United States
Environmental Protection
Agency

Office of
Research and Development
Washington, DC 20460

EPA/625/6-91/014
June 1991

Technology Transfer

EPA

Handbook

Control Technologies for Hazardous Air Pollutants

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Handbook

Control Technologies for Hazardous Air Pollutants

Center for Environmental Research Information
Office of Research and Development
U.S. Environmental Protection Agency
Cincinnati, OH 45268

Notice

The information in this document has been funded wholly, or in part, by the U.S. Environmental Protection Agency (USEPA) under Contract No. 68-C8-0011, Work Assignment No. 1-31, issued to Pacific Environmental Services, Inc. (PES), as a subcontractor to the Eastern Research Group, Inc. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

Acknowledgment

This Handbook was prepared by Michael K. Sink, Pacific Environmental Services, Inc., for the U.S. Environmental Protection Agency's Center for Environmental Research information (CERI) in conjunction with the EPA Control Technology Center. Carlos Nunez, Air and Energy Engineering Research Laboratory (AEERL), and Justice Manning, CERI, Office of Research and Development, served as technical project managers. Special acknowledgment is given to William M. Vatavuk for guidance on sources of cost information and a detailed review of Chapter 4. Peer review was provided by Robert H. Borgwardt, AEERL, and William J. Neuffer, Office of Air Quality Planning and Standards.

Preface

This document is a revision of the first (1986) edition of the Handbook. (See Reference 1, Section 1.3).

An associated project of upgrading a personal computer software package to accompany this handbook was undertaken concurrently and funded by the Control Technology Center (CTC). The software program (HAP PRO, version 1) is a revision of the earlier CAT (Controlling Air Toxics) program and is available from the CTC by calling 919/541-0800. (The CTC has plans to install the software on the CTC Bulletin Board, which is part of the OAQPS Technology Transfer Network, for ease of access to those with communication capabilities. Information on its availability may be obtained through the above-listed telephone number.) The handbook was the basis for the software design. This software was designed to be user-friendly and to duplicate the manual calculations of the handbook from user input data. The purpose of the software is to provide easy access to the calculational techniques in the handbook for those who have access to a personal computer.

The CTC was established by EPA's Offices of Research and Development and Air Quality Planning and Standards to provide technical assistance to State and local air pollution control agencies and EPA regional staff on air pollution control issues. Three levels of assistance can be accessed through the CTC. First, a CTC Hotline has been established to provide telephone assistance on matters relating to air pollution control technology. Second, more in-depth engineering assistance can be provided when appropriate. Third, the CTC can provide technical guidance through publication of technical guidance documents, development of personal computer software, and presentation of workshops on control technology matters.

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Nomenclature

θ = flame angle for flare, degrees
θ_{ad} = adsorption cycle time, hr
θ_{dcf} = bed drying and cooling fan operating time, hr
$\theta_{dry\text{-}cool}$ = bed drying and cooling time, hr
θ_{reg} = regeneration cycle time, hr
μ = gas viscosity, lb/ft-sec
μ_L = solvent viscosity, centipoise
µm = particle size, aerodynamic mean diameter
a = packing constant
A/C = air to cloth ratio, $(ft^3/min)/ft^2$
A_{bed} = bed area, ft^2
ABS = flooding correlation absicca
A_{column} = column area, ft^2
A_{con} = condenser surface area, ft^2
A_{cyc} = cyclone inlet area, ft^2
a_d = ductwork parameter
Aex = auxiliary equipment cost, $
AEC = annual electricity cost, $
a_f = fan parameter
AF = absorption factor
A_{nc} = net cloth area, ft^2
A_p = collection plate area, ft^2
a_s = stack parameter
ASR = annual solvent requirement, gal/yr
A_{tc} = gross or total cloth area, ft^2
b = packing constant
b_d = ductwork parameter
b_f = fan parameter
Bldg. = building cost, $
b_s = stack parameter
c = packing constant
C_B = bag costs, $
C_c = carbon cost, $

CC = catalytic incinerator cost, \$
C_{cl} = replacement labor cost, \$/lb
C_{CW} = cooling water cost, \$/1,000 gal
CE = collection efficiency, percent
CEC = canister equipment cost, \$
C_L = bag replacement labor, \$
Cp_{air} = mean specific heat of air, Btu/lb-°F
$Cp_{coolant}$ = average specific heat of coolant, Btu/lb-°F
Cp_{HAP} = specific heat of HAP, BTU/lb-mol °F
C_{RB} = cost of replacement bags, \$
CRC = carbon replacement cost, \$
CRCT = catalyst replacement cost, \$
CRF = capital recovery factor, decimal fraction
CRF_B = capital recovery factor for bags
CRF_C = capital recovery factor for carbon
C_{req} = amount of carbon required, lb
C'_{req} = amount of carbon required per vessel, lb
C_s = steam cost, \$
C_v = vessel cost, \$
d = packing constant
D = density, lb/ft^3
d_c = critical particle size, m
DAC = direct annual cost, \$
DC = direct capital cost, \$
D_{column} = column diameter, ft
d_{duct} = duct diameter, in
D_{duct} = duct diameter, ft
D_e = density of emission stream, lb/ft^3
DE = destruction efficiency, percent
D_f = density of fuel gas, lbs/ft^3
d_{fan} = diameter of fan, in
D_G = density of gas stream, lb/ft^3
D_{HAP} = density of HAP, lb/ft^3
D_L = density of liquid, lb/ft^3
D_p = particle diameter, µm
D_{tip} = flare tip diameter, in
D_v = vessel diameter, ft
D_w = density of water vapor, lb/ft^3
e = packing constant
EC = equipment cost, \$

