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Performance and Costs of Air Pollution Control Technologies

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1. INTRODUCTION

1.1. Air Emission Sources and Control

In general, air toxics are hazardous air pollutants (HAPs) that cause cancer or other human health effects. One hundred ninety compounds are specifically identified in the Clean Air Act (CAA) amendments of 1990 as air toxics that the US Environmental Protection Agency (US EPA) must investigate and regulate. Air emission control is one of important tasks of the US EPA (1–23).

The top 14 HAPs identified by the US EPA are toluene, formaldehyde, methylene chloride, methyl chloroform, ethylene, *m*-xylene, benzene, *o*-xylene, perchloroethylene, *p*-xylene, chlorobenzene, acetic acid, trichlorotrifluoroethane, and trichloroethylene (22,23).

Most HAPs can be classified as volatile organic compounds (VOCs), semivolatile organic compounds (SVOCs), particulate matters (PMs), and pathogenic micro-organisms (19–26). HAP control will be very active in the 21st century on several fronts: new regulations, the Maximum Achievable Control Technology (MACT) hammer,

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and residual risk. Each presents issues for industrial plant compliance in the forthcoming years(27).

Air emission controls can be divided into (1) controls for point sources of emissions and (2) controls for area sources of emissions. Point sources include stacks, ducts, and vents from industrial plants and from remediation technologies such as air stripping, soil vapor extraction, thermal desorption, and thermal destruction. Add-on emission controls usually can be added readily to point sources. Area sources include lagoons, landfills, spill sites, and remediation technologies such as excavation. Air emission controls for area source controls are generally more difficult to apply and less effective than controls for point sources. Some emission sources such as solidification/stabilization, bioremediation, and storage piles may be either point or area sources of emissions. Area sources can be converted to point sources using enclosures or collection hoods (3,8,10,12,28,29).

1.2. Air Pollution Control Devices Selection

There are many air pollution control devices (APCDs) available (1,3–5,8–11,30–35). Each APCD has relative advantages and disadvantages and no single control option will always be the best choice for air pollution control or site remediation technology. Selection criteria for APCDs include (a) demonstrated past use of the control technology for the specific application of interest, (b) ability meet or exceed the required average capture and/or control efficiency, (c) compatibility with the physical and chemical properties of the waste gas stream, (d) reliability of control equipment and process, (e) capital cost of control equipment, (f) operating costs of system (including byproducts disposal or regeneration costs), and (g) permitting requirements.

The information in this chapter is intended to be used to screen potential APCD options and used in conjunction with detailed engineering evaluations, vendor data, and feasibility studies to select air pollution control technologies.

The cost-effectiveness of APCDs is very process- and site-specific. In general, a control system is designed or modified for each specific application; so, in theory, any desired removal or control efficiency can be achieved. In practice, a trade-off exists between removal or control efficiency and cost (26,28,29,36–48).

2. TECHNICAL CONSIDERATIONS

2.1. Point Source VOC Controls

Various APCDs for controlling VOC from point sources of air emission are evaluated and summarized in Table 1. Carbon adsorption, thermal oxidation, catalytic oxidation, condensation, biofiltration, ultraviolet, and emerging control technologies are introduced in volume 1 of this handbook series (48). Only the internal combustion engines (ICEs) and membrane process are briefly introduced in below.

The principle of operation of a control device that incorporates an ICE is to use a conventional automobile or truck ICE as a thermal incinerator. The major components include the standard automobile or truck engine, supplemental fuel supply (propane or natural), carburetor and off-gas lines from a point emission control device (adsorbent bed, catalytic converter, etc.). ICEs may be used for VOC control from any point source where the airstream must meet certain air quality criteria (2–12).

Table 1
Typical Required Emission Stream and Contaminant Characteristics for Point Sources VOC Controls

Control	Concentration (ppm)	Flow rate (scfm)	Applicable organics	Inorganic/corrosive contaminants	PM damage	Temperature (ºC)	Humidity	Variable stream	Pressure drop (in. H_2O)
Carbon adsorption	<10,000	Regenerable: <500,000 Disposal: <1,500	Most compounds with 50<MW<200	Some inorganics and metals can be controlled	PM must be removed	<120 (most effective around 38)	<50%	Variable flow or concentration present no problems	23–125
Thermal oxidation (incineration)	<25% LEL	Packaged: <50,000 custom to 100,000 and above	Most organics acceptable Formation of acid gases or PICs possible	Extra controls may be required for halogenated organics and sulfur	PM not a problem	Combustion at 760–870	High humidity streams may reduce Btu content	Low flow rates require supplementary fuel	4 (a 70% efficient heat exchanger may have a drop of 15)
Catalytic oxidation (incineration)	<25% LEL >10 Btu/scf may overheat catalyst	Packaged: <50,000	Halogenated organics usually a problem	Corrosives and metals can degrade catalyst	PM can clog catalyst	260–593	Increasing humidity increases required supplementary heat	Variable flow required dilution/ supplemental fuel; Might overheat catalyst	6 (a 70% efficient heat exchanger may have a drop of 15)
Condensers	>5,000	< 2,000	BP > 38ºC preferred	Corrosive gases a problem	PM not a problem	As close to dew point of HAPs as possible	Humid streams can ice over refrigeration unit	Changes in VOC content, concentration, or temperature can reduce condensation	Minimal
Internal combustion engines	<25 % LEL	<1,000/unit (200 typical)	All combustible organics	Corrosive gases unacceptable; will not treat metals or other combustibles	PM may cause fouling	Must be less than combustion temperature	High humidity stream may reduce Btu content	Variable flowrate requires supplementary fuel; excessive loading dumps untreated hydrocarbons	Pressure increases across device (power is generated)
Soil beds/ biofilters	1,000 (pilot system)	600–90,000	Most organics acceptable	SO_2, NO_x, H_2S can be controlled	PM can plug soil pores	38: optimal (highly sensitive)	90% RH required to prevent drying out bed	Variable flow or concentration may impact microbe culture	2–3 (pilot system)
Emerging/ miscellaneous controls (membrane, UV)	Membrane: >300, UV: 100 in pilot studies	Low	Some organics acceptable	Corrosive gases may degrade membrane	PM may be problem for membrane	Unknown effects	Unknown	Unknown	Varies

Source: ref. 28.

Membrane filtration is an emerging APCD for removing VOCs and SVOCs from waste gas streams. The membrane module acts to concentrate the toxic organic compounds by being more permeable to organic constituents than air. The imposed pressure difference across a selective membrane drives the separation of the VOCs and SVOCs from the waste gas streams.

2.2. Point Source PM Controls

Various APCDs for controlling PMs from point sources of air emissions are evaluated and summarized in Table 2. Fabric filtration (baghouse), wet scrubbers, dry scrubbers, electrostatic precipitators (ESPs), quench chambers, Venturi scrubbers, and operational controls are all introduced in detail in other chapters of this handbook series. Only the high efficiency particulate air (HEPA) filter is briefly described in this subsection.

The HEPA filters are commonly used in medical and environmental facilities requiring 99.9% or greater PM removal. HEPA filters can be used as a PM polishing step in ventilation and air conditioning systems for buildings undergoing asbestos or lead paint removal, for enclosures, or with solidification and stabilization mixing bins at a remediation site. The major components of a PM control system employing HEPA filters include the following: (1) HEPA filters, (2) filter housing, (3) duck work, and (4) fan.

2.3. Area Source VOC and PM Controls

Various APCDs for controlling VOCs and PMs from area sources of air emissions are evaluated and summarized in Table 3. Table 4 indicates the ranges of removal efficiency (RE) for point source PM controls. The applicable APCDs, which are briefly described in the following section, include covers, foams, wind screen, water sprays, operational controls, enclosures, and collection hoods (28,29).

Covers control emissions of contaminated particulate matter and VOCs/SVOCs by physically isolating the contaminated media from the atmosphere. Some cover materials (e.g., sawdust and straw) are tilled into the contaminated soil or contaminated media as an anchoring mechanism.

Modified fire-fighting foams are commonly used to control PMs/VOCs/SVOCs emissions during the remediation of hazardous waste sites or hazardous spill sites. Suppressing of PM/VOC/SVOC is accomplished by blanketing the emitting source (liquid, slurry, soil, or contaminated equipment) with foam, thus forming a physical barrier to those HAP emissions. Some foams are "sacrificial," meaning that the chemicals compromising the foam will react with specific VOCs/SVOCs and further suppress their emissions.

Wind screens can be used to reduce PM emissions from storage piles, excavation sites, and other area sources. The principle is to provide an area of reduced wind velocity that allows settling of the large particles and reduces the particle flux from the exposed surfaces on the leeward side of the screen. In addition, wind screens reduce moisture loss of a contaminated medium (such as soil), resulting in decreased VOC/SVOC and PM emissions.

The control mechanism of water sprays is the agglomeration of small particles with large particles or with water droplets. Also, water will cool the surface of a contaminated medium, such as soil. Typically, water is applied with mobile water wagons or fixed perforated pipes.

Table 2
Typical Required Emission Stream and Contaminant Characteristics for Point Source PM Controls

Control	Loading (grains/dscfm)	Flow rate (scfm)	PCDD/PCDF, PICs control	Inorganic/corrosive contaminants	PM size	Inlet temperature (°C)	Variable stream	Pressure drop (in. H_2O)
Fabric filter (baghouse)		Any rate	Effectiveness disputed	Various fabrics susceptible to various corrosive compounds; no "sticky" PMs	>0.3 µm (varies with fabric)	Above stream dew point, but <300 (special fabrics up to 1200)	Not a problem	<20 (6–8 optimum)
Wet scrubbers; packed tower, ionizing wet	>200 for 90% or better RE	1,000–200,000	Effectiveness disputed	Acid gases, IWS, metals	>10µm	Insensitive for PMs	Not a problem	12–32
Dry scrubbers DSI, SDA	0.02 grains/dscfm	Better for >1,000	SDA may be effective when used with baghouse	Acid gases, heavy metals		DSI: optimum efficiency at 15 from saturation SDA: to 1000	Not a problem	Small
Electrostatic precipitator	>2 g/scf	<200,000	No	Not effective for resistive particles	0.01–70 µm	30–60- above stream dew point	Sensitive to loading	0.4
Quench chambers	Any	Any rate	No	Can remove 50% acids,depending on liquor used		Incineration temperature	Sensitive to loading	
Venturi scrubber	Any	<80,000	Effectiveness disputed	HCl, SO_2, NO_x, HCN can be controlled	85–99% RE for PM > 0.5 µm	30–60 above stream dew point	Not a problem	<50
Operational controls	Varies	Any rate	Yes	N/A	N/A			
HEPA filter	Low	Any rate			>0.03 µm	Dew point of stream	Not a problem	

Source: ref. 28.

Table 3
Typical Required Emission Source and Contaminant Characteristics for Area Source VOC and PM Controls

Control	Medium	Wind	Site Surface	Equipment required	Duration of control effectiveness	Sunlight/temperature	Precipitation
Covers: soil, organics, synthetics, paving, road carpet/slag	Soil, liquid, or sludge	Little effect	Level surface is best	Graders, front end loaders, other heavy equipment	Months	UV, weather may degrade synthetic and organic covers	May wash away soil cover
Foams	Soil, liquid, or sludge	Application difficult in winds > 10 mph	Some foams unsuited for steep slopes	Pump, foaming nozzle, water, application unit	From a few hours up to several months	Increased temperature will decrease useful life of foam	Can wash away some foams
Wind screen	Soil, liquid, or sludge	High winds may cause damage	Any	Supports	Easily damaged, otherwise no limit	No effect	No effect
Water sprays	Soil	Wind increases evaporation rate	Not used near surface waters	Nozzles, water wagon, pump	Effective until water evaporates	Heat decreases control time	Improves efficiency
Water sprays with additives	Soil	Wind reduces life of spay	Not used near surface waters	Nozzles, water wagon, pump	Effective until water evaporates	Heat decreases control time, freezing weather may preclude application	Improves efficiency
Operational controls	Soil, liquid, or sludge	No effect	No effect	Varies	Varies	No effect	May improve efficiency
Enclosures	Soil, liquid, or sludge	No effect	No effect	Structure	Months to years	Not effect	No effect
Collection hoods	Soil, liquid, or sludge	High winds may necessitate use of wind screen	Level surface best	Hood, ducting, blower	Indefinite	Effectiveness may decrease somewhat as temperature rises	No effect

Source: ref. 28.

Table 4
Ranges of % RE for Point Source PM Controls

	Fly ash	PCDD/PCDF	Acid gases	<10 μm	>10 μm	Metals
Baghouses	—	Entrained fraction removed		99+[a]	99+[a]	90–95[b]
Wet scrubbers	—	—	95–99+	Low	—	40–50[b]
Venturi scrubbers	—	—	99	80–95	80–95	Variable
Dry scrubbers	—	90–99+	95–99+	99+	99+	95–99[b]
ESP	99+	98 with SDA	—	99[c]	99[c]	85–99[b]
Quench Chambers	—	—	50	—	—	—
HEPA filters	—	Entrained fraction removed	—	99.9+[d]	99+[d]	—

[a]Except for "sticky" particles.
[b]Lower removal efficiency for mercury.
[c]For resistive particles.
[d]With high pressure drop.
Source: refs. 26 and 28.

Operational controls are those procedures and practices inherent to most air emission control projects that can be instituted to reduce VOC/SVOC/PM emissions. These may include: (1) cleaning practices, (2) seasonal scheduling, (3) vehicle speed control, (4) storage pile orientation, (5) excavation practices, (6) dumping practices, and (7) soil/materials handling practices.

Enclosures provide a physical barrier between the emitting area and the atmosphere and, in essence, convert an area source to a point source HAP emission. Prior to releasing the air trapped within the enclosure, conventional point source controls are employed to control VOC/SVOC/PM emissions.

Collection hoods are commonly used to capture VOCs/SVOCs/PMs emitted from small-area sources and route those emissions to appropriate APCDs. In practice, hoods are designed using the capture velocity principle, which involves the creation of an airflow sufficient to remove the contaminated air after the emitting source.

2.4. Pressure Drops Across Various APCDs

The total system pressure drop is the summation of duct pressure drop, stack pressure drop, APCD #1 pressure drop, APCD #2 pressure drop, APCD #3 pressure drop, and so forth. The assumed pressure drops across various APCDs are shown in Table 5. Equation (1) can be used to calculate the total system pressure drop, ΔP_t (in. H_2O).

$$\Delta P_t = \Delta P_{\text{duct}} + \Delta P_{\text{stack}} + \Delta P_{\text{device\#1}} + \Delta P_{\text{device\#2}} + \Delta P_{\text{device\#3}} + \Delta P_{\text{device\#}n} \qquad (1)$$

3. ENERGY AND COST CONSIDERATIONS FOR MINOR POINT SOURCE CONTROLS

3.1. Sizing and Selection of Cyclones, Gas Precoolers, and Gas Preheaters

Gas conditioning equipment includes those components that are used to temper or pretreat the gas stream to provide the most efficient and economical operation of the downstream control devices. Preconditioning equipment, installed upstream of the control devices, consists of mechanical dust collectors, wet or dry gas coolers, and gas

Table 5
Assumed Pressure Drops Across Various Components

System component	Pressure drop (in. H_2O)
Stack	0.6
Ductwork	0.6
Thermal incinerator	4.1
Heat exchanger	2
Catalytic incinerator	6
Absorber	Variable[a]
Carbon adsorber	6
Condenser	3
Fabric filter	6
Electrostatic precipitator	0.5
Venturi scrubber	ΔP_v

[a]Use Eq. (1) to determine the pressure drop.

preheaters. Where the control device is a fabric-filter system or electrostatic precipitator, mechanical dust collectors are required upstream if the gas stream contains significant amounts of large particles (3).

Gas stream pretreatment equipment can be installed upstream of the control device (i.e., cyclones, precoolers, and preheaters) and enable the emission stream to fall within the parameters specified by the downstream process equipment manufacturers. The best solution for compliance with Clean Air Act regulations may be one or a combination of technologies. Accordingly, cyclones and other airstream pretreatment equipment become very important to a complete air emission control systems (1,3–18).

Mechanical dust collectors, such as cyclones, are used to remove the bulk of the heavier dust particles from the gas stream. These devices operate by separating the dust particles from the gas stream through the use of centrifugal force. The efficiency of a cyclone is determined by the entering gas velocity and the diameter at the cyclone inlet. The cyclone inlet area can be calculated from Eq. (2). In this equation, d is the critical particle size in (μm). The critical particle size is the size of the smallest particle the cyclone can remove with 100% efficiency. Therefore, simply select a critical particle size and then calculate the appropriate cyclone dimensions which will remove 100% of all particles that size and larger.

$$A_{cyc} = 3.34\left[Q_{e,a}\left(r_p - D_G\right)/\mu\right]^{1.33}(d)^{2.67} \tag{2}$$

where $Q_{e,a}$ is the actual emission stream flow rate (acfm), r_p is the density of the particle (lb/ft^3), D_G is the density of the emission stream (lb/ft^3), μ is the emission stream viscosity (lb-ft/s), and d is the critical particle size (μm)

Gas stream coolers can be wet or dry. Dry-type coolers operate by radiating heat to the atmosphere. Wet-type coolers (spray chambers) cool and humidify the gas by the addition of water sprays in the gas stream; the evaporating water reduces the temperature of the gas stream. A third method of cooling is through the addition of dilution air. The applications and operational conditions of gas stream coolers are introduced in Chapter 10.

Gas preheaters are used to increase the emission stream temperature. Condensation causes corrosion of metal surfaces and is of particular concern in fabric-filter applications where moisture can cause plugging or "blinding" of the fabric pore. Therefore, gas preheaters can be used to elevate the temperature of an emission stream above its dew point. The temperature of the emission stream should be 50–100ºF above its dew point if the emission stream is to be treated (i.e., PM collected) by a downstream ESP or a fabric filter (26).

