the centrifugal force.

The terminal velocity that will just allow a particle initially at distance $W$ away from the wall to be collected in time is

$$ V_t = \frac{W}{\Delta t} $$

where $V_t$ = particle drift velocity in the radial direction (m/s or ft/s).
The particle drift velocity is a function of particle size.

Assuming Stokes regime flow (drag force = $3\pi\mu d_p V_t$) and spherical particles subjected to a centrifugal force $mv^2/r$, with $m =$ mass of particle in excess of mass of air displaced, $v = V_i$ of inlet flow, and $r = D/2$, we obtain

$$V_t = \frac{(\rho_p - \rho_a) d_p^2 V_i^2}{9 \mu D}$$

where

- $V_t =$ terminal drift transverse velocity (m/s or ft/s)
- $d_p =$ diameter of the particle (m or ft)
- $\rho_p =$ density of the particle (kg/m$^3$)
- $\rho_a =$ air density (kg/m$^3$)
- $\mu =$ air viscosity (kg/m.s).

Substitution of the 2nd equation into the 3rd eliminates $\Delta t$. Then, setting the two expressions for $V_t$ equal to each other and rearranging to solve for particle diameter, we obtain

$$d_p = \left[ \frac{9 \mu W}{\pi N V_i (\rho_p - \rho_a)} \right]^{1/2}$$

It is worth noting that in this expression, $d_p$ is the size of the smallest particle that will be collected if it starts at the inside edge of the inlet duct. Thus, in theory, all particles of size $d_p$ or larger should be collected with 100% efficiency.

Note that the units must be consistent in all equations. One consistent set is m for $d_p$, R and W; m/s for $V_i$ and $V_t$; kg/m.s for $\mu$; and kg/m$^3$ for $\rho_p$ and $\rho_a$. An equivalent set in English units is ft for $d_p$, R and W; ft/sec for $V_i$ and $V_t$; lbm/ft.sec for $\mu$; and lbm/ft$^3$ for $\rho_p$ and $\rho_a$. 
The preceding equation shows that, in theory, the smallest diameter of particles collected
with 100% efficiency is directly related to gas viscosity and inlet duct width, and inversely
related to the number of effective turns, inlet gas velocity, and density difference between
the particles and the gas.

In practice, collection efficiency does, in fact, depend on these parameters. However, the
model has a major flaw: It predicts that all particles larger than \( d_p \) will be collected with
100% efficiency, which is incorrect. This discrepancy is the result of all our approximations.

Lapple (1951) developed a semi-empirical relationship to calculate a “50% cut diameter”
\( d_{pc} \), which is the diameter of particles collected with 50% efficiency. The expression is

\[
d_{pc} = \left[ \frac{9 \mu W}{2 \pi VN (\rho_p - \rho_g)} \right]^{1/2}
\]

where \( d_{pc} \) = diameter of particle collected with 50% efficiency.

Note the similarity between the last two equations. The only difference is a factor 2 in the
denominator.

### Particle collection efficiency versus particle size ratio for standard conventional
cyclones

Lapple then developed a general curve for standard conventional cyclones to predict the
collection efficiency for any particle size (see side figure).

If the size distribution of particles is known, the overall collection efficiency of a cyclone
can be predicted by using the figure.

Theodore and DePaola (1980) then fitted an algebraic equation to the curve, which makes
Lapple’s approach more precise and more convenient for application to computers.
The efficiency of collection of any size of particle is given by

\[
\eta_j = \frac{1}{1 + \left( d_{pc} / d_{pj} \right)^2}
\]

where

\( \eta_j \) = collection efficiency of particles in the \( j \)th size range (0 < \( \eta_j < 1 \))

\( d_{pj} \) = characteristic diameter of the \( j \)th particle size range (in \( \mu m \)).
The overall efficiency, called performance, of the cyclone is a weighted average of the collection efficiencies for the various size ranges, namely

\[
\eta = \frac{\sum \eta_j m_j}{M}
\]

where

- \(\eta\) = overall collection efficiency (0 < \(\eta\) < 1)
- \(m_j\) = mass of particles in the \(j\)th size range
- \(M\) = total mass of particles.

**Example of Cyclone Analysis**

*Given:*

Conventional type (standard proportions)

- \(D = 1.0\) m
- Flow rate = \(Q = 150\) m\(^3\)/min
- Particle density = \(\rho_p = 1600\) kg/m\(^3\)
- Particle size distribution as follows:

<table>
<thead>
<tr>
<th>Particle size ((d_p))</th>
<th>% mass in that size</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-2 (\mu)m</td>
<td>1.0%</td>
</tr>
<tr>
<td>2-4 (\mu)m</td>
<td>9.0%</td>
</tr>
<tr>
<td>4-6 (\mu)m</td>
<td>10.0%</td>
</tr>
<tr>
<td>6-10 (\mu)m</td>
<td>30.0%</td>
</tr>
<tr>
<td>10-18 (\mu)m</td>
<td>30.0%</td>
</tr>
<tr>
<td>18-30 (\mu)m</td>
<td>14.0%</td>
</tr>
<tr>
<td>30-50 (\mu)m</td>
<td>5.0%</td>
</tr>
<tr>
<td>50-100 (\mu)m</td>
<td>1.0%</td>
</tr>
</tbody>
</table>

*Question:*

What is the collection efficiency?
Two distinct approaches in cyclone analysis

1. **Performance analysis**

   The cyclone exists — All dimensions and characteristics are known.
   The engineer calculates its collection efficiency ($\eta$).

2. **Design analysis**

   The cyclone needs to be chosen for a given task.
   A target performance ($\eta$) is imposed.
   Typically, the engineer knows the amount of air flow ($Q$),
   & characteristics of particles (range of $d_i$'s, mass fractions $m_j / M$).
   The engineer needs to determine
   - the type of cyclone needed (conventional, high-throughput, …)
   - the required size of the device (diameter $D$).

   **Note**: Design analysis usually necessitates an iterative approach.
   (Successive guesses until the required performance is achieved.)