f = flooding fraction
FC = flare cost, \$
F_m = material cost factor
Fp = fan power requirement, kWh/yr
FR_{dcf} = drying and cooling fan flow rate, ft^3/hr
g = packing constant
G = gas stream flow rate, lb/hr
G_{area} = gas stream flow rate based on cross-sectional area, lb/ft^2-sec
$G_{area,f}$ = gas stream flow rate of flooding, lb/ft^2-sec
g_c = gravitational constant, ft/sec^2
G_{mol} = gas stream flow rate, lb-moles/hr
ΔH = heat of vaporization, Btu/lb-mole
H = flare height, ft
HAP_{con} = moles of HAP condensed, moles/min
HAP_e = HAP emission stream concentration, ppmv
$HAP_{e,m}$ = moles of HAP in inlet stream, moles/min
HAP_o = HAP outlet concentration, ppmv
$HAP_{o,m}$ = moles of HAP in outlet stream, moles/min
H_{con} = enthalpy change of condensed vapors, Btu/min
h_d = emission stream desired heat content, Btu/scf
h_e = emission stream heat content, Btu/lb or Btu/scf
h_f = supplementary fuel heating value, Btu/lb
h_{flg} = flare gas heat content, Btu/scf
H_G = height of gas transfer unit, ft
H_L = height of liquid transfer unit, ft
H_{load} = condenser heat load, Btu/hr
H_{noncon} = enthalpy change of noncondensed vapors, Btu/min
H_{og} = height of overall gas transfer unit, ft
hp = horesepower requirement, hp
hp_{cw} = cooling water horsepower, hp
hp_{sf} = system fan horsepower, hp
HR = heat recovery in heat exchanger, percent
HRS = operating hours per year, hr/yr
H_{stack} = stack height, ft
Ht_{column} = column height, ft
Ht_{total} = total column heigh, ft
IAC = indirect annual cost, \$
IC = indirect capital cost, \$
k = empirical parameter

L = solvent flow rate, lb/hr
L'' = liquid flow rate, per cross-sectional area of column, lb/hr-ft^2
LEL = lower explosive limit, percent
L_{gal} = solvent flow rate, gal/min
L_{mol} = solvent flow rate, lb-moles/hr
L_v = vessel length, ft
$L_{w,a}$ = inlet lb H_2O/lb dry air
$L_{w,s}$ = saturated lb H_2O/lb dry air
m = empirical parameter or slope of equilibrium curve
M = molecular weight, lb/lb-mole
MC = annual maintenance cost, \$/yr
M_e = moisture content, percent
M_{HAP} = HAP inlet loading rate, lb/hr
MW_e = molecular weight of the emission stream, lb/lb-mole
MW_{flg} = molecular weight of the flare gas, lb/lb-mole
MW_{HAP} = molecular weight of HAP, lb/lb-mole
$MW_{solvent}$ = molecular weight of solvent, lb/lb-mole
n = efficiency, fraction
N = number of beds
NA = number of beds adsorbing
ND = number of beds desorbing
N_{og} = number of gas transfer units
O_2 = emission stream oxygen content, percent
OP = annual ESP operating power, kWh/yr
ORD = flooding correlation ordinate
ΔP = pressure drop, in. H_2O
P = system pressure drop, in. H_2O
P_a = pressure drop, lb/ft^2-ft
P_b = pressure drop for carbon adsorbers, in. H_2O
P_c = canister system pressure drop, in. H_2O
P_{cw} = cooling water price, \$1,000/gal
P_{cyc} = cost of cyclone, \$
P_{damp} = cost of damper, \$
P_{dcf} = bed cooling and drying fan power, kWh/yr
P_{def} = power requirement for the fan, kWh/yr
P_{divert} = cost of two-way diverter valve, \$
P_e = pressure, mm Hg
PEC = purchased equipment cost, \$
P_{fan} = cost of fan system, \$