3.2. Sizing and Selection of Fans, Ductworks, Stacks, Dampers, and Hoods

Other auxiliary process equipment include but are not limited to fans, ductworks, stacks, dampers, and hood, which are self-explanatory. Figure 1 shows the components of a typical hood exhaust system, which includes the hood, duct, cyclone cleaners, and a fan (28,29). Detailed procedures and examples for designing fans, ducts and so forth can be found in Chapter 6 of this book.

Hoods are commonly used to capture PMs/VOCs emitted from small-area sources (e.g., waste stabilization/solidification mixing silos, bioremediation reactors) and route those emissions to appropriate APCDs. Three hood designs that are commonly used are depicted in Fig. 2. The selection of hood type will be dependent on the emitting source characteristics (e.g., source area and accessibility, emitting air velocity, surrounding air currents) and the required capture efficiency. Major components of a hood exhaust system are depicted in Fig. 1.

Hoods can be used to capture PM/VOC emissions from exsitu waste stabilization/solidification mixing silos and bioremediation reactors. The use of a hood will be contingent upon access to the emitting source and upon the area of the emitting source. As the distance between a source and hood increases, so does the required total volumetric flow rate of air into the hood to maintain a given capture efficiency. Because the cost of most air pollution control equipment is proportional to the volumetric flow rate, a point is reached where it is not economically feasible to use a hood. The emitting

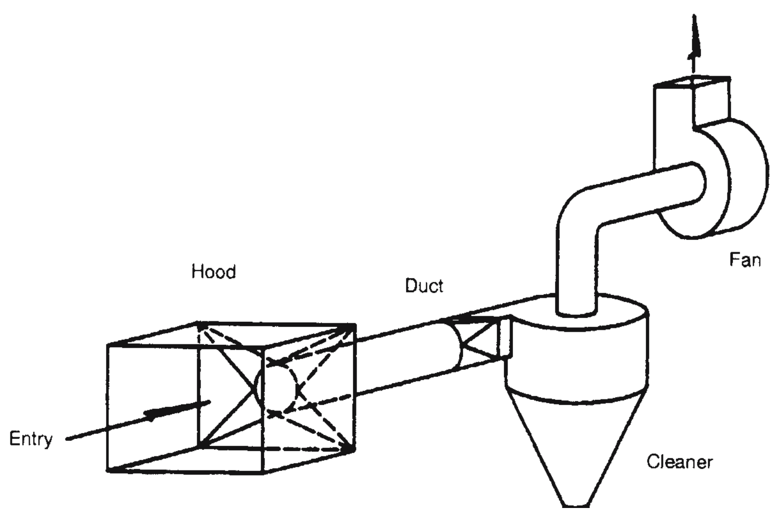


Fig. 1. Components of a hood exhaust system. (From ref. 7.)

source area will impact the hood size required, and for canopy and capturing hoods, it will impact the airflow rate required to maintain a given capture efficiency. The advantages/disadvantages of using a hood to capture PM/VOC emissions are outlined in Table 6. Parameters that influence the capture efficiency of hood exhaust systems are given in Table 7.

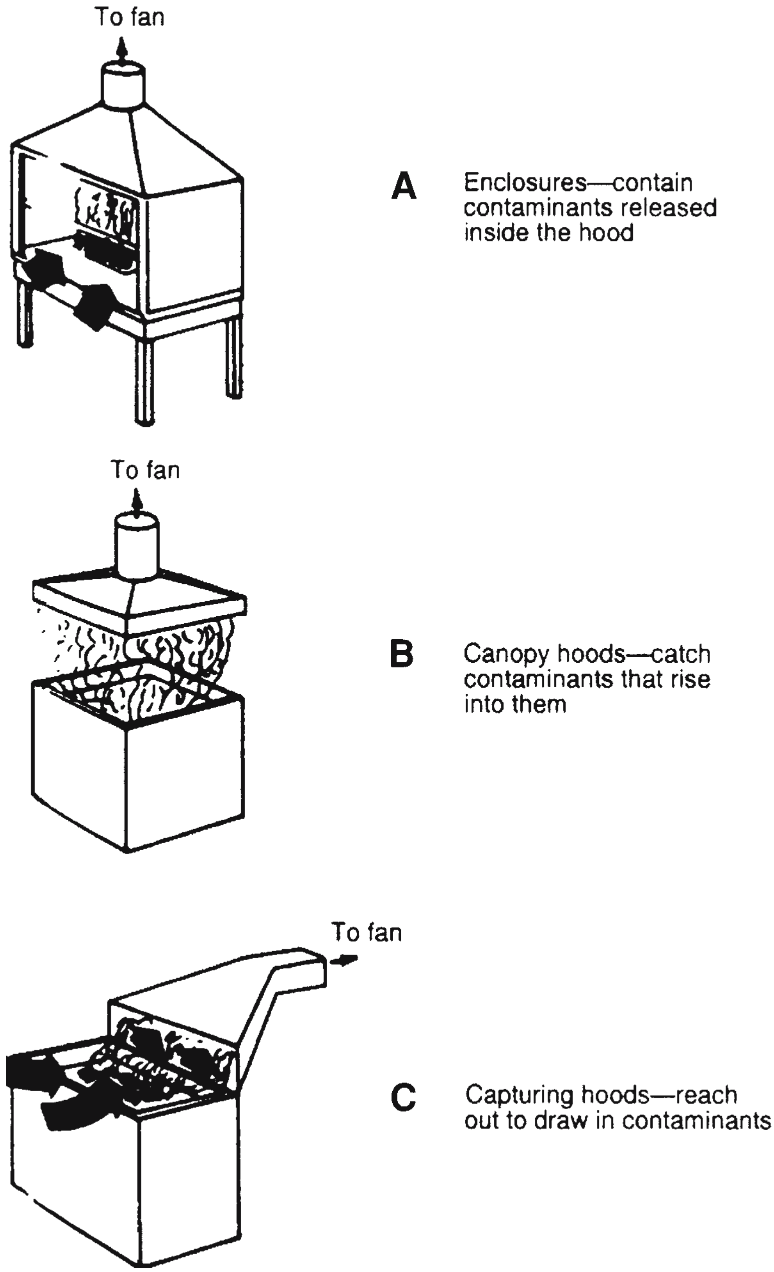


Fig. 2. Three commonly used hood designs. (From refs. 28 and 33)

Table 6
Advantages/Disadvantages of Hoods to Capture PM/VOC Emissions

Advantages	Disadvantages
90–100% PM/VOC capture efficiencies are possible.	Emission source must be accessible to hood.
Much data available regarding selection and design of hoods.	Contaminant diluted by airflow into hood. This can affect air pollution control efficiencies (e.g., carbon adsorption, incineration).
Conversion of an area source into a point source. Most air pollution control equipment is designed for point sources.	Power cost may be high as a result of required capture velocity and head loss through ductwork. Use of hoods is practical for small-area sources only. Hoods subject to corrosion (e.g., acid gases, lime).

Source: US EPA.

Hood PM/VOC capturing efficiencies can be as high as 90–100%. However, PM/VOC control efficiencies are functions of both the hood capture efficiency and the air pollution control equipment removal efficiency. Hood exhaust systems designs are based on the hood aspect ratio (width/length of hood), the required capture velocity (v), and the distance of the furthest point of the emitting source from the hood centerline (X). Ranges of capture velocities required as a function of surrounding air turbulence and the emitting source are listed in Table 8. The velocities obtained from Table 8 can then be used in hood design. Various hood designs are shown in Table 9. For a more thorough presentation on hood design, see ref. 4. The following are design equations of various hoods:

1. Slot hood

$$Q = 3.7LVX \tag{3}$$

Table 7
Parameters That Affect Hood Capture Efficiencies

Parameter	Comment
Distance between hood and farthest point of emitting source	As this distance increases, for a given volumetric flow rate into the hood, the capture efficiency decreases.
Volumetric flow rate into the hood	As the volumetric flow rate into the hood increases, the capture efficiency increases.
Surrounding air turbulence	As the surrounding air turbulence increases, the required volumetric flow rate into the hood increases to maintain a given capture efficiency.
Hood design	Hood designs are tailored to specific types of emitting sources. For example, canopy hoods are designed to collect emissions from heated open-top tanks.

Source: US EPA

Table 8
Range of Capture Velocities

Condition of dispersion of contaminant	Examples	capture velocity (fpm)
Released with practically no velocity into quiet air	Evaporation from tanks; degreasing, etc.	50–100
Released at low velocity into moderately still air	Spray booths; intermittent container filling; low-speed conveyor transfers; welding; plating; pickling.	100–200
Active generation into zone of rapid air motion	Spray painting in shallow booths; barrel filling; conveyor loading; crushers.	200–500
Released at high initial velocity into zone of very rapid air motion	Grinding; abrasive blasting.	500–2000

Note: In each category, a range of capture velocity is shown. The proper choice of value depends on several factors:

Lower end of range	Upper end of range
1. Room air current minimal or favorable to capture	1. Disturbing room air current
2. Contaminants of low toxicity or of nuisance value only	2. Contaminants of high toxicity
3. Intermittent, low production	3. High production, heavy use
4. Large hood, large air mass in motion	4. Small hood, local control only

2. Flanged hood

$$Q = 2.8LVX \tag{4}$$

3. Plain opening

$$Q = V\left(10X^2 + A\right) \tag{5}$$

4. Flanged opening

$$Q = 0.75V\left(10X^2 + A\right) \tag{6}$$

5. Booth

$$Q = VA = VWH \tag{7}$$

6. Canopy

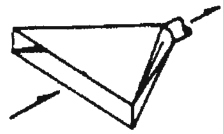
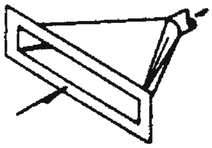
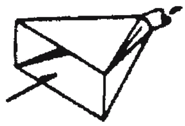
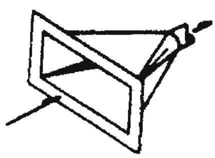
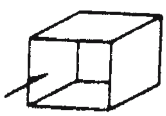
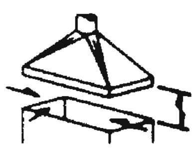
$$Q = 1.4PVD \tag{8}$$

where X is the centerline distance to point x in the emissions plume (ft), L is the length (ft), W is the width (ft), H is the height (ft), D is the distance between hood and source (ft), A is the area (ft^2), Q is the flow rate, (ft^3/min), P is the perimeter of hood (ft), and V is the velocity at point x (ft/min)

3.3. Cyclone Purchase Costs

Cyclones are used upstream of particulate control devices (e.g., fabric filters, ESPs) to remove larger particles entrained in a gas stream. Equation (9) yields the cost of a carbon steel cyclone with a support stand, fan and motor, and a hopper or drum to collect the dust:

Table 9
Hood Design [U.S. EPA]

	Description	Aspect ratio (W/L)
	Slot	0.2 or less
	Flanged slot	0.2 or less
	Plain opening	0.2 or greater and round
	Flanged opening	0.2 or greater and round
	Booth	To suit work
	Canopy	To suit work

$$P_{cyc} = 6{,}520 A_{cyc}^{0.9031} \tag{9}$$

where P_{cyc} is the cost of cyclone, (August 1988 \$) and A_{cyc} is the cyclone inlet area, (ft^2 [0.200 ft$^2 \leq A_{cyc} \leq$ 2.64 ft^2]). The cost of a rotary air lock for the hopper or drum is given by

$$P_{ral} = 2{,}730 A_{cyc}^{0.965} \tag{10}$$

where P_{ral} is the cost of the rotary air lock (August 1988 \$) and A_{cyc} is the cyclone inlet area (ft^2 [0.350 ft$^2 \leq A_{cyc} \leq$ 2.64 ft^2])

3.4. Fan Purchase Cost

In general, fan costs are most closely correlated with fan diameter. The readers are referred to Chapter 6 for detailed fan design. Equations (11)–(13) can be used to obtain fan prices. Costs for carbon steel fan motor ranging in horsepower from 1 to 150 hp are provided in Eqs. (14) and (15). Equation (12) or (13) is used in conjunction with Eq. (14) or (15), respectively.

The cost of a fan is largely a function of the fan wheel diameter, d_{fan}. The wheel diameter is related to the ductwork diameter through use of manufacturer's multirating tables. The readers should be able to obtain the fan wheel diameter for a given ductwork diameter by consulting the appropriate multirating table or by calling the fan manufacturer.

For a centrifugal fan consisting of backward curved blades including a belt-driven motor and starter and a static pressure range between 0.5 and 8 in. of water, the cost as a function of fan diameter in July 1988 dollars is provided by

$$P_{\text{fan}} = 42.3 d_{\text{fan}}^{1.20} \quad (11)$$

where P_{fan} is the cost of the fan system (July 1988 \$) and d_{fan} is the fan diameter (in. [12.25 in. ≤ (d_{fan} ≤ 36.5 in.]).

The cost of a fiber-reinforced plastic (FRP) fan, not including the cost of a motor or starter, is provided by

$$P_{\text{fan}} = 53.7 d_{\text{fan}}^{1.35} \quad (12)$$

where P_{fan} is the cost of the fan without a motor or starter, (April 1988 \$) and d_{fan} is the fan diameter (in. [10.5 in. $\leq d_{\text{fan}} \leq$ 73 in.]). The cost of a motor and starter as obtained in Eq. (14) or (15) should be added to the fan cost obtained in Eq. (12).

A correlation for a radial-tip fan with welded, carbon steel construction and an operating temperature limit of 1000ºF without a motor or starter is provided by

$$P_{\text{fan}} = a_f \times \left(d_{\text{fan}}\right)^{b_f} \quad (13)$$

where P_{fan} is the cost of the fan without motor or starter (July 1988 \$), and a_f, b_f are coefficients, and d_{fan} is the fan diameter (in.). The values for the parameters a and b are provided in Table 10.

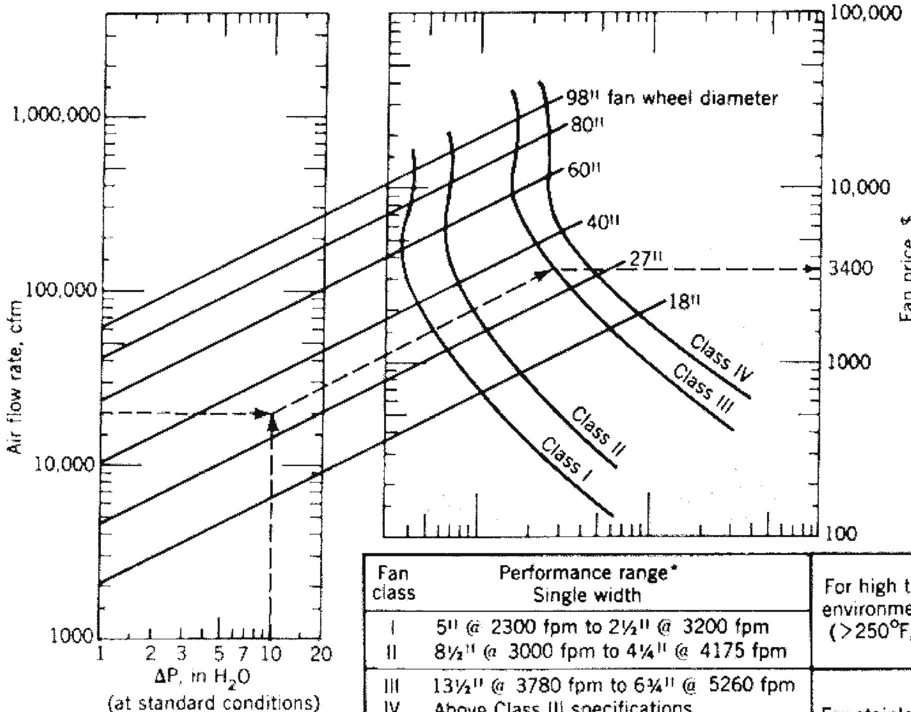
The cost of fan motors and starters is given in Eq. (14) or (15) as a function of the horsepower requirement. The cost obtained from either of these equations should be added to the fan cost obtained in Eq. (12) or (13). For low-horsepower requirements,

$$P_{\text{motor}} = 235\ \text{hp}^{0.256} \quad (14)$$

where P_{motor} is the cost of the fan motor, belt, and starter (February 1988 \$) and hp is the motor horsepower ($1 \leq \text{hp} \leq 7.5$).

Table 10
Equation (13) Parameters

Parameter	Group 1	Group 2
Static pressure (in.)	2–22	20–32
Flow rate (acfm)	700–27,000	2,000–27,000
Fan wheel diameter (in.)	19.125–50.5	19.25–36.5
a_f	6.41	22.1
b_f	1.81	1.55



Fan class	Performance range* Single width	
I	5" @ 2300 fpm to 2½" @ 3200 fpm	For high temperature environment add 3% (>250°F, <600°F)
II	8½" @ 3000 fpm to 4¼" @ 4175 fpm	
III	13½" @ 3780 fpm to 6¾" @ 5260 fpm	For stainless steel construction multiply price by 2.5
IV	Above Class III specifications	

*Performance range designations are indicated by static pressure (inches of water) at fan outlet velocity (feet per minute).

Fig. 3. Fan price. (From ref. 30.)

For high-horsepower requirements,

$$P_{\text{motor}} = 94.7\ \text{hp}^{0.821} \tag{15}$$

where P_{motor} is the cost of the fan motor, belt, and starter (February 1988 $) and hp is the motor horsepower ($7.5 \leq \text{hp} \leq 250$). More, but different, fan purchase cost data are provided in refs. 26 and 30.

The fan purchase cost (*see* Fig. 3) is a function of the flow rate moved by the fan and the pressure drop (ΔP) across the control system. The fan is assumed to be located downstream of the final control device in the control system. Therefore, the fan capacity must be based on the final control device's exit gas flow rate at actual conditions ($Q_{fg,a}$). The control system pressure drop (ΔP) is the total of the pressure drops across the various control system equipment, including the stack and ductwork. Table 5 presents conservative pressure drops across specific control system components that can be used if specific data are unavailable.

Using the actual flow rate and total parameters, we can obtain the fan purchase cost from Fig. 3. Fans are categorized into classes I to IV according to control system pressure drop. Guidelines are presented in Fig. 3 for determining which class of fan to use. There is some overlap between the classes. The lower-class fan is generally selected because of cost savings. To estimate the cost of a motor for the fan, multiply the fan cost by 15%. (*Note*: The fan and motor costs are included in the cost curves for thermal incinerators and packaged carbon adsorbers.)

3.5. Ductwork Purchase Cost

The cost of ductwork for a HAP control system is typically a function of material (e.g., PVC, FRP), diameter, and length. To obtain the duct diameter requirement as a function of the emission stream flow rate at actual condition ($Q_{e,a}$) use Eq. (16), which assumes a duct velocity (U_{duct}) of 2000 ft/min:

$$d_{\text{duct}} = 12\left[(4/\pi)\left(Q_{e,a}/U_{\text{duct}}\right)\right]^{0.5} = 0.3028Q_{e,a}^{0.5} \tag{16}$$

The cost of PVC ductwork (in $/ft) for diameters between 6 in. and 24 in. is obtained using

$$P_{\text{PVCD}} = a_d\left(d_{\text{duct}}\right)^{b_d} \tag{17}$$

where P_{PVCD} is the cost of PVC ductwork, ($/ft [August 1988 $]), d_{duct} is the duct diameter (in. [factor of 12 in./ft above]), a_d=0.877 (6 in. $\leq d_{\text{duct}} \leq$ 12 in.) or 0.0745 (14 in. $\leq d_{\text{duct}}$ $\leq$ 24 in.), and b_d = 1.05 (6 in. $\leq d_{\text{duct}} \leq$ 12 in.) or 1.98 (14 in. $\leq d_{\text{duct}} \leq$ 24 in.).

For FRP duct having a diameter between 2 and 5 ft, the following equation can be used to obtain the ductwork cost:

$$P_{\text{FRPD}} = 24D_{\text{duct}} \tag{18}$$

where P_{FRPD} is the cost of FRP ductwork ($/ft [August 1988 $]) and D_{duct} is the duct diameter (ft). Note that the duct diameter is in units of feet for this equation.

It is more difficult to obtain ductwork costs for carbon steel and stainless-steel construction because ductwork using these materials are almost always custom fabricated. For more information on these costs, consult other sources (1,3).

The ductwork purchase cost is typically proportional to the ductwork weight, which is a function of (1) the material of construction, (2) length, (3) diameter, and (4) thickness. Carbon steel ducts are normally used for noncorrosive flue gases at temperatures below 1150ºF. Stainless-steel ducts are generally used with gas temperatures between 1150ºF and 1500ºF or if the gas stream contains corrosive materials. Figures 4 and 5 present purchase costs for carbon steel and stainless-steel ducts, respectively. It is assumed that the major portion of ductwork is utilized to transport the emission stream from the process to the control system; therefore, the flow rate, $Q_{e,a}$, of the emission stream at actual conditions is used to size the ductwork.

3.6. Stack Purchase Cost

It is difficult to obtain stack cost correlations because stacks are usually custom fabricated. Smaller stacks are typically sections of straight ductwork with supports. However, the cost of small (e.g., 50–100 ft) FRP stacks can be roughly estimated as 150% of the cost of FRP ductwork for the same diameter and length. Similarly, the cost of small carbon steel and stainless-steel stacks is also approx 150% of the cost of corresponding ductwork (1,3).

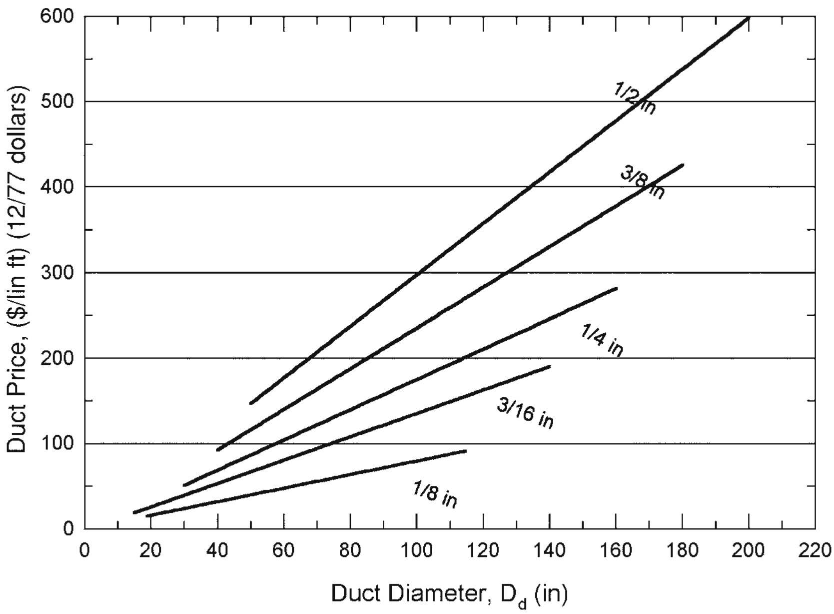


Fig. 4. Carbon steel straight-duct fabrication price at various thicknesses. (From ref. 30.)

For larger stacks (200–600 ft), the cost is typically quite high, ranging from \$1,000,000 to \$5,000,000 for some applications. Equation (19) and Table 11 can be used to obtain costs of large stacks:

$$P_{\text{stack}} = aH_{\text{stack}}^{b} \tag{19}$$

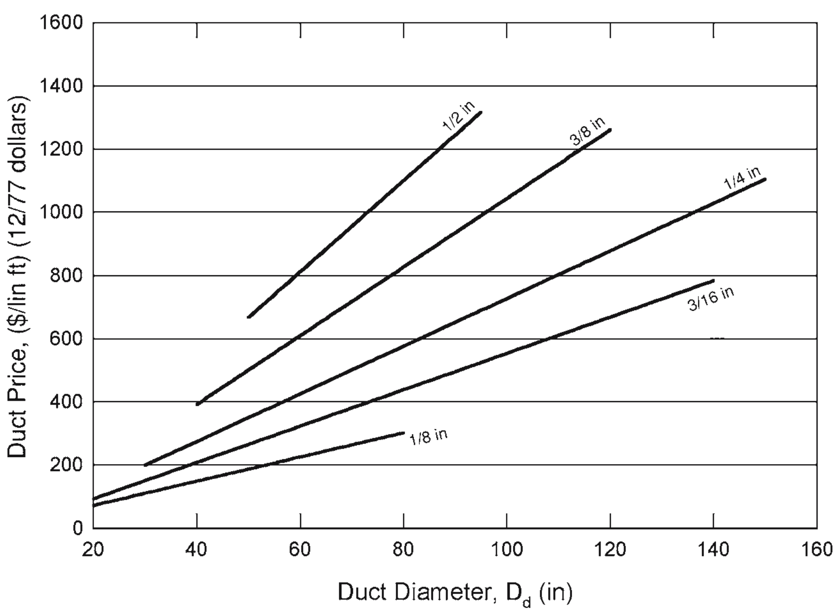


Fig. 5. Stainless-steel straight-duct fabrication price at various thicknesses. (From ref. 30.)

Table 11
Parameters for Costs of Large Stacks

Lining	Diameter (ft)	*a*	*b*
Carbon steel	15	0.0120	0.811
316L Stainless steel	20	0.0108	0.851
Steel in top	30	0.0114	0.882
Section	40	0.0137	0.885
Acid resistant	15	0.00601	0.952
Firebrick	20	0.00562	0.984
	30	0.00551	1.027
	40	0.00633	1.036

Source: ref. 1.

where P_{stack} is the total capital cost of large stack(10^6 \$), H_{stack} is the stack height (ft), and *a* and *b* are coefficients. (*see* Table 11).

The stack purchase cost is a function of: (1) the material of construction, (2) stack height, (3) stack diameter, and (4) stack thickness. In addition, minimum stack exit velocities should be at least 1.5 times the expected wind velocity; for instance, in the case of 30-mph winds, the minimum exit velocity should be at least 4000 ft/min. For purposes of this handbook, the stack cost is estimated with respect to the final control device's exit gas flow rate at actual conditions. Figures 6 and 7 present purchased costs for unlined, carbon steel stacks.

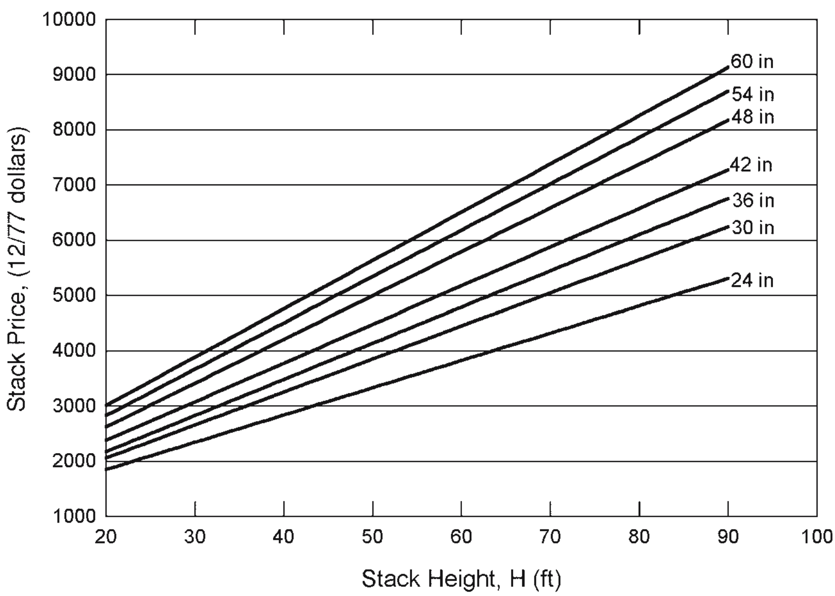


Fig. 6. Carbon steel stack fabrication price for a 0.25-in. plate. (From ref. 30.)

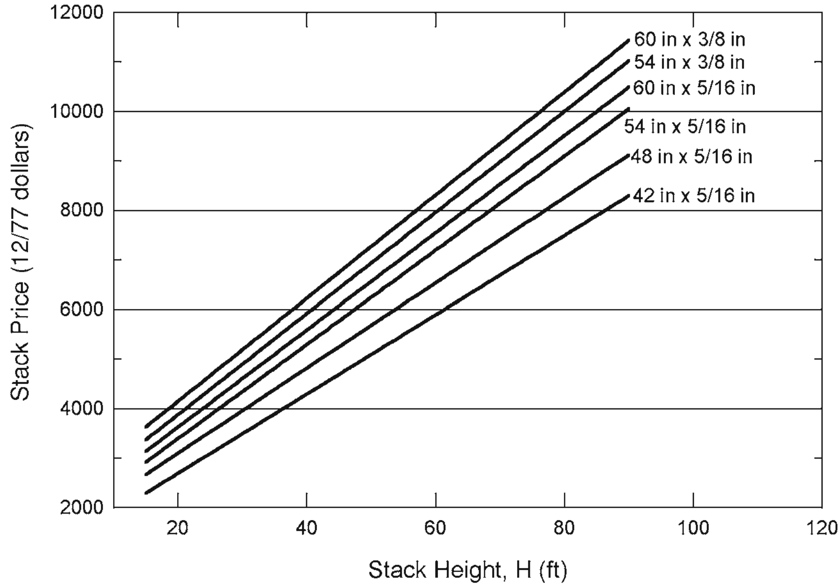


Fig. 7. Carbon steel stack fabrication price for 5/16-in. and 3/8-in. plates. (From ref. 30.)

Without specific information, assume the following items to simplify the costing procedures:

1. The stack is constructed with 0.25-in.-thick carbon steel plate.
2. The stack height equals 50 ft.
3. The stack diameter is calculated using a stack exit velocity of 4000 ft/min. Therefore,

$$D_{\text{stack}} = 12\left(\frac{4}{\pi} \times \frac{Q_{fg,a}}{U_{\text{stack}}}\right)^{0.5} = 0.2141\left(Q_{fg,a}\right)^{0.5} \tag{20}$$

where D_{stack} is the stack diameter (in.), $Q_{fg,a}$ is the flue gas flow rate at actual conditions, (acfm), and U_{stack} is the velocity of the gas stream in the stack (ft/min).

3.7. Damper Purchase Cost

Dampers are commonly used to divert airflow in many industrial systems. Two types of damper are discussed: backflow and two-way diverter valve dampers. The cost of backflow dampers for duct diameters between 10 and 36 in. is given by

$$P_{\text{damp}} = 7.46 d_{\text{duct}}^{0.944} \tag{21}$$

where P_{damp} is the cost of the damper (February 1988 \$) and d_{duct} is the ductwork diameter (in.).

The cost of a two-way diverter valve for ductwork diameters between 13 and 40 in. are given by:

$$P_{\text{divert}} = 4.84 d_{\text{duct}}^{1.50} \tag{22}$$

where P_{divert} is the cost of the two-way diverter valve (February 1988 \$) and d_{duct} is the ductwork diameter (in.).

4. ENERGY AND COST CONSIDERATIONS FOR MAJOR POINT SOURCE CONTROLS

4.1. Introduction

The auxiliary APCDs discussed in Section 3 include cyclones, gas precoolers, gas preheaters, fans, ductworks, stack, dampers, and hoods, which are required pretreatment and collection means for almost all point source air pollution control projects. This section provides generalized evaluation procedures for a given major add-on HAP control system, which can be one or a combination of the following: (1) thermal incinerator, (2) heat exchanger, (3) catalytic incinerator, (4) carbon adsorber, (5) absorber (scrubber), (6) condenser, (7) fabric filter, (8) electrostatic precipitator, or (9) Venturi scrubber.

The auxiliary APCDs will always be needed for point source air emission controls. Usually, only one or two major APCDs will be the add-on HAP control units.

4.2. Sizing and Selection of Major Add-on Air Pollution Control Devices

Selection of one or more major add-on APCDs for a specific air emission control project will be decided based on both the technical feasibility and the economical feasibility of using the intended APCDs. The readers are referred to other related chapters for a specific major APCD and Tables 1 and 2 for their technical evaluation and comparison.

4.3. Purchased Equipment Costs of Major Add-on Air Pollution Control Devices

This subsection provides generalized procedures for estimating capital and annualized costs for a given add-on HAP control system. (*Note*: The calculation of the cost of HAP waste disposal is outside the scope of this handbook; however, this cost must be included in any rigorous control cost estimation.) The procedures are presented in a step-by-step format and illustrated at each step with cost calculations.

The major equipment purchased cost (i.e., the cost of the major components that comprise the control system) is related to a specific equipment design parameter and can be expressed either analytically or graphically. Gathering current costs from vendors was beyond the scope of this project and necessitates use of dated cost data compiled by others. In general, the cost estimates may be escalated using the *Chemical Engineering* Fabricated Equipment cost indices (36), partially reported in Table 12.

If more recent cost data are available, they should be substituted for the cost curve data presented. These cost curves should not be extrapolated beyond their range. The cost data presented in these figures were obtained from cost information published in US EPA reports. Using the specific value for the design variable, obtain purchased costs form the specific cost curve for each major control system component. Presented in the following subsections are brief descriptions of the equipment costs included in each HAP control cost curve.

4.3.1. Thermal Incinerator Purchase Costs

The cost curve for thermal incinerators (*see* Fig. 8) includes the fan plus instrumentation and control costs, in addition to the major equipment purchase cost. The heat-exchanger cost and other auxiliary equipment cost (*see* Section 3) should also be included. More thermal incinerator costs for comparison with bio-oxidation costs are reported by Boswell (17).

Table 12
Chemical Engineering Equipment Index

Date	Index	Date	Index	Date	Index
Feb. 1990	389.0	May 1988	369.5	Aug. 1986	334.6
Jan. 1990	388.8	Apr. 1988	369.4	July 1986	334.6
Dec. 1989	390.9	Mar. 1988	364.0	June 1986	333.4
Nov. 1989	391.8	Feb. 1988	363.7	May 1986	334.2
Oct. 1989	392.6	Jan. 1988	362.8	Apr. 1986	334.4
Sept. 1989	392.1	Dec. 1987	357.2	Mar. 1986	336.9
Aug. 1989	392.4	Nov. 1987	353.8	Feb. 1986	338.1
July 1989	392.8	Oct. 1987	352.2	Jan. 1986	345.3
June 1989	392.4	Sept. 1987	343.8	Dec. 1985	348.1
May 1989	391.9	Aug. 1987	344.7	Nov. 1985	347.5
Apr. 1989	391.0	July 1987	343.9	Oct. 1985	347.5
Mar. 1989	390.7	June 1987	340.4	Sept. 1985	347.2
Feb. 1989	387.7	May 1987	340.0	Aug. 1985	346.7
Jan. 1989	386.0	Apr. 1987	338.3	July 1985	347.2
Dec. 1988	383.2	Mar. 1987	337.9	June 1985	347.0
Nov. 1988	380.7	Feb. 1987	336.9	May 1985	347.6
Oct. 1988	379.6	Jan. 1987	336.0	Apr. 1985	347.6
Sept. 1988	379.5	Dec. 1986	335.7	Mar. 1985	346.9
Aug. 1988	376.3	Nov. 1986	335.6	Feb. 1985	346.8
July 1988	374.2	Oct. 1986	335.8	Jan. 1985	346.5
June 1988	371.6	Sept. 1986	336.6	Dec. 1984	346.0

[a](2, 30)

Note: CE Equipment Index = 437.4 in April 2000; CE Equipment Index = 273.7 in December 1979; CE Equipment Index = 226.2 in December 1977.

Source: refs. 2 and 36.

4.3.2. Heat-Exchanger Purchase Costs

If the HAP control system includes a heat exchanger, the cost (*see* Fig. 9) is part of the major equipment purchase cost and, thus, must be added. The remaining auxiliary equipment (ductwork and stack) purchase costs and costs of freight and taxes must be added to obtain the total purchased cost.