P_{FRPD} = cost of FRP ductwork, $
P_{motor} = cost of fan motor and starter, $
P_{ms} = power requirement for fabric filters, kWh/yr
P_p = pump power requirement, kWh/yr
$P_{partial}$ = partial pressure, mm Hg or psia
P_{PVCD} = cost of PVC ductwork, $
P_{ral} = cost of rotary air lock for cyclone, $
P_s = steam price, $/1,000 lb
P_{stack} = cost of stack, $
P_{total} = pressure drop, in. H_2O
Pv = venturi scrubber pressure drop, in. H_2O
P_{vapor} = vapor pressure, mm Hg
Q_{com} = flow rate of combined gas stream, scfm
$Q_{coolant}$ = coolant flow rate, lb/hr
q_{cw} = cooling water flow rate, gal/min
Q_d = dilution air required, scfm
Q_e = emission stream flow rate, scfm
$Q_{e,a}$ = actual emission stream flow rate, acfm
$Q'_{e,a}$ = actual emission stream flow rate per adsorbing bed, acfm
$Q_{e,ad}$ = actual flow rate of dry air, acfm
$Q_{e,s}$ = saturated emission stream flow rate, acfm
Q_f = supplementary fuel gas flow rate, scfm
Q_{fg} = flue gas flow rate, scfm
$Q_{fg,a}$ = actual flue gas flow rate, acfm
Q_{flg} = flare gas flow rate, scfm
$Q_{flg,a}$ = actual flare gas flow rate, acfm
Q_L = liquid flow rate, gal/min
Q_{rec} = recovered product, lb/hr or lb/yr
Q_s = steam flow rate, lb/min
Q_w = volume of water added, ft^3/min
r = packing constant
r_p = density of particles in gas stream, lb/ft^3
R = gas constant
R_c = auxiliary equipment cost factor for carbon adsorption
RCN = required canister number
RE = removal efficiency, percent
Ref = refrigeration capacity, tons
R_{hum} = relative humidity, percent
RTCC = capital cost of refrigerant system, $

s = packing constant
S = vessel surface area, ft^2
SCA = specific collection plate area, ft^2/1,000 acfm
Sc_G = Schmidt number for gas
Sc_L = Schmidt number for liquid
S_g = specific gravity of fluid
SP = site preparation, $
St = steam regeneration rate, lb steam/lb carbon
SV = space velocity through catalyst bed, hr^{-1}
T = temperature, °R
ΔT_{LM} = log mean temperature difference, °F
TAC = total annual cost, $
t_b = bed thickness, ft carbon
T_c = combustion temperature, °F
TC = thermal incinerator cost, $
TCC = total capital cost, $
T_{ci} = temperature of gas stream entering catalyst bed, °F
T_{co} = temperature of flue gas leaving catalyst bed, °F
T_{con} = temperature of condensation, °F
$T_{cool,i}$ = inlet coolant temperature, °F
$T_{cool,o}$ = outlet coolant temperature, °F
T_e = emission stream temperature, °F
$T_{e,s}$ = saturation temperature, °F
T_{flg} = temperature of flare gas, °F
T_{he} = temperature of emission stream exiting heat exchanger, °F
t_r = residence time, sec
T_R = reference temperature, 77° F
U = overall heat transfer coefficient, Btu/hr-ft^2-°F
U_d = drift velocity, ft/sec (same as w_e = migration velocity, ft/sec)
U_{duct} = duct velocity, ft/min
U_e = emission stream velocity, ft/sec
UEL = upper explosive limit, percent
U_{flg} = flare gas exit velocity, ft/sec
U_{max} = maximum flare exit velocity, ft/sec
V_{bed} = volume of required catalyst bed, ft^3
V_c = combustion chamber volume, ft^3
$V_{packing}$ = packing volume, ft^3
VSC = venturi scrubber cost, $
V_w = wind velocity, mph

W_c = carbon bed working capacity, lb HAP/lb carbon

W_e = carbon bed equilibrium capacity, lb HAP/lb carbon

WR = water consumption, gal/yr

Y = packing constant

Z = fluid head, ft

Conversion Factors

Quantity	Equivalent Values	
Mass	1 kg	= 1000 g = 0.001 metric ton = 2.20462 lb_m = 35.27392 oz.
	I lb_m	= 16 oz = 5 x 10^{-4} ton = 453.593 g = 0.453593 kg
Length	1 m	= 100 cm = 1000 mm= 10^6 µm 10^{10} angstroms (A) = 39.37 in. = 3.2808 ft = 1.0936 yards = 0.0006214 mile
	1 ft	= 12 in. = 1/3 yd = 0.3048 m = 30.48 cm
Volume	1 m^3	= 1000 liters = 10^6 cm^3 = 10^6 ml = 35.3145 ft^3 = 220.83 imperial gallons = 264.17 gallons = 1056.68 quarts
	1 ft^3	= 1728 $in.^3$ = 7.4805 gallons = 0.028317 m^3 = 28,317 liters = 28,317 cm^3
Force	1 N	= 1 kg m/s^2 = 10^5 dynes = 10^5 g-cm/s^2 = 0.22481 lb_f
	1 lb_f	= 32.17 lb_m-ft/s^2 = 4.4482 N = 4.4482 x 10^5 dynes
Pressure	1 atm	= 1.01325 x 10^5 N/m^2 (Pa) = 1.01325 bars = 1.01325 x 10^6 dynes/cm^2 = 760 mm Hg @ 0°C (torr) = 10.333 m H_2O @ 4°C = 14.696 lb_f/ $in.^2$ (psi) = 33.9 ft H_2O @ 4°C = 29.921 in. Hg @ 0°C
Energy	1 J	= 1 N m = 10^7 ergs = 10^7 dyne-cm = 2.778 x 10^{-7} kWh = 0.23901 cal = 0.7376 ft-lb_f = 9.486 x 10^{-4} Btu
Power	1 W	= 1 J/s = 0.23901 cal/s = 0.7376 ft-lb_f/ s = 9.486 x 10^{-4} Btu/s = 1.341 x 10^{-3} hp