4.3.3. Catalytic Incinerator Purchase

The cost curve for catalytic incinerators (*see* Fig. 10) provides the cost of an incinerator less catalyst. Catalyst costs [$2750 per cubic foot in June 1985 (26)] and the cost of a heat exchanger, if applicable (*see* Fig. 9), must be added to obtain the major equipment purchase cost. All auxiliary equipment (ductwork, fan, and stack) purchase costs, the cost of instrumentation and controls, and freight and taxes must be added to obtain the total purchase cost. Boswell reported catalytic incinerator's costs in comparison with bio-oxidation costs (17).

4.3.4. Carbon Adsorber Purchase Costs

Two cost curves are presented for carbon adsorbers: Fig. 11 for packed carbon adsorbers and Fig. 12 for custom carbon adsorbers. The cost curve for packaged carbon

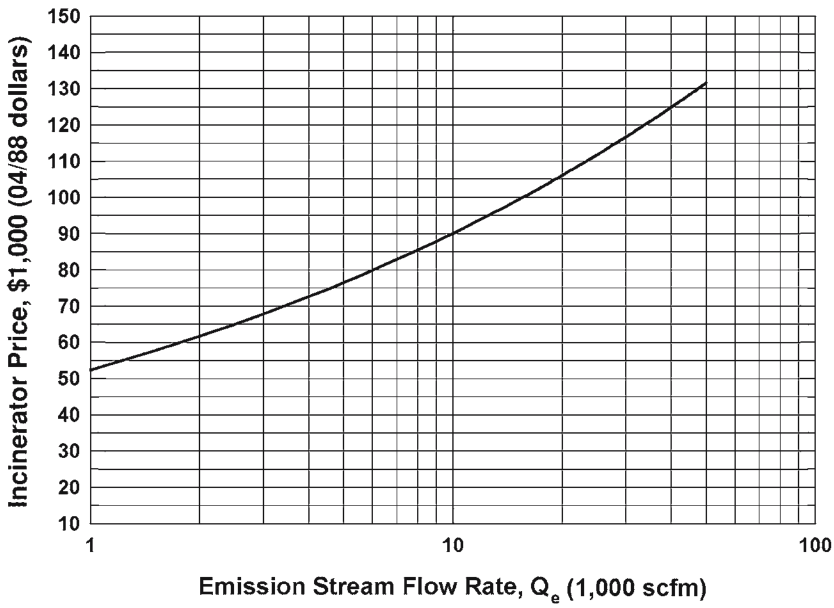


Fig. 8. Price for thermal incinerators, including fan and motor, and instrumentation and controls costs. (From ref. 34.)

adsorbers includes the fan plus instrumentation and control costs, in addition to the major equipment purchase cost. The cost of the remaining auxiliary equipment (ductwork, and stack) as well as costs of freight and taxes must be added to obtain the total purchase cost. The cost curve for custom carbon adsorbers does not include the cost of

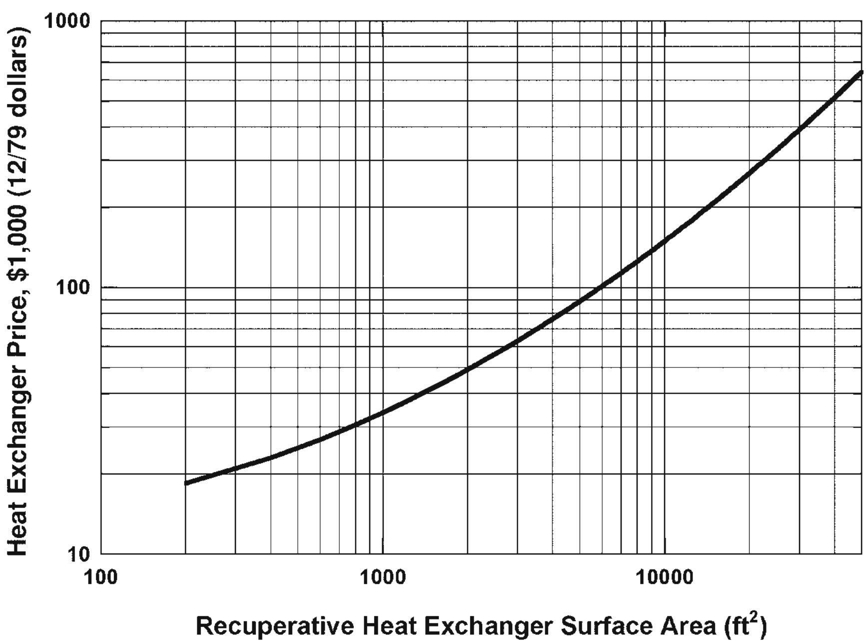


Fig. 9. Price for thermal oxidation recuperative heat exchangers. (From ref. 30.)

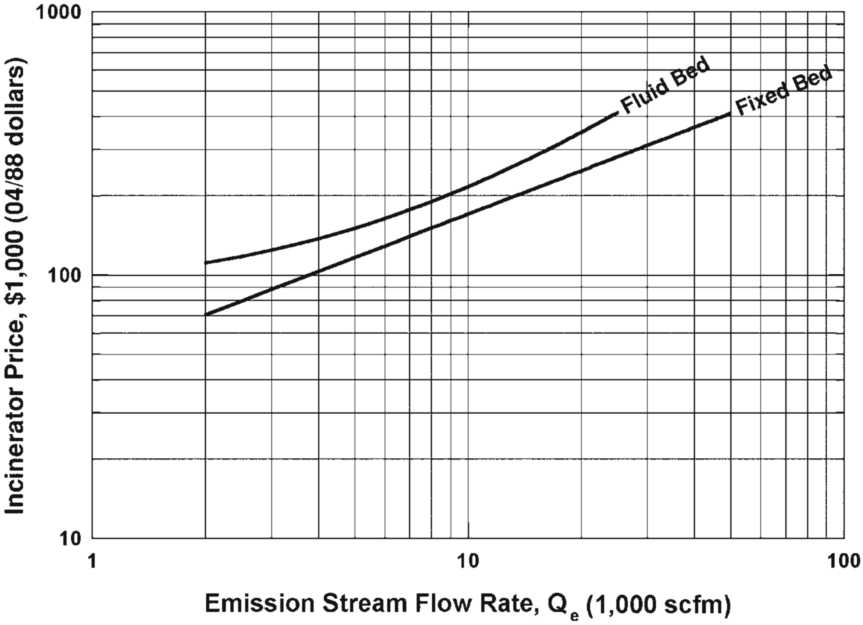


Fig. 10. Price for catalytic incinerators, less catalyst. (From ref. 34.)

carbon (part of the major equipment purchased cost), however, it does include the cost of instrumentation and controls. The cost of carbon is $1.80 to $2.00 per pound in 1991 (26). All auxiliary equipment (ductwork, fan, and stack) purchase costs and freight and taxes must be added to obtain the total purchase cost.

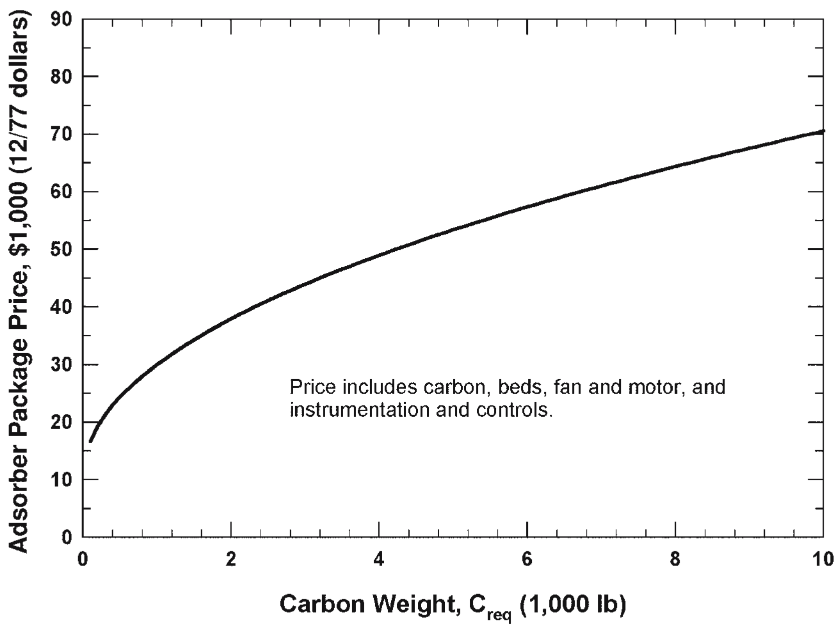


Fig. 11. Price for carbon adsorber packages. (From ref. 32.)

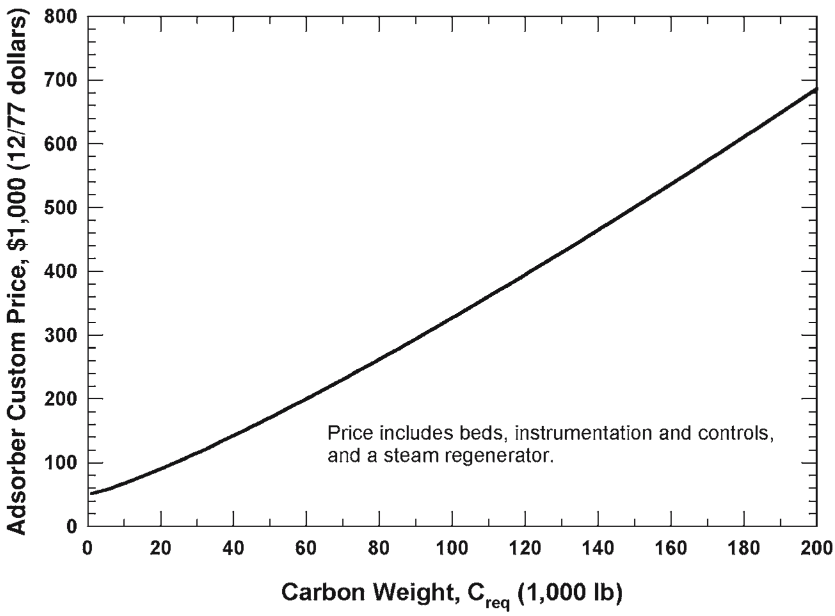


Fig. 12. Price for custom carbon adsorbers, less carbon. (From refs. 28 and 32.)

4.3.5. Absorber Purchase Costs

The cost curve for absorbers (*see* Fig. 13) does not include the cost of packing, platforms, and ladders. The cost of platform and ladders (*see* Fig. 14) and packing (*see* Table 13) must be added to obtain the major equipment purchase cost. All auxiliary equipment (ductwork, fan, and stack) purchase costs, the cost of instrumentation and controls, and freight and taxes must be added to obtain the total purchase cost.

4.3.6. Condenser Purchase Costs

The cost curve for condensers (*see* Fig. 15) yields the total capital cost for cold-water condenser systems. For systems needing a refrigerant (ethylene glycol), the applicable cost from Fig. 16 must be added to the cost obtained Fig. 15. Because a total capital cost is determined, no additional cost estimates are necessary; therefore, proceed to Section 6 to calculate annualized operating costs. The cost of a refrigerant (ethylene glycol) is estimated to be $0.31 per pound for June 1985 (30).

4.3.7. Fabric Filter Purchase Costs

The cost curve for a negative pressure fabric filter (*see* Fig. 17) does not include the cost of bags (*see* Table 14), which depend on the type of fabric used. This cost must be added to obtain the major equipment purchase cost. All auxiliary equipment (ductwork, fan, and stack) purchase costs, the cost of instrumentation and controls, and freight and taxes must be added to obtain the total purchase cost.

4.3.8. Electrostatic Precipitator Purchase Costs

The cost curve presented in Fig. 18 provides the major equipment purchase cost for an insulated electrostatic precipitator. All auxiliary equipment (ductwork, fan, and

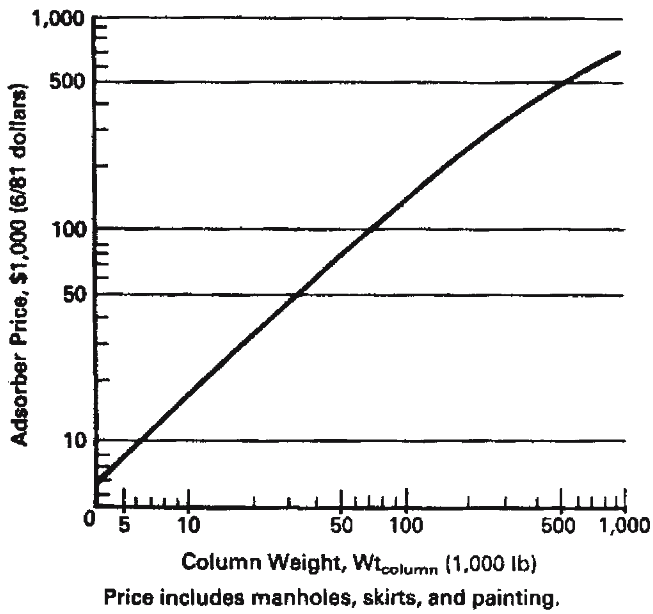


Fig. 13. Prices for adsorber column. (From ref. 1, 9, 36.)

stack) purchase cost, the cost of instrumentation and controls, and freight and taxes must be added to obtain total purchase cost.

4.3.9. Venturi Scrubber Purchase Costs

The cost curve for Venturi scrubbers (*see* Fig. 19) includes the cost of instrumentation and controls, in addition to the major equipment purchase cost. This cost curve

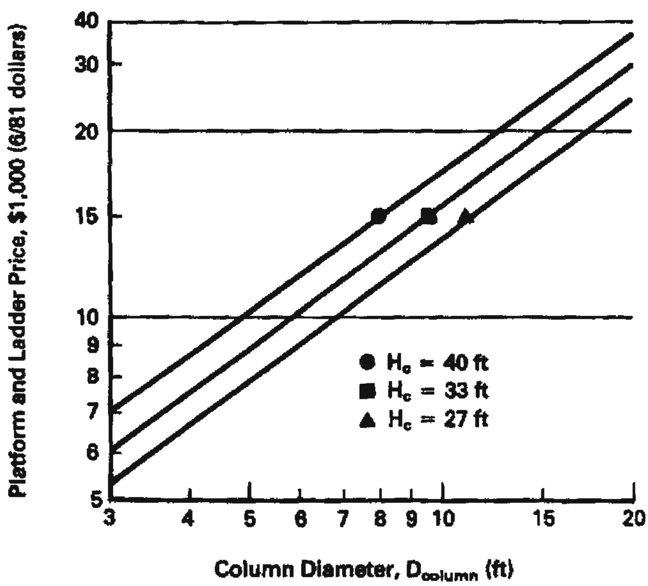


Fig. 14. Prices for adsorber platform and ladders. (From ref. 1, 9, 36.)

Table 13
Price of Packing for Absorber System

Packing Type and Material	Cost/ft^2 (6/81 dollars)			
Packing diameter (in.)	1	1.5	2	3
Pall rings				
Carbon steel	24.3	16.5	15.1	—
Stainless steel	92.1	70.3	0.8	—
Polypropylene	21.9	14.8	13.8	—
Berl saddles				
Stoneware	28.1	21.7	—	—
Porcelain	34.5	25.6	—	—
Intalox saddles				
Polypropylene	21.9	—	13.6	7.0
Porcelain	19.4	14.8	13.3	12.2
Stoneware	18.2	13.3	12.2	11.0
Packing rings				
Carbon steel	30.3	19.8	17.0	13.9
Porcelain	13.2	10.6	9.7	8.1
Stainless steel	109.0	82.6	22.9	—

Source: ref. 26.

is based on a Venturi scrubber constructed from 1/8-in. carbon steel. Figure 20 is used to determine if 1/8-in. steel is appropriate for a given application (use the high curve). If thicker steel is required, Fig. 21 presents a price adjustment factor for various steel thickness; this factor is used to escalate the cost obtained from Fig. 19. In addition,

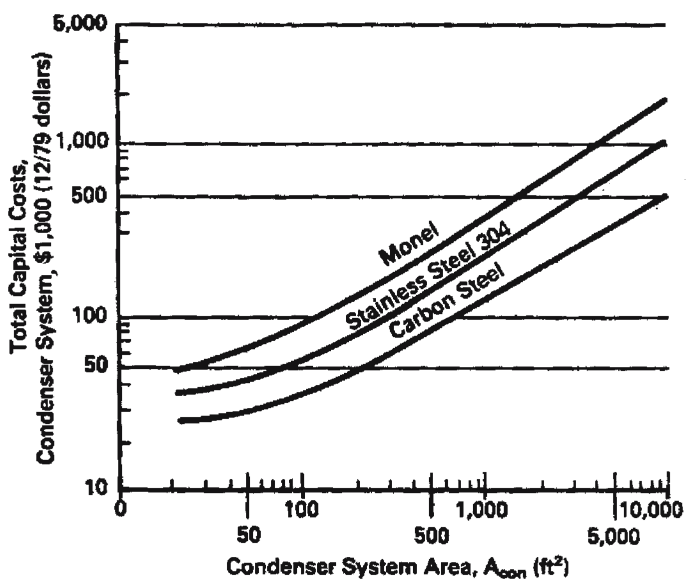


Fig. 15. Total capital costs for cold water condenser systems. (From ref. 37.)

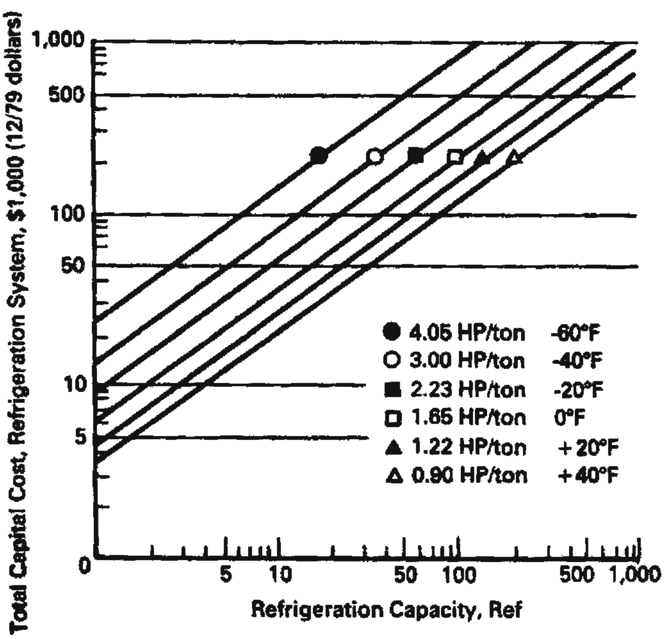


Fig. 16. Additional capital costs for refrigerant condenser systems. (From ref. 37.)

if stainless steel is required, multiply the scrubber cost estimate by 2.3 for 304L stainless steel or by 3.2 for 316L stainless steel. Costs of all auxiliary equipment (ductwork, fan, and stack) and freight and taxes must be added to obtain the total purchased cost.

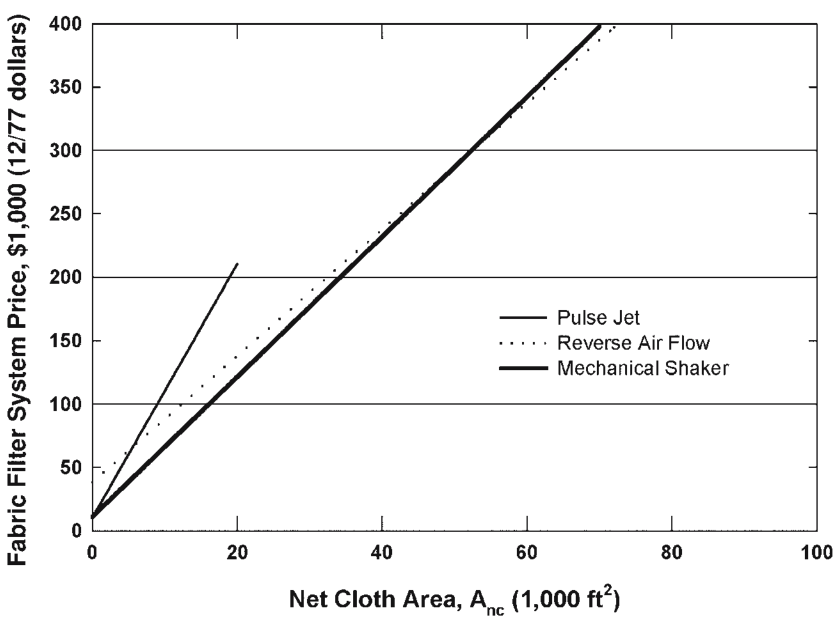


Fig. 17. Price for negative-pressure, insulated fabric-filter system, less bags. (From ref. 30.)

Table 14
Bag Prices

Class	Type	12/77 Dollars/gross ft^2						
		Dacron	Orlon	Nylon	Nomex	Glass	Polypropylene	Cotton
Standard	Mechanical shaker <20,000 ft^2	0.40	0.65	0.75	1.15	0.50	0.65	0.45
Standard	Mechanical shaker >20,000 ft^2	0.35	0.50	0.70	1.05	0.45	0.55	0.40
Standard	Pulse jet[a]	0.60	0.95	—	1.30	—	0.70	—
Custom	Mechanical shaker	0.25	0.35	0.45	0.65	0.30	0.35	0.40
Custom	Reverse air	0.25	0.35	0.45	0.65	0.30	0.35	0.40

[a]For heavy felt, multiply source by 1.5.
Source: Data from refs. 26 and 30.

5. ENERGY AND COST CONSIDERATIONS FOR AREA SOURCE CONTROLS

5.1. Introduction

Energy and cost information about various control technologies used to control emissions from area sources is presented in this section. The control technologies generally are applicable to the control of all classes of air contaminants, including VOCs, SVOCs, PM, and metals associated with PM. The specific control technologies addressed in this section are covers and physical barriers, foams, wind barriers, water sprays, water sprays with additives, operational controls, enclosures, collection hoods, and miscellaneous controls.

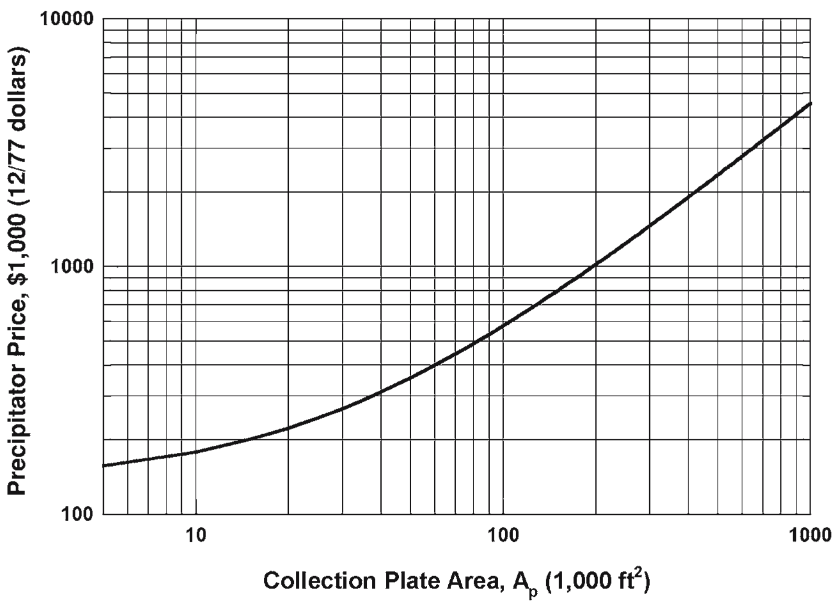


Fig. 18. Price for insulated electrostatic precipitators. (From ref. 30.)

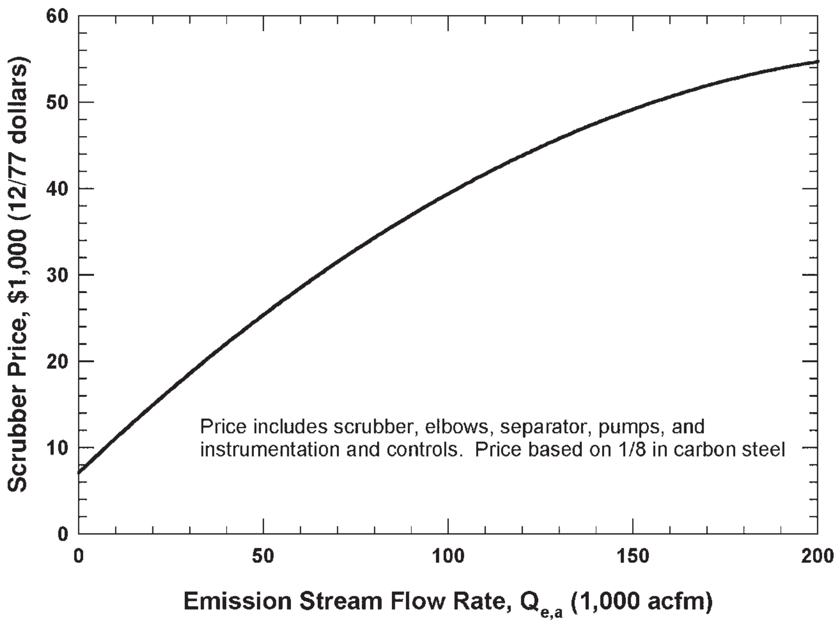


Fig. 19. Price for venturi scrubbers (From ref. 30.).

Emissions from area sources are more difficult to measure, model, and control than emission from point sources. The sources may be several acres in size and the concentration of emissions in the source/atmospheric boundary layer is generally very low. Therefore, the types of control suitable for point sources are not applicable to area sources. Two general control approaches exist for area sources: (1) collect the emissions in a hood or enclosure and route the airstream to a point source control device and (2) prevent the emissions from occurring. The first approach is merely a conversion of the area source to a point source and is the most suitable for batch or in situ remediation processes such as solidification/stabilization and bioremediation. The second approach is primarily suited for materials handling operations such as excavation.

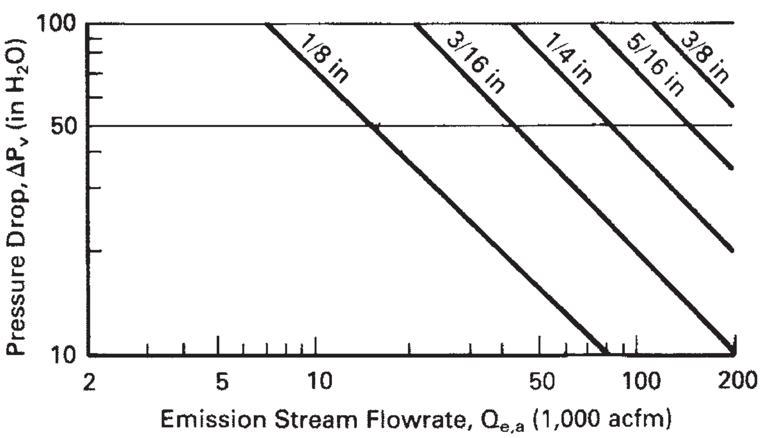


Fig. 20. Required steel thicknesses for Venturi scrubbers. (Data from refs. 26 and 30.)

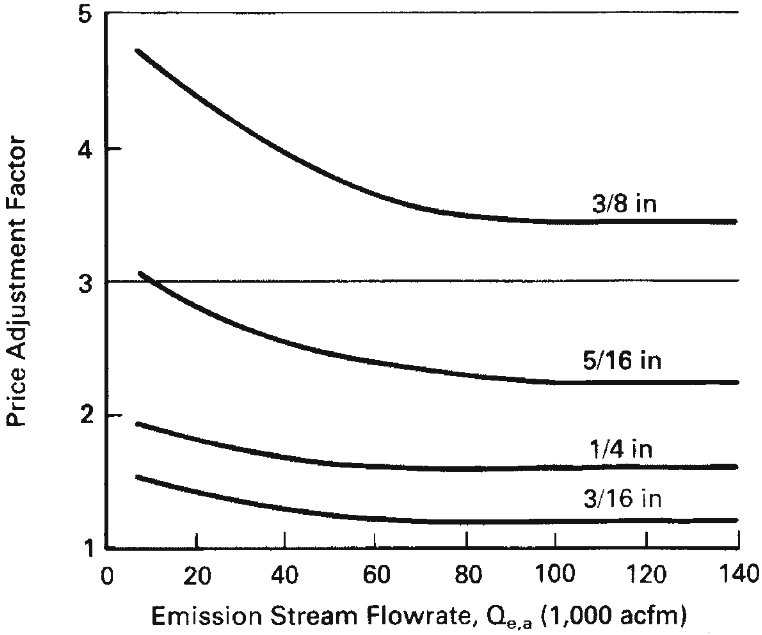


Fig. 21. Price adjustment factors for Venturi scrubbers. (Data from refs. 26 and 30.)

5.2. *Cover Cost*

The amount (depth, thickness, etc.) of cover material required to achieve a given control efficiency is not well defined in the literature. However, there are general sizing guidelines reported in the literature. Cost estimates of implementing cover-based VOC/PM control measures are presented in Table 15. Caution should be exercised when using these cost estimates because costs are highly dependent on the site characteristics, labor costs, weather conditions, and the availability of specific cover materials at each site.

Table 15
Cost (1992 $) of Implementing Cover-Based Area Control Measures

Cover material	Equipment[a]	Labor/materials
Backfill dirt	2.0 m^3	15/m^3
Clay	1.0 m^3	15/m^3
Road base, road carpet, and gravel[b]	3–6 m	4–10/m
Asphalt, road base[c]	6–12/m	200–300/m
Wood fibers with plastic[d]	0.5/m^2	0.5/m^2
Polymer sheeting	1.0/m^2	1.0/m^2

[a]Assumes material not already on site.
[b]7.5 m wide and 0.15 m gravel.
[c]7.5 m wide and 0.10 m asphalt.
[d]Wood fiber depth not stated.
Source: Data from refs. 6 and 14.

Table 16
Foam Costs

Foam	Brand name	Cost ($/m^3)
Temporary	FX9162	1.10
	AC6545	0.54–0.86
Long term	FX 9162/9161	3.80
	AC904	1.30–1.94
	AC912	1.94–2.70
	AC918	2.70–3.77
	AC930	3.77–5.28

Source: Data from refs. 12–15.

5.3. Foam Cost

Costs for various foam types are given in Table 16. These costs are a function of the area to be treated at the application depths recommended by the manufacturer. Costs for foam application units range from $8000 to $12,000 per month for manifold application units (including bulk storage tanks) and $3250 to $7750 for hand-line application units. Small 3M application units can be rented for about $660 per week; about $500 of ancillary equipment is also required (1992 dollars).

5.4. Wind Screen Cost

Capital costs for wind screens vary with the type of control desired (VOC or PM) and the operation requiring control (e.g., inactive sites, excavation, etc.). Costs as a function of pollutant to be controlled and operation requiring control are outlined in Table 17.

5.5. Water Spray Cost

For mobile water spray systems, capital costs are estimated to be $23,000/water wagon per year, with operating and maintenance (O&M) costs (fuel, water, labor, and truck maintenance) estimated to be $44,000/water wagon per year. Furthermore, the number of water wagons required can be estimated by assuming that a single truck applying 1 L/m^2 can treat roughly 1 mile^2/h, (approx 11,000 m^2). Capital and O&M costs for fixed water systems will vary with the type of emission source to be controlled (e.g., "truck-out," excavation, loading operations) and the amount of plumbing required.

Table 17
Wind Screen System Costs

Type of pollutant	Control	Cost
VOC	Inactive surface impoundment	$0.7–1.4/m^2 impoundment area
Particulate matter	Inactive sites[a]	$0.6–13/m^2 of inactive area
	Storage piles[b]	$721/m^2 of pile area
	Excavation[c]	$11/m^2 of excavation area

[a]Minimum price assumes chain link fence is available to secure wind screen (valid for small areas). Cost per linear meter for wind screen is about $40, not including support structure.

[b]Assumes conical-shaped storage pile roughly 10 m in diameter.

[c]Assumes 60-m-diameter excavation site and 1.8-m-high wind screen around two-thirds of site.

Source: ref. 8.

5.6. Water Additives Costs

Water additives costs include the costs associated with water spray systems and also include the cost of additives and storage tanks for the additives. Storage tank costs will vary depending on the size of the operation, the water/additive application rate, and the time between deliveries of additive. The dilution ratio, application rate, and frequency must be determined to predict the cost per square foot. Some additive costs by product name and classification are as follows:

1. Hygroscopic salt = \$0.02–0.10/ft^2
2. Bitumens/adhesives = \$0.15–0.32/ft^2
3. Surfactant = \$0.002/ft^2

5.7. Enclosure Costs

Enclosures range in size from 30 ft in diameter to 130 ft wide × 62 ft tall × unlimited length. For self-supported structures wider than 60 ft, footings may be required. Prior to erecting an enclosure, the site may require grading so that the slope is less than 3%. The costs of air-supported and self-supported enclosures are as follows:

1. Air-supported enclosure = \$5.5/m^2-month rent + unknown O&M
2. Self-supported enclosure = \$19/m^2-month rent + \$48/m^2 O&M

The costs presented do not include the costs of gas collection/treatment systems.

5.8. Hood Costs

Hood exhaust systems designs are based on the hood aspect ratio (width/length of hood), the required capture velocity (v), and the distance of the furthest point of the emitting source from the hood centerline (x).

The costs of hood exhaust systems are highly dependent on the volumetric flow rate, the length of ducting required, the hood/ducting materials of construction required (e.g., carbon steel, stainless steel), hood size, and fan size required to move the air. An example of a hood exhaust system cost breakdown is presented in Table 18.

5.9. Operational Control Costs

For a target control efficiency, the operational practices/procedures required can generally be determined. Operational practices/procedures that are amenable to this approach are as follows:

1. Road cleaning practices
2. Seasonal scheduling
3. Vehicle speed control
4. Excavation practices
5. Dumping practices

Quantification of PM emission controls achievable for soil loading practices and storage pile geometry/orientation is not possible. However, guidelines are available for each of these operational control measures.

For the majority of the operational control measures presented in this section, the cost is negligible, with the exception of road cleaning equipment and possibly seasonal scheduling. The cost of seasonal scheduling will vary with season primarily because of

Table 18
Hood Exhaust System Cost Estimate

Equipment	Applicable dimensions	Cost
Canopy hood	3/16-in.-thick carbon steel, 10 ft in diameter	\$2400
Ductwork	100 ft of 1-ft-diameter, 16-gage carbon steel straight duct	\$1300
	Four 1-ft diameter, 16-gage carbon steel 90º elbows.	\$1750
Radial-tip fan	Moves 11,000 acfm at 10 in. H_2O with a 45.5-in. wheel diameter.	\$7700
	Total cost:	\$13,150

Source: ref. 8.

labor costs and equipment availability. Cost for street cleaning practices are estimated to be \$140 per day per street cleaner and \$66 per day per crew. The use of larger excavation equipment to minimize emissions will increase costs to some extent.

6. CAPITAL COSTS IN CURRENT DOLLARS

In this handbook, the total capital cost includes only manufacturing area costs; therefore, it excludes offsite costs. The total capital cost of a control system is the sum of direct costs, indirect costs, and contingency costs.

Direct costs include the total purchase equipment cost (i.e., the major equipment purchase cost plus the auxiliary equipment purchase cost), instrumentation and controls, freight and taxes, and installation costs (i.e., foundation and supports, erection and handling, electrical, piping, insulation, and painting). (*Note*: The summation of the total purchased equipment cost, the cost of instrumentation and controls, and freight and taxes is defined as the total purchase cost.)

Indirect costs consist of in-house engineering design and supervision costs, architect and engineering contractor expenses, and preliminary testing costs. An example of contingency costs is the penalties incurred for failure to meet completion dates or performance specifications.