Example: The factor to convert grams to pound (mass) is $\frac{2.20462\ lb_m}{1000\ g}$ or 0.00220462 lb

Chapter 1

Introduction

1.1 Background and Objective

This manual is a revision of the first (1986) edition of the *Handbook: Control Technologies for Hazardous Air Pollutants,*[1] which incorporated information from numerous sources into a single, self-contained reference source focusing on the design and cost of VOC and particulate control techniques. However, many of the references used in the 1986 version were published in the mid-to-late 1970's, meaning some information in the first edition is somewhat dated. This is particularly true for the cost data presented in Chapter 5[1] which were based on 1977 data. Since that time, a great deal of design and cost information on selected control techniques has been published, and EPA concluded that this more recent information should be incorporated into a revised manual. This revision has been undertaken to incorporate more recent design and cost information where applicable, while adhering to the original focus and intent of the 1986 manual. The objective of this revised manual is described and the reader is introduced to its overall organization in the following paragraphs. A corresponding computer program (HAP PRO, Version 1.0), which performs the necessary calculations from user input data, is also available.[2]

The objective of this handbook is to present a methodology for determining the performance and cost of air pollution control techniques designed to reduce or eliminate the emissions of potentially hazardous air pollutants (HAPs) from industrial/commercial sources. (Note: The term "hazardous" in this document is very broad. It is not limited to the specific compounds listed under current regulations [i.e., the Clean Air Act, the Resource Conservation and Recovery Act, and the Toxic Substances Control Act].) This handbook is to be used by EPA regional, State, and local air pollution control agency technical personnel for two basic purposes: (1) to respond to inquiries from interested parties (e.g., prospective permit applicants) regarding the HAP control requirements that would be needed at a specified process or facility, and (2) to evaluate/review permit applications for sources with the potential to emit HAPs. It should be noted that this document provides general technical guidance on controls and does not provide guidance for compliance with specific regulatory requirements for hazardous air pollutants. Specifically, it does not specify design requirements necessary to achieve compliance with standards established under specific programs such as Section 112 of the Clean Air Act or standards established under the Resource Conservation and Recovery Act. Such requirements vary with the hazardous air pollutant emitted and with the emission source; thus, regulatory-specific detailed specifications are beyond the scope of this handbook.

The use of this handbook is discussed in Section 1.2. Chapter 2 assists the user in identifying HAPs and their respective potential emission sources. Chapter 2 also identifies the key emission stream characteristics necessary to select appropriate control techniques. Chapter 3 provides additional information to assist the user in the control technique selection process for each HAP emission source/stream. Chapter 4 presents simple step-by-step procedures to determine basic design and cost parameters of the specific control devices and auxiliary equipment. The capital and annual costs obtained for a given control system reflect study-type (±30 percent) estimates in Appendices A and B. Supplementary data and calculation procedures are presented. Appendix C contains blank worksheets to be used while performing the functions described in this handbook. These worksheets are masters from which to make copies.

A good source of current information pertaining to HAPs is the "National Air Toxics Information Clearinghouse," which was established by EPA in response to State and local agency requests for assistance in the exchange of information on toxic air pollutants. The Clearinghouse is operated by EPA's Office of Air Quality Planning and Standards (OAQPS) in close coordination with the State and Territorial Air Pollution Program Administrators (STAPPA) and the Association of Local Air Pollution Control Officials (ALAPCO). Information from State and local agencies is collected and disseminated at the Clearinghouse, along with making users aware of air toxics information available from EPA and other Federal agencies. Specifically, the following air toxic information is collected from State and local agencies: regulatory program descriptions, acceptable ambient concentrations on ambient standards, toxic pollutant research, source permitting, ambient monitoring, toxicity testing, and source testing.

The Clearinghouse provides an on-line data base containing all toxic-related information submitted by State and local agencies, bibliographic citations for relevant reports by EPA and other Federal agencies, and references for ongoing EPA air toxic projects is provided at the Clearinghouse. A quarterly newsletter is published also with articles on current air toxics concerns. Finally, the Clearinghouse periodically publishes various special reports on topics of interest to users. For further information regarding the "National Air Toxics Information Clearinghouse," contact the appropriate EPA regional office air toxics contact, or EPA/OAQPS, Pollutant Assessment Branch, MD-12, Research Triangle Park, North Carolina 27711; (919) 541-5645 or FTS 629-5645.

An additional source of information on potential toxic pollutants is the Toxic Air Pollutant/Source Crosswalk: A Screening Tool for Locating Possible Sources Emitting Toxic Air Pollutants, Second Edition, EPA 450/2-89-017, December 1989[3]. A qualitative indication of potential toxic pollutants for a given SIC or SCC process is provided in this document. Some of the information contained in this source has been used to update appropriate tables presented in Chapter 2. This reference utilizes information contained in the National Air Toxics Information Clearinghouse (NATICH, mentioned above), the Specific Toxic Chemical Listings for Title III, Section 313 (SARA Title III), the Volatile Organic Compound (VOC) Species Data Manual (2nd edition), and the National Emissions Data Systems (NEDS) Source classification codes (SCC) and emission factor listings.