The capital cost estimation procedure presented in this handbook is for a factored or "study" estimate. Usual reliability for a study type estimate is ±30%. To determine the total capital cost by a factored cost estimate, a reliable estimate of the total purchase cost is calculated and predetermined factors are applied to determine all other capital cost elements.

The procedure to estimate the total capital cost is as follows: (1) Obtain the total purchased equipment cost by estimating the purchased cost of major and auxiliary equipment; (2) estimate the cost of instrumentation and controls plus freight and taxes as a percentage of the total purchased equipment cost; (3) estimate the total purchase cost by adding items 1and 2; and (4) estimate total capital cost by applying a predetermined cost factor to the total purchase cost.

Table 19 shows how the capital cost in current dollars can be estimated for an intended APCD system. Table 20 presents the capital cost elements and factors (26). The following are the footnotes to Table 19.

Table 19
Estimate of Capital Costs in Current Dollars

Cost elements	Figure of table cost	Escalation factor (current FE/base FE) (*see* Table 12)	Current cost
1. Major equipment purchase cost			
Thermal Incinerator[a]	$ ________×	(______/______)	=$ ______
Heat Exchanger[b]	$ ________×	(______/______)	=$ ______
Catalytic incinerator[c]	$ ________×	(______/______)	=$ ______
Catalyst,[c] V_{cat} = ____ft^3	×________$/$ft^3$	(______/______)	=$ ______
Carbon adsorber[d]	$ ________×	(______/______)	=$ ______
Carbon,[d] C_{req} = ____lb	× ________$/lb	(______/______)	=$ ______
Absorber[e]	$ ________×	(______/______)	=$ ______
Platforms and ladders[e]	$ ________×	(______/______)	=$ ______
Packing,[e] V_{pack}=____ft^3	×________$/$ft^3$	(______/______)	=$ ______
Condenser[f]	$ ________×	(______/______)	=$ ______
Refrigerant[f]	$ ________×	(______/______)	=$ ______
Fabric filter[g]	$ ________×	(______/______)	=$ ______
Bags,[g] A_{tc} = ____ft^2	×________$/$ft^2$	(______/______)	=$ ______
ESP[h]	$ ________×	(______/______)	=$ ______
Venturi scrubber[i]	$ ________×	(______/______)	=$ ______
Design factors[i]	________× (Thickness Factor)	(Composition Factor)	=$ ______
		Subtotal	=$ ______
2. Auxiliary equipment purchase cost			
Ductwork[j]	$ ____×____× (Length)	(____/____)	=$______
Fan[k]	$ ________×	(____/____)	=$ ______
Motor[l]	$ ________× (Fan Current Cost)	0.15	=$ ______
Stack[m]	$ ________×	(____/____)	=$ ______
		Subtotal	=$ ______
3. Pretotal purchase equipment cost	Item 1 Subtotal + Item 2 Subtotal		$ ______
Adjustments[n]	(Item 3)×(–0.091)		$ ______
4. TOTAL purchase equipment cost	Item 3 + Adjustments		$ ______
5. Instrumentation and controls	10% of Item 4		$ ______
6. Freight and taxes	8% of Item 4		$ ______
7. TOTAL Purchase Cost	Item 4 + Item 5 + Item 6		$ ______
8. TOTAL CAPITAL COSTS	F^o×(Item 7), where F=		$ ______

Source: ref. 26.

(a) Thermal incinerator: Figure 8 includes fan plus instrumentation and control costs for thermal incinerators, in addition to the major equipment purchase cost. Additional auxiliary equipment (ductwork and stack) purchase costs and costs of freight and taxes must be added to obtain the total purchase cost.
(b) Heat exchangers: If the HAP control system requires a heat exchanger, obtain the cost from Fig. 9, escalate this cost using the appropriate factor, and add to the major equipment purchase cost.
(c) Catalytic incinerator: Figure 10 provides the cost of a catalytic incinerator, less catalyst costs. The "table" catalyst cost is estimated by multiplying the volume of catalyst required (V_{cat}) by the catalyst cost factor ($/ft^3) found in the literature. Catalyst costs, all auxiliary

Table 20
Capital Cost Elements and Factors[a]

Cost Elements	Control technique						
	ESP	Venturi scrubbers	Fabric filter	Thermal and catalytic incinerators	Adsorber	Absorber	Condensers
DIRECT COSTS							
Purchased equipment cost[b]	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Other direct costs							
Foundation and supports	0.04	0.06	0.04	0.08	0.08	0.12	0.08
Erection and handling	0.50	0.40	0.50	0.14	0.14	0.40	0.14
Electrical	0.08	0.01	0.08	0.04	0.04	0.01	0.08
Piping	0.01	0.05	0.01	0.02	0.02	0.30	0.02
Insulation	0.02	0.03	0.07	0.01	0.01	0.01	0.10
Painting	0.02	0.01	0.02	0.01	0.01	0.01	0.01
Total Direct Cost	1.67	1.56	1.72	1.30	1.30	1.85	1.43
INDIRECT COSTS							
Engineering and supervision	0.20	0.10	0.10	0.10	0.10	0.10	0.10
Construction and filed expenses	0.20	0.10	0.20	0.05	0.05	0.10	0.05
Construction fee	0.10	0.10	0.10	0.10	0.10	0.10	0.10
Start up	0.01	0.01	0.01	0.02	0.02	0.02	0.02
Performance test	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Model study	0.02	—	—	—	—	—	—
Total Indirect Cost	0.54	0.32	0.42	0.28	0.28	0.32	0.28
CONTINGENCY[c]	0.07	0.06	0.07	0.05	0.05	0.07	0.05
TOTAL[d]	2.27	1.94	2.21	1.63	1.63	2.24	1.76

[a]As fractions of total purchased equipment cost. They must be applied to the total purchased equipment cost.
[b]Total of purchase costs of major equipment and auxiliary equipment and others, which include instrumentation and controls at 10%, taxes and freight at 8% of the equipment purchase cost.
[c]Contingency costs are estimated to equal 3% of the total direct and indirect costs.
[d]For retrofit applications, multiply the total by 1.25.
Source: ref. 26.

equipment (ductwork, fan, and stack) purchase costs, the cost of instrumentation and controls, and freight and taxes must be added to obtain the total purchase cost.

(d) Carbon adsorber: Figure 11 (packaged carbon adsorber systems) includes the cost of carbon, beds, fan and motor, instrumentation and controls, and a steam regenerator. Additional auxiliary equipment (ductwork, and stack) purchase costs and costs of freight and taxes must be added to obtain the total purchase cost. Figure 12 (custom carbon adsorber systems) includes beds, instrumentation and controls, and a steam regenerator, less carbon. The "table" carbon cost for custom carbon adsorbers is estimated by multiplying the weight of carbon required (C_{req}) by the carbon cost factor ($/lb) found in the literature. Costs of carbon, all auxiliary equipment (duct, fan, stack) purchase costs, and freight and taxes must be added to obtain the total purchase cost.

(e) Absorber: Figure 13 does not include the cost of packing, platforms, and ladders. The cost of platforms and ladders (*see* Fig. 14) and packing must be added to obtain the major purchased equipment cost. The "table" packing cost is estimated by multiplying the volume of packing required (V_{pack}) by the appropriate packing cost factor found in Table 13. All auxiliary equipment (ductwork, fan, and stack) purchase costs and costs of freight and taxes must be added to obtain the total purchase cost.

(f) Condenser systems: Figure 15 yields total capital costs for cold-water condenser systems. For systems needing a refrigerant, the applicable cost from Fig. 16 must be added to obtain the total capital costs. In either case, the escalated cost estimate is then placed on the TOTAL CAPITAL COSTS line.

(g) Fabric filter systems: Figure 17 gives the cost of a negative-pressure, insulated baghouse. The curve does not include bag costs. The "table" bag cost is estimated by multiplying the gross cloth area required by the appropriate bag cost factor found in Table 14. Bag costs, all auxiliary equipment (ductwork, fan, and stack) purchase costs, the cost of instrumentation and controls, and freight and taxes must be added to obtain the total purchase cost.

(h) Electrostatic precipitators: Figure 18 provides the cost for an insulated ESP. All auxiliary equipment (duct, fan, and stack) purchase costs, the cost of instrumentation and controls, and freight and taxes must be added to obtain the total purchase cost.

(i) Venturi scrubber: Figure 19 includes the cost of instrumentation and controls in addition to the major equipment purchase cost. This cost curve is based on a Venturi scrubber constructed form (1/8)-in. carbon steel. Figure 20 is used to determine if (1/8)-in. steel is appropriate for a given application (use the higher curve). If thicker steel is required, Fig. 21 yields an adjustment factor for various steel thicknesses; this factor is used to escalate the cost obtained from Fig. 19. In addition, if stainless steel is required, multiply the scrubber cost estimate by 2.3 for 304L stainless steel or by 3.2 for 316L stainless steel. Costs of all auxiliary equipment (ductwork, fan, and stack) and freight and taxes must be added to obtain the total purchase cost.

(j) Ductwork: Figure 4 gives the cost of straight ductwork made of carbon steel for various thicknesses, based on the required duct diameter. Figure 5 gives the cost of straight ductwork made of stainless steel for various thicknesses, based on the required diameter. Preliminary calculations are necessary to estimate ductwork costs.

(k) Fan: Figure 3 gives the cost of a fan based on the gas flow rate at actual conditions and the HAP control system pressure drop (in in. H_2O). The applicable fan class is also based on the HAP control system pressure drop. Calculation of the total system pressure drop is required.

(l) The cost of a motor is estimated as 15% of the fan cost.

(m) Stack: Figure 6 gives the cost of a carbon steel stack at various stack heights and diameters. Figure 7 gives the price of a stainless-steel stack at various stack heights and diameters. Preliminary calculations are necessary to estimate stack costs. For both figures, use the curve that best represents the calculated diameter.

(n) For thermal incinerators, carbon adsorbers, and Venturi scrubbers, the purchase cost curve includes the cost for instrumentation and controls. This cost (i.e., the "Adjustment") must be subtracted out to estimate the total purchased equipment cost. This is done by adding the Item 1 subtotal and the Item 2 subtotal and multiplying the result by –0.091. This value is added to the total purchased equipment cost. For all other major equipment, the "Adjustment" equals zero.

(o) Obtain factor F from "TOTAL" line in Table 20.

7. ANNUALIZED OPERATING COSTS

7.1. Introduction

The annualized cost of an air pollution control system can be divided into direct operating costs, indirect operating costs, and credits. In this handbook, the inflation effect on costs is not considered, annualized costs are assumed to be constant in real dollars, and the total annualized cost is estimated on a before-tax basis.

7.2. Direct Operating Costs

The direct operating costs consist of utilities, operating labor charges, maintenance charges, and replacement parts and labor charges.

1. Utilities (i.e., fuel, electricity, water, steam, and materials required for the control system) are annual costs that vary depending on the control system size and operating time. They are calculated using gas stream characteristics and control equipment capacity data.
2. Operating labor costs consist of operator labor and supervision, whereas maintenance costs consist of maintenance labor and materials. The direct operating costs are established by estimating annual quantities of utilities consumed and operator and maintenance labor used and by applying unit costs to these quantities. The annual quantities of utilities and labor requirements are assumed to be proportional to the annual operating hours for the control system. Operating labor supervision and maintenance materials are taken as %ages of the operator and maintenance labor costs.
3. Costs of replacement parts are estimated as applicable, and the cost of replacement labor is assumed to equal the cost of replacement parts.

Table 20 presents June 1985 unit costs for utilities, operator labor, and maintenance labor as well as cost factors for other direct operating cost elements.

The procedures used to estimate direct operating costs (including utilities, direct labor, maintenance, and replacement costs) and indirect operating costs (including overhead, property tax, insurance, administration, and capital recovery cost) were taken from US EPA. These unit costs and cost factors are applied to estimated quantities of utilities consumed, labor expended, and parts used to obtain total direct operating costs.

If a given control system contains two or more control devices, the direct operating costs must be calculated for each device and summed. The capital recovery cost for a multiple control devices system should be calculated using a weighted-average capital cost factor.

Unless specified, use 8600 h per year, 8 h per shift, and 24 h per day, as necessary, to estimate the annual costs for utilities consumed, operator labor, and maintenance labor.

7.2.1 Utility Requirement: Electricity Requirement

The utility requirements for a control system are obtained from each component's design calculations. Use the costing information in Tables 21–23 to estimate the total utility costs. A procedure to estimate fan electricity costs is provided below, as these costs are applicable to all control techniques. Table 24 is a summary table for estimation of annualized costs in current dollars. As Tables 21–24 are important for estimation of annualized costs, they are further explained in detail.

Table 21 is further explained by the following footnotes to the table:

(a) The readers are referred to Tables 22 and 23 to estimate utility costs and replacement costs for each HAP control technique.
(b) Maintenance materials include operating supplies (e.g., lubrication, paper).
(c) CRF=capital recovery factor. For an average interest rate of 10%, the CRF for specific control devices are as follows:
    ESP and fabric filter: CRF=0.117 (based on 20-y life span)
    Venturi scrubber, thermal and catalytic incinerators, adsorber, absorber, and condenser: CRF=0.163 (based on 10-y life span).

Table 22 is explained by the following footnotes:

Table 21
Unit Costs to Calculate Annualized Cost

Cost Elements	Unit costs/factor
Direct Operating Costs	
1. Utilities[a]	
a. Natural gas	$0.00425/ft^3$
b. Fuel oil	$1.025/gal
c. Water	$0.0003/gal
d. Steam	$0.00504/lb
e. Electricity	$0.059/kWh
f. Solvent	As applicable
2. Operating labor	
a. Operator labor	$11.53/hour
b. Supervision	15% of operator labor
3. Maintenance	
a. Labor	$11.53/hour
b. Materials[b]	100% of maintenance labor
4. Replacement	
a. Parts	As applicable
b. Labor	100% of replacement parts
Indirect Operating Costs	
1. Overhead	80% of 2a+2b+3a+4a
2. Property tax	1% of Total Capital Cost
3. Insurance	1% of Total Capital Cost
4. Administration	2% of Total Capital Cost
5. Capital recovery	(CRF[c])×Total Capital Cost
Credits	As applicable

Note: See text for additional information.
Source: ref. 26.

Table 22
Utility/Replacement Operating Costs for HAP Control Techniques

HAP control device	Utilities/replacement parts
Thermal incinerator	Natural gas or fuel oil; Electricity (fan)
Catalytic incinerator	Catalyst cost (V_{cat}); Natural gas or fuel oil; Electricity (fan)
Carbon adsorber systems	Carbon (C_{req}); Steam Cooling water; Electricity (fan)
Absorber systems	Absorbent (water or solvent); Electricity (fan)
Condenser system	Refrigerant; (Ref); Electricity (fan)
Fabric-filter system	Bags (A_{tc}); Electricity (fan + control device)
Electrostatic precipitator	Electricity (fan + control device)
Venturi scrubbers	Water; Electricity (fan)

Note: See Text for additional information.

Table 23
Additional Utility Requirements

Fuel requirement for incinerators, (ft^3)

(*Note*:The design sections for thermal and catalytic incinerators are developed under the assumption that natural gas is used as the supplementary fuel. Fuel oil could be used, however, the use of natural gas is normal industry practice. If fuel oil is used, the following equation can be used by replacing Q_f with the fuel oil flow rate in units of gallons per minute. The product of the equation then equals gallons of fuel oil.)

Fuel requirement = 60 $Q_f \times$ HRS, where Q_f is the supplementary fuel required (scfm) and HRS is the annual operating hours (h). (*Note*: Use 8600 h unless otherwise specified.)

Steam requirement for carbon adsorber (lb)

(*Note*: Assume 4 lb of steam required for each of recovered product.)

Steam requirement = 4(Q_{rec}) × HRS, where Q_{rec} is the quantity of HAP recovered (lb/h).

Cooling water requirement for carbon adsorber (gal)

(*Note*: Assume 12 gal of cooling water required per 100 lbs steam.)

Water requirement = 0.48(Q_{rec}) × HRS

Absorbent requirement for absorbers (gal)

(*Note*: Assume no recycle of absorbing fluid [water or solvent].)

Absorbent requirement = 60(L_{gal}) × HRS, where L_{gal} is the absorbing fluid flow rate (gal/min).

Water requirement for venturi scrubbers (gal)

(*Note*: Assume 0.01 gal water is required per actual cubic feet of emission stream.)

Water requirement = 0.6 $Q_{e,a} \times$ HRS, where $Q_{e,a}$ is the emission stream flow rate into scrubber (acfm).

Baghouse electricity requirement (kWh)

(*Note*: Assume 0.0002 kW are required per square feet of gross cloth area.)

Baghouse electricity requirement = 0.0002 $A_{tc} \times$ HRS, where A_{tc} is the gross cloth area required (ft^2).

ESP electricity requirement (kWh)

(*Note*: Assume 0.0015 kW are required per square feet of collection area.)

ESP electricity requirement = 0.0015 $A_p \times$ HRS, where A_p is the collection plate area (ft^2).

Note: See text for additional information.
Source: ref. 26.

Table 24
Estimate of Annualized Costs in Current Dollars

Cost elements	Units costs/factors	Annual expenditure	Current dollars
Direct Operating Costs			
1. Natural gas	$0.00425/ft^3	× ________ ft^3	= $ ________
2. Fuel oil	$1.025/gal	× ________ gal	= $ ________
3. Water	$0.003/gal	× ________ gal	= $ ________
4. Steam	$0.00504/lb	× ________ lb	= $ ________
5. Electricity	$0.059/kWh	× ________ kWh	= $ ________
6. Solvent	$ ________ per gal	× ________ gal	= $ ________
7. Replacement Parts	As applicable		$ ________
8. Replacement Labor	100% of Line 7		$ ________
9. Operator Labor	$11.53/h	× ________ h	= $ ________
10. Supervision labor	15% of Line 9		$ ________
11. Maintenance Labor	$11.53/h	× ________ h	= $ ________
12. Maintenance Materials	100% of Line 11		$ ________
Subtotal	Add Items 1–12		$ ________
Indirect Operating Costs			
14. Overhead	80 % of Sum of Lines 8–11		$ ________
15. Property tax	1% of Total Capital Cost[a]		$ ________
16. Insurance	1% of Total Capital Cost[a]		$ ________
17. Administration	2% of Total Capital Cost[a]		$ ________
18. Capital recovery	(CRF) × Total Capital Cost[a], where CRF =		$ ________
19. Subtotal	Add Items 14–18		$ ________
20. Credits	As applicable		$ ________
Net Annualized Costs	Items 13 + Item 19 − Item 20		$ ________

Note: See text for additional information.
[a]Total capital cost from Line 8 of Table 19.