1.2 How to Use the Handbook

Figure 1.1 is a flowchart of the steps performed when responding to inquiries; Figure 1.2 contains the same type of flowchart when reviewing permits. As shown by these figures, these two functions are basically the same; the only substantive difference is that the review process also compares the determined/calculated parameters with the corresponding parameters stated in the permit application to ensure that the control system(s) proposed by the applicant will provide the required reduction of HAP emissions.

Once an inquiry or permit application is received, determine the HAPs applicable to the source category in question (Section 2.2. The HAPs are categorized under four headings: organic vapor, organic particulate, inorganic vapor, and inorganic particulate. (**Note**: For each HAP group, a list of potentially or suspected hazardous compounds that may be emitted as a HAP from the source category is provided. This listing is neither all-inclusive nor a declaration that the compounds presented are hazardous.) Next, identify the potential emission sources for each HAP group (Section 2.2). The HAP emission sources are listed under one of three classifications: process point sources, process fugitive sources, and area fugitive sources. (**Note**: See Section 2.2 for classification definitions.) After each emission source is determined, identify the key HAP emission stream characteristics (e.g., HAP concentration, temperature, flow rate, heat content, particle size) needed to select the appropriate control technique(s) (Section 3.2). Obtain the actual values for these characteristics from the owner/operator or from available literature if the owner/operator cannot provide the necessary data. If two or more emission streams are combined prior to entry into an air pollution control system, determine the characteristics of the combined emission stream (Appendix B.1).

Depending upon the specific regulation and the type/characteristics of the HAP emission source/stream, the remaining steps in the methodology will differ. Four basic "formats" for a regulation are: (1) a particular "control device" may be required, (2) a "numerical limit" may be specified, (3) a "technology forcing" requirement may be imposed, and (4) a specific work practice or "other" related practice may be required. The regulation format will define the steps that lead to the selection of the appropriate control technique(s). The "control device" and "other" formats specify the appropriate control technique(s). A "numerical limit" format requires the determination of the HAP removal efficiency before the appropriate control technique(s) can be identified. Lastly, the "technology forcing" format has two paths: one where the cost of the control system is a factor in the decision, and one where cost is not a factor. If control system cost is a factor, the agency must determine the cost constraints that will be imposed on the control technique selection process (e.g. $/ton). The steps that occur in defining the HAP control requirements will depend upon each agency's regulatory policies.

The HAP emission stream characteristics, in conjunction with the limitations imposed by the applicable regulations, are used to select the appropriate control techniques (Chapter 3) for each HAP emission source/stream. General guidelines are provided that match specific control devices with specified emission stream properties (e.g., HAP content, temperature, moisture, heat content, particle size, flow rate). Basic design parameters are then determined to provide general design conditions that should be met or exceeded for each selected control technique to achieve the specified HAP removal efficiency (Chapter 4). This exercise also identifies which of the selected control techniques will not achieve the desired HAP control requirement. The basic design parameters calculated in Chapter 4 are used to obtain a "study-type" cost estimate for each control device. The cost algorithm follows the design variables for each control technique that is presented in Chapter 4. As noted above, this cost information can be an integral part of the HAP control system selection process. After completing the above process, a HAP control program can be recommended or evaluated.

Figure 1.1 Steps used when responding to inquiries.