(a) The readers are referred to Table 21 for utility unit costs, Sections 4.3.2–4.3.4, Table 14 for replacement part unit costs, and Table 12 for FE cost indices.
(b) See Table 23 for additional utility requirement.
(c) Annualized replacement catalyst costs are calculated as

$$\text{Annualized cost} = \frac{V_{\text{cat}}\left(\text{ft}^3\right) \times \$/\text{ft}^3}{3\ \text{yr}}\left(\text{current FE / Base FE}\right) \tag{23}$$

(d) Annualized replacement carbon costs are calculated

$$\text{Annualized cost} = \frac{C_{\text{req}}(\text{lb}) \times \$/\text{lb}}{5\ \text{yr}}\left(\text{current FE / Base FE}\right) \tag{24}$$

(e) Refrigerant replacement is the result of the system leaks; however, the loss rate of refrigerant is very low and varies for every unit. Therefore, assume that the cost of refrigerant replacement is negligible.
(f) Annualized replacement bag costs are calculated as

$$\text{Annualized cost} = \frac{A_{tc}\left(\text{ft}^2\right) \times \$/\text{ft}^2}{2\ \text{yr}}\left(\text{current FE / Base FE}\right) \tag{25}$$

Table 24 is further explained by the following footnotes:

(a) The readers are referred to Section 7.2.2 for the costs of natural gas, fuel oil, water, steam, and solvent.
(b) The readers are referred to Section 7.2.1 for the electricity costs.
(c) As applicable.
(d) Total capital cost can be obtained from Line 8 of Table 19.

The annualized electricity requirement of fan, baghouse, and ESP can be calculated by the following equations.

(a) Fan electricity requirement (FER)

$$\text{FER (kWh)} = 0.0002\left(Q_{fg,a}\right) \times \Delta P \times \text{HRS} \tag{26}$$

where $Q_{fg,a}$ is the actual flue gas flow rate (acfm), ΔP is the total HAP control system pressure drop (in. H_2O) (*see* Table 5), HRS is the annual operating hours (hr) (*Note*: use 8600 unless otherwise specified).

(b) Baghouse electricity requirement, (BER), (*Note*: assume 0.0002 kW are required per square feet of gross cloth area)

$$\text{BER (kWh)} = 0.0002\left(A_{tc}\right) \times \text{HRS} \tag{27}$$

where A_{tc} is the gross cloth area required (ft^2).

(c) ESP electricity requirement, (EER) (*Note*: assume 0.0015 kW are required per square feet of collection area)

$$\text{EER (kWh)} = 0.0015\left(A_p\right) \times \text{HRS} \tag{28}$$

where A_p is the collection plate area (ft^2).

(d) Annual electricity requirement (AER)

$$\text{AER (kWh)} = \text{FER} + \text{BER} + \text{EER} \tag{29}$$

7.2.2. Utility Requirement: Fuel, Steam, Absorbent, and Water Requirements

The design sections for thermal and catalytic incinerators are developed under the assumption that natural gas is used as the supplementary fuel. Fuel oil could be used; however, the use of natural gas is normal industry practice. If fuel oil is used, eq. (30) can be used by replacing Q_f with the fuel oil flow rate in units of gallons per minute. The resultant product of the equation (gallons of fuel oil required) is then used on Line 2 of Table 24.

(a) Fuel requirement for incinerators (Line 1 or Line 2, Table 24)

$$\text{Fuel Requirement}\left(\text{ft}^3\right) = 60\left(Q_f\right) \times \text{HRS} \tag{30}$$

where Q_f is the supplementary fuel required, (scfm), and HRS is the annual operating hours, (h) (*Note*: use 8600 unless otherwise specified).

(b) Steam requirement for carbon adsorber (Line 4, Table 24) (*Note*: assume 4 lb of steam required for each lb of recovered product)

$$\text{Steam Requirement(lb)} = 4\left(Q_{\text{rec}}\right) \times \text{HRS} \tag{31}$$

where Q_{rec} is the quantity of HAP recovered (lb/h).

(c) Cooling water requirement for carbon adsorber (Line 3, Table 24) (*Note*: assume 12 gal of cooling water required per 100 lb steam)

$$\text{Water Requirement (gallon)} = 0.48\left(Q_{\text{rec}}\right) \times \text{HRS} \tag{32}$$

(d) Absorbent requirement for absorbers (Line 3, Table 24) (*Note*: assume no recycle of absorbing fluid [water or solvent])

$$\text{Absorbent Requirement (gallon)} = 60\left(L_{\text{gal}}\right) \times \text{HRS} \tag{33}$$

where L_{gal} is the absorbing fluid flow rate (gal/min).

(e) Water requirement for Venturi scrubbers (Line 3, Table 24) (*Note*: assume 0.01 gal of water required per acf of emission stream)

$$\text{Water Requirement (gallon)} = 0.6\left(Q_{e,a}\right) \times \text{HRS} \tag{34}$$

where $Q_{e,a}$ is the emission stream flow rate into scrubber (acfm).

7.2.3. Replacement Parts Annualized Costs

(a) Annualized catalyst replacement costs (Line 7, Table 24). Over the lifetime of a catalytic incinerator, the catalyst is depleted and must be replaced (assume catalyst lifetime is 3 yr).

$$\text{Annual Catalist Cost, \$} = \left(\text{Catalyst Current Cost}\right)/3 \tag{35}$$

(b) Annualized carbon replacement costs (Line 7, Table 24). Over the lifetime of a carbon adsorber, the carbon is depleted and must be replaced (assume carbon lifetime is 5 yr):

$$\text{Annual Carbon Cost, \$} = \left(\text{Carbon Current Cost}\right)/5 \tag{36}$$

(c) Annualized refrigerant replacement costs. Refrigerant in a condenser needs to be replaced periodically because of system leaks; however, the loss rate is typically very low. Therefore, assume that the cost of refrigerant is negligible.

(d) Annualized bag replacement costs (Line 7, Table 24). Over the lifetime of a fabric filter system, the bags become worn and must be replaced (assume bag lifetime is 2 yr).

$$\text{Annual Bag Cost, \$} = \left(\text{Bag Current Cost}\right)/2 \tag{37}$$

The bag current cost can be obtained from Table 14.

7.3. Indirect Operating Costs

7.3.1. Introduction

The indirect operating costs include overhead costs, property tax, insurance, administration costs, and the capital recovery costs. Overhead costs are estimated as a %age of operating labor costs. Property tax, insurance, and administrative costs are estimated as a %age of the total capital cost. The capital recovery cost is estimated as the product of the capital recovery factor and the total capital cost. The factor for capital recovery costs (the total of annual depreciation and interest on capital) is determined from the expected life of the control device and the interest rate at which the capital is borrowed. The expected life of a given control device depends on the type of control application, maintenance service, and operating duty. For costing purposes, pre-established expected life values are used.

Some control technologies recover the HAPs from a given emission stream as a salable product. Therefore, any cost credits associated with the recovered material must be deducted from the total annualized cost to obtain the net annualized cost for the system.

The amount, purity, and commercial value of the recovered material determine the magnitude of credits.

7.3.2. Capital Recovery Factor

Estimate the overhead costs as 80% of the direct labor cost (the summation of operating labor and supervision labor costs) and the maintenance labor cost. The property tax estimate is calculated as 1% of the total capital cost, insurance is 1% of the total capital cost. Estimate the capital recovery cost portion of the fixed capital charges by multiplying the total capital cost by a capital recovery factor. The capital recovery factor (CFR) is calculated as follows:

$$\mathrm{CFR} = \left[i(1+i)^n\right] \Big/ \left[(1+i)^n - 1\right] \quad (38)$$

where i is the interest rate on borrowed capital (decimal) and, n is the control device life (yr).

For the purpose of this handbook, an interest rate of 10% is used. Table 25 contains data on expected control device life (n). Calculated capital recovery factors at 10% interest rate are 0.163 and 0.117 for 10- and 20-yr control device lifetimes, respectively. If more than one control device is used by the control system, use a weighted-average capital recovery factor. A weighted-average capital recovery factor (CRF_w) is determined as follows:

$$\mathrm{CRF_W} = \mathrm{CRF_1}\left[\mathrm{PC_1}/\left(\mathrm{PC_1}+\mathrm{PC_2}\right)\right] + \mathrm{CRF_2}\left[\mathrm{PC_2}/\left(\mathrm{PC_1}+\mathrm{PC_2}\right)\right] \quad (39)$$

where CRF_1 is the capital recovery factor for control device 1, CRF_2 is the capital recovery factor for control device 2, PC_1 is the purchased equipment cost for control device 1, and, PC_2 is the purchased equipment cost for control device 2.

7.3.3. Calculation of Capital Recovery Factor, Annualized Operator Labor, and Annualized Maintenance Labor

(a) Calculation of capital recovery factor (CRF) (Line 18, Table 24)

$$\mathrm{CFR} = \left[i(1+i)^n\right] \Big/ \left[(1+i)^n - 1\right] \quad (38)$$

Table 25
Estimated Labor Hours per Shift and Average Equipment Lift

	Labor Requirements (h/shift)		
Control device	Operator labor	Maintenance labor	Average equipment life (yr)
Electrostatic precipitator	0.5–2	0.5–1	20
Fabric filter	2–4	1–2	20
Venturi scrubber	2–8	1–2	10
Incinerator	0.5	0.5	10
Adsorber	0.5	0.5	10
Absorber	0.5	0.5	10
Condenser	0.5	0.5	10

Source: ref. 26.

where i is the interest rate on borrowed capital (decimal) (use 10% unless otherwise specified) and, n is the control device life, (yr).

(b) Calculation of annualized operator labor (OL) (Line 9, Table 24)

$$\text{OL (hr)} = \text{(HRS)(operator hours per shift)} / \text{(operating hours per shift)} \tag{40}$$

(*Note*: Obtain operator hours per shift value from Table 25.)

(c) Calculation of annualized maintenance labor (ML) (Line 11, Table 24)

$$\text{ML (hr)} = \text{(HRS)(maintenance hours per shift)} / \text{(operating hours per shift)} \tag{41}$$

(*Note*: Obtain maintenance hours per shift value from Table 25.)

8. COST ADJUSTMENTS AND CONSIDERATIONS

8.1. Calculation of Current and Future Costs

For purposes of this handbook, auxiliary equipment cost is defined to include the cost of fans, ductwork, stacks, dampers, and cyclones (if necessary), which commonly accompany control equipment. These costs must be estimated before the purchased equipment cost (PEC) can be calculated. Costs for auxiliary equipment were obtained from refs 1, 3, 9, 12, 26, 28, 30, and 34. Readers are referred to other chapters of this handbook and other references for primary, secondary, and tertiary APCD costs (12–17, 25,26,28–35,37,38).

If equipment costs must be escalated to the current year, the *Chemical Engineering* (CE) Equipment Index can be used. Monthly indices for 5 yr are provided in Table 12 (2,36). The following equation can be used for converting the past cost to the future cost, or vice versa.

$$\text{Cost}_b = \text{Cost}_a \times \left(\text{Index}_b / \text{Index}_a\right) \tag{42}$$

where Cost_a is the cost in the month-year of a ($), Cost_b is the cost in the month-year of b ($), Index_a is the CE Fabricated Equipment Cost Index in the month-year of a and Index_b is the CE Fabricated Equipment Cost Index in the month-year of b.

It should be noted that although the CE Fabricated Equipment Cost Indices (2,36) are recommended here for Index_a and Index_b, the ENR Cost Indices (37,39) can also be adopted for updating the costs. Cost data for construction and O&M have originated from a variety of reference sources and reflect different time periods and geographic locations. Values presented in this handbook have been converted to a specific month–year (constant dollar) base except where noted.

8.2. Cost Locality Factors

In addition to adjusting to a constant dollar base, cost indexes, such as those previously described, are used to perform economic analyses, adjust to current dollars, and make cost comparisons. However, such indexes, when applied to the several components of construction or operation and maintenance costs, will only adjust the data on a national average basis.

In order to arrive at a more accurate cost figure than one that results from the use of the national average indexes alone, the locality factor can be applied to an estimated cost or cost index. The use of locality factors, which have been calculated from generally available statistics, permits the localizing of national average cost data for construction labor, construction materials, total construction cost, O&M labor costs, and power costs. The factor for labor and materials are given in Table 26 and those for power costs are given in Table 27.

8.3. Energy Conversion and Representative Heat Values

Whenever various forms of energy are interconverted, there will be some loss resulting from inefficiencies. For example, whenever electrical energy is converted to mechanical energy, some of the energy is lost as heat energy in the motor. Similarly, if an engine operating on a Carnot cycle has a source temperature of 1100ºF (1560ºR) and a receiver temperature of 500ºF (960ºR), the efficiency is only (1.0 – 960/1560) or 38.5%. Because no heat engine can be more efficient than a Carnot engine, it is clear that this is the maximum efficiency for these source and receiver temperatures.

The efficiency of pumps and blowers is usually in the range of 70–80% so that mechanical energy can be converted to hydraulic energy with no more than about 30% loss. Similarly, mechanical and electrical energy can be converted from one form to the other with a loss of less than 10%. On the other hand, the conversion of heat energy to mechanical energy necessitates the wasting of roughly two-thirds of the heat energy. For

Table 26
Cost Locality Factors

	Construction[a]			
	Labor	Materials	Total	O&M Labor[b]
Atlanta	0.66	1.03	0.79	0.77
Baltimore	0.90	0.95	0.92	0.79
Birmingham	0.66	1.02	0.79	0.79
Boston	1.12	0.90	1.04	0.97
Chicago	1.25	1.10	1.20	1.02
Cincinnati	1.10	1.05	1.08	0.98
Cleveland	1.19	1.01	1.13	1.05
Dallas	0.63	0.83	0.70	0.92
Denver	0.76	1.07	0.87	1.00
Detroit	1.17	0.98	1.10	1.32
Kansan City	0.97	1.25	1.07	0.88
Los Angeles	1.17	1.16	1.17	1.32
Minneapolis	0.93	1.03	0.97	1.21
New Orleans	0.88	1.05	0.94	0.66
New York	1.43	0.91	1.24	1.14
Philadelphia	1.23	1.00	1.15	1.05
Pittsburgh	1.05	0.96	1.02	0.97
St. Louis	1.29	0.99	1.18	0.83
San Francisco	1.23	0.96	1.13	1.13
Seattle	1.16	0.91	1.07	1.21
National Index Values	1.00	1.00	1.00	1.00

[a]Calculated from EPA Sewage Treatment Plant and Sewer Construction Cost Index Third Quarter 1979.
[b]US Department of Commerce Bureau of Census, City Employment in 1976, GE76 No. 2 July 1977. Based on average earnings by city of noneducation employees (40).

Table 27
Power Cost Locality Factor[a]

Region	Power cost factor
New England	1.31
Mid-Atlantic	1.18
Northeast Central	1.10
Northwest Central	0.98
South Atlantic	0.94
Southeast Central	0.98
Southwest Central	0.87
Mountain	0.79
Pacific	0.86
US average	1.00

[a]Basis: BLS, September 1979, Producers Price Index.

example, if electrical energy is converted to heat energy, 1 kWh will generate about 3413 Btu of heat. However, if heat energy is used to generate electrical energy in a modern coal fired power plant, about 10500 Btu of heat energy is needed to generate 1 kWh; this is a conversion efficiency of only 32.5%. Typical energy conversion percentage efficiencies (%) are as follows:

1. Heat to mechanical ≤ 38.5%
2. Heat to electrical ≤ 32.5%
3. Mechanical to electrical > 90%
4. Mechanical to hydraulic 70–80%
5. Electrical to mechanical > 90%
6. Electrical to heat approx 100%
7. Electrical to hydraulic 65–80%

Representative heat values of common fuels are as follows:

1. Anthracite coal = 14,200 Btu/lb coal
2. Digester gas = 600 Btu/ft^3
3. Fuel oil = 140,000 Btu/gal
4. Lignite coal = 7400 Btu/lb Coal
5. Liquefied natural gas (LNG) = 86,000 Btu/gal
6. Municipal refuse (25% moisture) = 4200 Btu/lb
7. Natural gas = 1000 Btu/ft^3
8. Propane gas = 2500 Btu/ft^3
9. Waste Paper (10% moisture) = 7600 Btu/lb
10. Wastewater Sludge = 10,000 Btu/lb dry VS

8.4. Construction Costs, O&M Costs, Replacement Costs, and Salvage Values

The construction costs incurred by the project represent single-payment costs that occur at certain times throughout the planning period. The single-payment present-worth factor (sppwf) is used to determine the present-worth cost and is determined by:

$$\text{sppwf} = \frac{1}{(1+i)^n} \tag{43}$$

where i is the interest rate and n is the number of interest periods.

The O&M cost includes both constant and variable costs. The constant O&M cost is based on the flow rate at the beginning of the planning period. The variable O&M cost represents the difference between the O&M cost at the flow rate in the final year of the planning period and the constant O&M cost identified by the flow rate at the beginning of the planning period. The uniform-series present-worth factor (uspwf) is used to convert the constant annual O&M cost to a present-worth cost:

$$\text{uspwf} = \frac{(1+i)^n - 1}{i(1+i)^n} \tag{44}$$

The facility replacement cost identifies the cost required to extend the useful life of equipment to the end of the planning period. This is computed when a capital item has a service life of less than the remaining years in the planning period and is computed by

$$\text{Replacement Cost} = \frac{\text{Planning Period} - \text{Remaining Service Life}}{\text{Service Life}} \times \text{Capital Value} \tag{45}$$

Capital value is the capital that would be required today to completely replace the facility. This is a single-payment cost, with present worth computed using the factor sppwf.