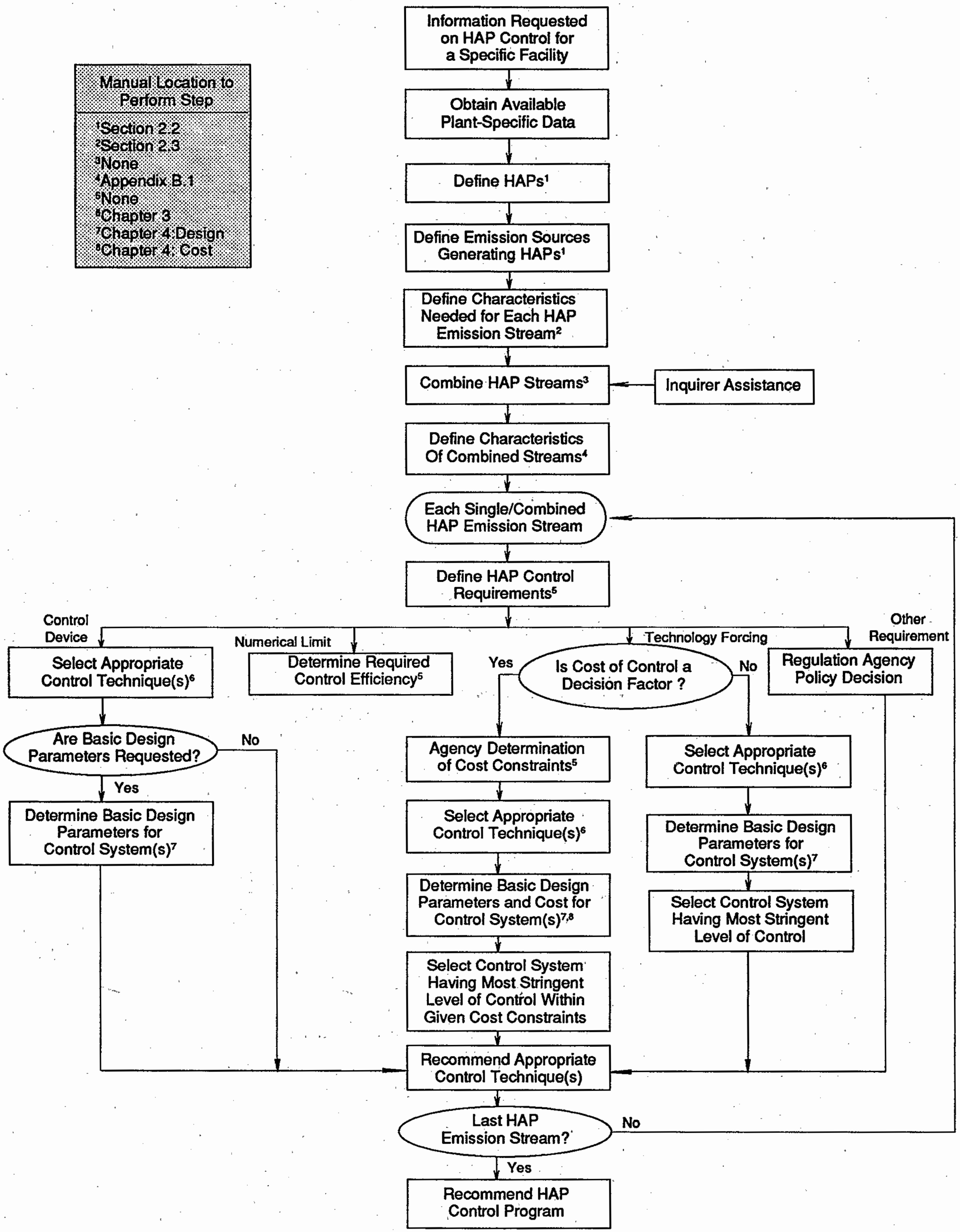
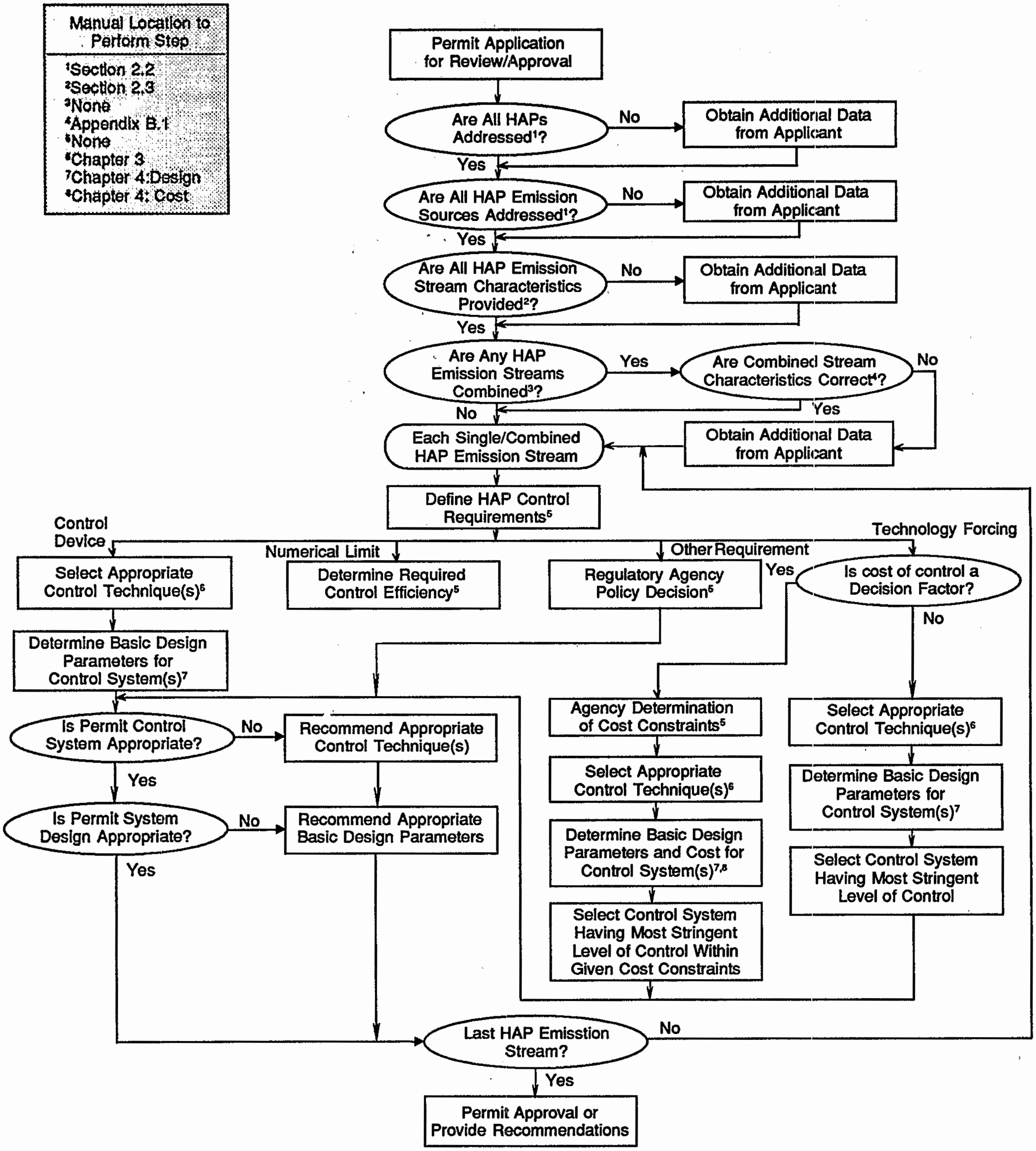


Figure 1.2. Steps used when reviewing permits.



Example Case

To guide the user through the steps and calculations described in this handbook, examples are provided throughout the text. As shown here, each example is always highlighted by a surrounding box and is shaded within the box. Example cases are presented for all streams given in Chapter 3 and are related to the appropriate control device design and cost information presented in Chapter 4.

1.3 References

1. U.S. EPA. Handbook: Control Technologies for Hazardous Air Pollutants, EPA/625/6-86/014 (NTIS PB 91-228809). Cincinnati, OH. September 1986.

2. U.S. EPA. HAP PRO: Software Program for Control Technologies for HAP, Control Technology Center, Research Triangle Park, NC. June 1991.

3. U.S. EPA. Evaluation of Control Technologies for Hazardous Air Pollutants, Volume 2. Appendices. EPA/600/7-86/009b (NTIS PB 86-167038). Research Triangle Park, NC. February 1986.

4. U.S. EPA. Toxic Air Pollutant/Source Crosswalk: A Screening Tool for Locating Possible Sources Emitting Toxic Air Pollutants, Second Edition. EPA/450/2-89/017 (NTIS PB 90-170002). Research Triangle Park, NC. December 1989.

Chapter 2

HAP Emissions by Source Category and Key Physical Properties

2.1 Background

The primary goal of this chapter is to identify the following: (1) potential HAPs for a given source category and the specific sources that may emit the potential HAPs and (2) key emission stream physical properties needed to select appropriate control strategies and size control devices for the HAP emission sources. Specific source categories are divided into nine general classifications in this manual. [**Note:** The general classification system is a hybrid of the classification systems used in references 6 and 78.] Every possible source category cannot be listed; however, similarities exist between many categories. Thus, the user should be able to obtain some guidance for any specific facility. Common source categories that are known to emit potential HAPs are presented in this manual. The tables in this chapter have been updated to incorporate recent information on additional potential pollutants for the source categories. Appendix A.1 contains a list of compounds currently considered hazardous along with the corresponding CAS number. While a list of hazardous compounds is provided in this table, the user should not necessarily use it as a definitive guide. As discussed in Chapter 1, the term "HAP" is broad and encompasses numerous compounds. This appendix is designed to assist in determining HAPs, rather than act as a definitive list. Other information sources discussed in Chapter 1 can also be used to obtain information on HAPs from a given source.

An original intent was to provide the reader with a table listing potential pollutants on an SIC and SCC basis. In other words, given a particular SIC or SCC facility, the potential pollutants expected to be emitted from this facility would be listed. This table would enable the reader to target industries or source categories having the potential to emit a given HAP or HAPs. However, given the length of this list as presently compiled (over 350 pages) it was decided to instead refer the reader to Reference 76 to obtain this list. Appendix A.2 gives the cover page and the first page of this table is listed in Appendix A.2 so that the reader can be certain he is referencing the correct document and table.

Individual source categories have been classified based on the manufacturing process associated with emissions of potential HAPs. The Solvent Usage Operations classification includes processes dependent on solvents, such as surface coating and dry cleaning operations. Individual HAPs from this category are given in Appendix A.3. Metallurgical Industries include processes associated with the manufacture of metals, such as primary aluminum production. Processes and operations associated with the manufacture of organic and inorganic chemicals have been grouped into the Synthetic Organic and Inorganic Chemical Manufacturing classifications, respectively. Industries using chemicals in the formulation of products are classified as Chemical Products Industries. The Mineral and Wood Products Industries classifications include operations such as asphalt batch plants and kraft pulp mills, respectively. The Petroleum Related Industries classification is defined as oil and gas production, petroleum refining, and basic petrochemicals production. Combustion Sources are utility, industrial, and residential combustion sources using coal, oil, gas, wood, or waste-derived fuels.

To assist the manual user in recording the pertinent information, a worksheet has been provided. A copy of this worksheet, the "HAP Emission Stream Data Form," is presented in Appendix C.1. An example of a partially completed worksheet is shown in Figure 2.1. This worksheet is designed to record information pertaining to one emission stream, be it a single stream or a combined stream consisting of several single streams.

Example Case

Information has been requested by a paper coating plant owner regarding the control of an emission stream from his facility's drying operations. The most likely generic classification to include a paper coating plant (one of many surface coating industries) would be Solvent Usage Operations. To determine if a paper coating facility is listed within this category, Section 2.1 and Table 2.1 should be reviewed. An inspection of Table 2.1 indicates that the initial choice was correct (i.e., paper coating is listed under SC-Paper, Tapes, Labels). Preliminary information on potential HAP emissions is then obtained by consulting Appendix A.3.