Finally, the salvage value represents the value remaining for all capital at the end of the planning period:

$$\text{Salvage Value} = \frac{\text{Service Life} - \text{Years to Planning End}}{\text{Service Life}} \times \text{Capital Value} \tag{46}$$

Capital value is the initial investment (or cost to replace today). This is a negative cost, with the present-worth value computed using the factor sppwf.

9. PRACTICE EXAMPLES

Example 1

Assume an emission stream actual flow rate of 1000 acfm, a particle density of 30 lb/ft^3, and emission stream density of 0.07 lb/ft3, an emission stream viscosity of 1.4×10^{-5} lb/ft-s, and a critical particle size of 20 µm. Determine the cyclone inlet area for the purpose of sizing and cost estimation.

Solution

Using Eq. (2), the cyclone inlet area is

$$A_{\text{cyc}} = 3.34\left[1000(30-0.07)/1.41\times10^{-5}\right]^{1.33} \times \left[20\times10^{-6}\right]^{2.67}$$
$$A_{\text{cyc}} = 2.41 \text{ ft}^2$$

Example 2

Assume an emission stream actual flow rate 1000 acfm, a n particle density of 30 lb/ft^3, an emission stream density of 0.07 lb/ft^3, an emission stream viscosity of 1.41×10^{-5} lb/ft-s, and a critical particle size of 20 µm. Determine the following:

1. The August 1988 cost of the cyclone body
2. The August 1988 cost of the rotary air lock
3. The August 1988 cost of the total cyclone system

4. The February 1990 cost of the total cyclone system
5. The April 2000 cost of the total cyclone system

Assume that the April 2000 CE Fabricated Equipment Index is 437.4 (*see* Table 12).

Solution

In Example 1, the cyclone inlet area has been calculated to be 2.41 ft^2 using Eq. (2).

1. The August 1988 cost of a cyclone is then obtained from Eq. (9) as follows:

$$P_{\text{cyc}} = 6{,}520(2.41)^{0.9031}$$
$$P_{\text{cyc}} = \$14{,}400$$

2. The August 1988 cost of a rotary air lock for this system is given by Eq. (10):

$$P_{\text{ral}} = 2{,}730(2.41)^{0.0965}$$
$$P_{\text{ral}} = \$2{,}970$$

3. The August 1988 cost of a cyclone is the sum of these two costs, or $17,400.
4. The February 1990 cost of a cyclone system is given by Eq. (42). The CE Fabricated Equipment Indexes for August 1988 and February 1990 are 376.3 and 389.0, respectively.

$$\text{Cost}_b = Cost_a(389.00 / 376.30)$$
$$\text{Cost}_b = \$2{,}970(389.00 / 376.30)$$
$$\text{Cost}_b = \$3{,}070.24$$

5. The April 2000 cost when the index = 437.40 is

$$\text{Cost}_b = \$2{,}970(437.40 / 376.30)$$
$$= \$3{,}452.24$$

Example 3

Determine the fan costs in July 1988 and in the future when the *Chemical Engineering* Fabricated equipment cost index is projected to be 650. Assume the required static pressure equals 8 in. of water with a fan diameter of 30 in.

Solution

Equation (11) can be used to obtain the fan cost as follows:

1. The July 1988 fan cost:

$$P_{\text{fan}} = 42.3(30)^{1.2}$$
$$P_{\text{fan}} = \$2{,}510$$

2. The future fan cost when CE Fabricated equipment cost index is 650. The July 1988 index is 363.7. Equation (42) can be used for the calculation.

$$\text{Cost}_b = \$2{,}510(650 / 363.7)$$
$$= \$4{,}485.84$$

Example 4

Determine the required FRP duct diameter assuming a duct velocity (U_{duct}) of 2000 ft/min and an actual air emission rate ($Q_{e,a}$) of 15,300 acfm.

Solution

d_{duct} is obtained using Eq. (16):

$$d_{\text{duct}} = 12\left(\frac{4}{\pi}\frac{Q_{e,a}}{U_{\text{duct}}}\right)^{0.5}$$
$$= 12\left(\frac{4}{\pi}\frac{15,300}{2000}\right)^{0.5}$$
$$= 37.4 \text{ in. or } 3.12 \text{ ft}$$

Example 5

Determine the cost of a 50-ft FRP duct ($d_{\text{duct}}=3.12$ ft) when the CE Fabricated equipment cost index reaches 437.4 in April 2000 and when the same cost index reached 700.

Solution

1. The August 1988 cost of FRP ductwork can be calculated using Eq. (18):

$$P_{\text{FRPD}} = 24 \times 3.12 = \$74.88/\text{ft}$$

   Thus, for a 50-ft length, the August 1998 cost of ductwork is $50\times 74.88=\$3744$
2. The April 2000 cost when the CE equipment cost index is 437.4 is

$$\text{Cost}_b = 3,744 \times (437.4/376.3)$$
$$= \$4,351.9$$

3. The future cost when the cost index reaches 700 is

$$\text{Cost}_b = 3,744 \times (437.4/376.3)$$
$$= \$6,964.66$$

Example 6

Assume that a 50-ft duct length and 3.12-ft diameter of FRP ductwork will be required. Determine the stack size and its future cost when the CE Fabricated equipment cost index reaches 700.

Solution

Assume a 50-ft FRP stack is required. The cost of this stack is approx 150% the cost of an equal length of ductwork. From the case given in Example 5, the cost of 50 ft of FRP ductwork is \$3744. The FRP stack cost in August 1988 is $1.5\times\$3744=\$5616$. The future FRP stack cost when the cost index reaches 700 will be \$5616 (700/376.3) = \$10,447.

Example 7

Assume that a two-way diverter valve is required for a duct of diameter 37 in. Determine the cost of the valve for the following conditions.

1. In February 1988
2. In the future when the CE Fabricated equipment cost index reaches 700

Solution

1. The cost of two-way diverter valve in February 1988 (cost index = 363.7) can be calculated using Eq (22).

$$P_{\text{damp}} = 4.84(37)^{1.50} = \$1,090$$

2. The future cost of the valve when the cost index reaches 700 will be

$$\begin{aligned}\text{Cost}_b &= \$1,090 \times (700/363.7) \\ &= \$2,097.88\end{aligned}$$

Example 8

Design a flanged slot hood assuming that the air emission stream flow rate is 18,600 ft^3/min for spray painting operation in shallow booths. The centerline distance to point (X) in the emission plume is 10 ft.

Solution

1. From Table 8, the ranges of capture velocities for spray painting operation in shallow booths is 200–500 fpm. The average capture velocity of 350 fpm is chosen for design.
2. From Table 9, the *W/L* ratio for flanged slot is 0.2 or less. The *W/L* ratio of 0.2 is chosen to fit the room.
3. From Eq. (4) for the flanged slot, the following calculations are presented:

$$Q = 2.8\ LVX$$

$$18,600\ \text{ft}^3/\text{min} = 2.8L \times 350\ \text{ft/min} \times 10\ \text{ft}$$

$L = 1.9$ ft. Select 2 ft for the length of hood.
$W = 0.2\ L = 0.4$ ft. Select 0.4 ft for the width of hood.

Example 9

The flue gas flow rate at actual conditions when exiting a heat exchanger is approx 40,000 acfm. Assume that there is no other available specific data for the stack. Calculate the stack diameter. Use the cost curve in Fig. 6 to estimate the stack cost. The CE Fabricated equipment index can be found in Table 12.

Solution

The actual gas flow rate exiting the heat exchanger (flue gas flow rate) is 40,000 acfm. Therefore, using Eq. (20), the stack diameter is

$$D_{\text{stack}} = 0.2140(40,000)^{1/2} = 43\ \text{in.}$$

With the stack diameter known, use the appropriate curve in Fig. 6 (use the closest curve: 42 in.) to estimate the stack cost as follows:

$4,500 × (347/226.2) = $6,903 (Note: 12/77 dollars escalated to reflect 6/85 dollars)

$4,500 × (437.4/226.2) = $8,701 (Note: 12/77 dollars escalated to reflect 4/00 dollars)

Example 10

A fan is carrying an airflow through an incinerator, a heat exchanger, ductwork, and stack. The flow rate exiting the heat exchanger is approx 40,000 acfm. The fan price curve (*see* Fig. 3) and the pressure drop information (*see* Table 5) are available. Consult Table 12 and CE Fabricated equipment cost indexes. Determine the fan cost and the motor cost.

Solution

For this example case, the fan and motor costs (*see* Fig. 3) are included in the thermal incinerator cost curve; however, these costs can be calculated separately. The total pressure drop across the control system is 7.3 in. H_2O (obtained from summing the values from Table 5 for the incinerator, heat exchanger, ductwork, and stack). The flow rate exiting the heat exchanger ($Q_{fg,a}$) is 40,000 acfm. The pressure drop from the guidelines on Fig. 3 indicates that a class II fan (the lower class fan) is appropriate. The estimated fan and motor costs are as follows:

1. Fan cost

$$\$5,000 \times (347.0 / 226.2) = \$7,670$$

(*Note*: 12/77 dollars escalated to reflect 6/85 dollars.)
or

$$\$5,000 \times (437.4 / 226.2) = \$9,668$$

(*Note*: 12/77 dollars escalated to reflect 4/00 dollars.)

2. Motor cost = Fan cost × 0.15
= \$7,670 × 0.15 = \$1,150.5 in June 1985
= \$9,668 × 0.15 = \$1,450.2 in April 2000

Example 11

The emission stream flow rate at actual conditions is approx 16,500 acfm. The ductwork is assumed to be 100 ft in length and made of 3/16-in.-thick plate. The emission stream contains no chlorine or sulfur compounds (noncorrosive) and has a gas temperature of 960ºF. The carbon steel straight-duct fabrication price (*see* Fig. 4) is available. Determine the duct diameter and the April 2000 duct price. Use the CE Fabricated equipment index (*see* Table 12).

Solution

In this example case, as no specific data on the ductwork are available, use the above assumptions to estimate the cost of the ductwork. The duct diameter is estimated using Eq. (16):

$$D_{\text{duct}} = 0.3028 \times (16,500)^{1/2} = 39 \text{ in.}$$

As the emission stream contains no chlorine or sulfur and the gas temperature is 960ºF, carbon steel ductwork is used. The cost of the ductwork is estimated using Fig. 4:

$$(\$52 / \text{ft}) \times 100 \text{ ft} \times (437.4 / 226.2) = \$10,055$$

(*Note*: 12/77 dollars escalated to reflect 4/00 dollars.)

Example 12

The example thermal incinerator system case consists of an incinerator with a combustion chamber volume (V_c) of approx 860 ft^3 and a primary heat exchanger with a surface area (A) of 4200 ft^2. Figures 8 and 9 are available. Consult Table 12. Determine the prices of incinerator and its heat exchanger.

Solution:

From the cost data presented in Figs. 8 and 9, June 1985 and April 2000 cost estimates are obtained as follows:

1. Incinerator plus instrumentation and control costs

$$\$98,000 \times (347.0 / 226.2) = \$150,336$$

(*Note*: 12/77 dollars escalated to reflect 6/85 dollars.)
or

$$\$98,000 \times (437.4 / 226.2) = \$189,501$$

(*Note*: 12/77 dollars escalated to reflect 4/00 dollars.)
2. Heat-exchanger cost

$$\$85,000\ (347.0/273.7) = \$107,764$$

(*Note*: 12/79 dollars escalated to reflect 6/85 dollars.)
or

$$\$85,000(437.4 / 273.7) = \$135,839$$

(*Note*: 12/79 dollars escalated to reflect 4/00 dollars.)

Example 13

Recommend a few references from which an environmental engineer may purchase fans, carbon adsorbers, fabric filters, ducts, stacks, and cyclones.

Solution

Many manufacturers and suppliers of the fans, carbon adsorbers, fabric filters, ducts, stacks, and cyclones can be found from the literature (41–43).

1. *Pollution Engineering*, 2000–2001 Buyer's Guide, Vol. 32, No. 12, November 2000.
2. *Environmental Protection*, 2003 Buyer's Guide, Vol. 14, No. 2, March 2003.
3. *Water Engineering and Management*, 2003 Annual Buyer's Guide, Vol. 149, No. 12, December 2002.

Example 14

Recommend a few reference sources from which an environmental engineer may purchase heat exchangers, air preheaters, motors, coolers, packings, condensers, solvents, surfactants, gas membrane filters, catalytic incinerators, and catalytic products.

Solution

The following are four excellent reference sources (44–48):

1. *Chemical Engineering*, Buyer's Guide 2001, Vol. 107, No. 9, August 2000.
2. *Environmental Technology*, 2000 Resource Guide, Vol. 9, No. 6, July 2000.
3. *Environmental Protection*, 2002 Executive Forecast, Vol. 13, No. 1, January 2002.
4. *Air pollution Control Engineering*, Humana Press, Totowa, NJ, 2004.

NOMENCLATURE

A	Area (ft^2)
A_{con}	Condenser system area (ft^2)
A_{cyc}	Cyclone inlet area (ft^2)
A_p	Collection plate area (ft^2)
A_{tc}	Total cloth area of bag filter (ft^2)
a, b	Coefficients in Table 11
a_d	0.877 ($6 < d_{duct} < 12$ in.) or 0.0745 ($14 < d_{duct} < 24$ in.)

a_f, b_f	Coefficients in Table 10
B	Dust outlet diameter
BER	Baghouse electricity requirement (kWh)
b_d	1.05 ($6 \leq d_{duct} \leq 12$ in.) or 1.98 ($14 \leq d_{duct} \leq 24$ in.)
C_{rep}	Replacement carbon (lb)
$Cost_a$	Cost in the month-year of a ($)
$Cost_b$	Cost in the month-year of b ($)
CRF	Capital recovery factor
CRF_w	Weighted average capital recovery factor
D	Distance between hood and source (ft)
d_{duct}	Duct diameter (in.)
d_{fan}	Fan diameter (in.)
D_{column}	Absorber column diameter (ft)
D_G	Density of emission stream (lb/ft^3)
D_o	Gas outlet diameter
D_{stack}	Stack diameter
EER	ESP electricity requirement (kWh)
ESP	Electrostatic precipitator
FE	CE (*Chemical Engineering*) Fabricated equipment cost index
FER	Fan electricity requirement (kWh)
H	Height (ft)
hp	Motor horsepower ($1 < hp < 7.5$)
HRS	Annual operating hours
H_{stack}	Stack height (ft)
ΔH	Pressure drop expressed as number of inlet velocity heads
i	Interest rate
$Index_a$	CE Fabricated Equipment Cost Index in the month-year of a
$Index_b$	The CE Fabricated Equipment Cost Index in the month-year of b
L	Length (ft)
L_{gal}	Absorbing fluid flow (gal/min)
ML	Annual maintenance labor (hr)
OL	Annual operator labor (hr)
n	Number of interest periods
P	Perimeter of hood (ft)
PC	Purchased equipment cost ($)
P_{cyc}	Cost of cyclone ($)
P_{damp}	Cost of damper ($)
P_{divert}	Cost of two-way diverter valve ($)
P_{fan}	Cost of fan system ($)
P_{FRPD}	Cost of FRP ductwork ($)
P_{motor}	Cost of fan motor, belt, and starter ($)
P_{PVCD}	Cost of PVC ductwork ($/ft)
P_{ral}	Cost of rotary air lock ($)
P_{stack}	Total capital cost of large stack ($)
ΔP	Pressure drop expressed as static pressure head

Q	Flow rate (ft^3/min)
Q_f	Supplementary fuel required (scfm)
$Q_{e,a}$	Actual emission stream flow rate (acfm)
$Q_{fg,a}$	Flue gas flow rate at actual conditions (acfm)
Q_{rec}	Recovered HAP (lb/hr)
sppwf	Single payment present worth factor
uspwf	Uniform series present worth factor
U_{stack}	Velocity of gas stream in stack (ft/min)
V	Velocity at point x (ft/min)
V_{cat}	Catalyst volume (ft^3)
W	Width (ft)
$\mathrm{Wt}_{\mathrm{column}}$	Absorber column weight (1000 lbs)
X	Centerline distance to point x in emission plume (ft)
μ	Emission stream viscosity (lb-ft/s)

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APPENDIX:
CONVERSION FACTORS

Multiply	By	To obtain
Acres	43,560	ft^2
Atmospheres	29.92	in. mercury
Atmospheres	33.90	ft water
Atmospheres	14.70	psi
Btu	1.055	kJ
Btu	777.5	ft-lb
Btu	3.927×10^{-4}	hp-h
Btu	2.928×10^{-4}	kW-h
Btu/lb	2.326	kJ/kg
ft^3	28.32	L
ft^3	0.03704	yd^3
ft^3	7.481	gal
ft^3/s	0.6463	mgd
ft^3/s	448.8	gpm
yd^3	0.765	m^3
ºF	0.555 × (ºF–32)	ºC
ft	0.3048	m
gal	3.785	L
gal, water	8.345	lb, water
gpd/ft^2	0.04074	m^3/m^2-d
gpm	0.06308	L/s
gpm/ft^2	0.06790	L/m^2-s
hp	0.7457	kW
hp	42.44	Btu/min
hp	33.00	ft-lb/min
hp-h	2.685	MJ
in	25.4	mm
lb (mass)	0.4536	kg
mil gal	3,785	m^3
mgd	3,785	m^3/d
ppm (by weight)	1.000	mg/L
psi	6.895	kN/m^2
sq ft	0.0929	m^2
tons (short)	907.2	kg

Note: Energy conversion in practice should take into account the efficiencies of using heat energy to produce an electrical power of 1 kW-hr, the Btu required is $1/(2.928 \times 10^{-4})(0.325) = 10{,}508$, but not $1/(2.928 \times 10^{-4}) = 3415$, which does not include the actual heat to electrical energy conversion efficiency.