*Figure 2.1. HAP emission stream data form**

Company: Glaze Chemical Company
Location (Street): 87 Octane Drive
(City): Somewhere
(State, Zip):

Plant Contact : Mr. John Leake
Telephone No: (999) 555-5024
Agency Contact: Mr. Efrem Johnson
No. of Emission Streams Under Review: 7

A Emission Stream Number/Plant Identification #1 / #3 Oven Exhaust

B.	HAP Emission Source	(a) paper coating oven	(b)	(c)
C.	Source Classification	(a) process point	(b)	(c)
D.	Emission Stream HAPs	(a) toluene	(b)	(c)
E.	HAP Class and Form	(a) organic vapor	(b)	(c)
F.	HAP Content (1,2,3)**	(a) 960 ppmv	(b)	(c)
G.	HAP Vapor Pressure (1,2)	(a) 28.4 mm Hg at 77° F	(b)	(c)
H.	HAP Solubility (1,2)	(a) insoluble water	(b)	(c)
I.	HAP Adsorptive Prop. (1,2)	(a) provided	(b)	(c)
J.	HAP Molecular Weight (1,2)	(a) 92 lb /lb.-mole	(b)	(c)

K. Moisture Content (1,2,3) 2% vol.
L. Temperature (1,2,3) 120° F
M. Flow Rate (1,2,3) 15,000 scfm (max)
N. Pressure (1,2) atmospheric
O. Halogen/Metals (1,2) none / none

P. Organic Content (1)*** 100 ppmv CH_4
Q. Heat/O_2Content (1) 4.1 scf/20.6 vol%
R. Particulate Content (3)
S. Particle Mean Diam. (3)
T. Drift Velocity/SO_3 (3)

U. Applicable Regulation(s)
V. Required Control Level
W. Selected Control Methods

* The data presented are for an emission stream (single or combined streams) prior to entry into the selected control method(s). Use extra forms if additional space is necessary (e.g., more than three HAPs) and note this need.

** The numbers in parentheses denote what data should be supplied depending on the data on lines C and E.
1 = organic vapor process emission
2 = inorganic vapor process emission
3 = particulate process emission

*** Organic emission stream combustibles less HAP combustibles shown on lines D and F.

2.2 Identification of Potential HAPs and Emission Sources

The purpose of this section is to present general information on emissions of potential HAPs by source category. Within each of the nine general classifications, information is presented on the types of potential HAPs that may be emitted by a particular source category. This information includes the names of specific compounds, the classification of the compounds (i.e., organic or inorganic), and the form in which these compounds would be emitted (i.e., vapor or particulate). Owing to process variations, actual emissions from specific facilities may differ from the general information presented. Complete identification of HAP emissions is best accomplished with assistance from the owner/operator of the facility.

Information on source categories is related to applicable SIC and SCC codes. Given the numerous SCC codes applicable to some source categories, the last two digits of the applicable SCC codes have been designated xx to make the SCC codes more generic. This indicates that all specific SCC classifications are included within that designation. For example, an SCC code designated 4-90-001-xx would include the following SCC codes: 4-90-001-01, 4-90-001-02, 4-90-001-03, 4-90-001-04, 4-90-001-05, and 4-90-001-99. This was done to avoid a lengthly list of SCC codes. In some instances, the SCC code has been broadened further, with the last five digits (instead of the last two) being unspecified.

This section also presents information pertaining to the sources (e.g., processes) within each specific source category that have the potential to emit HAPs. In this manual, emission sources are broadly classified into three groups: process point sources, process fugitive sources, and area fugitive sources. Point sources are, in general, individually defined. Reactors, distillation columns, condensers, furnaces, and boilers are typical point sources which discharge emissions through a vent-pipe or stack. These sources can be controlled through the use of add-on control devices. Process fugitive sources, like process point sources, are individually defined. Emissions from these sources include dust, fumes, or gases that escape from or through pumps, valves, compressors, access ports, and feed or discharge openings to a process (e.g., the open top of a vapor degreaser). Process fugitive sources also can include vent fans from rooms or enclosures containing an emissions source (e.g., a vent fan on a dry cleaner). These sources can be controlled by add-on control devices once the emissions are captured by hooding, enclosures, or closed vent systems and then transferred to a control device.

Area fugitive sources are characterized by large surface areas from which emissions occur. Area fugitive sources

Table 2.1. Potential HAPs and Emission Sources for Solvent Usage Operations

Source Category	Potential HAPs[a]				Potential Emission Sources		
	Organic		Inorganic		Process	Process	Area
	Vapor	Particulate	Vapor	Particulate	Point	Fugitive	Fugitive
Solvent Degreasing	x				A,B,C,D	A,B,D	K
Dry Cleaning	x				E,F,G	E,G,H,I	I,J,K
Graphic Arts[b]	x				F,L,M,N	L,M,N	
Waste Solvent Reclaiming	x				N	I	J,K
SC[c]-Flatwood Paneling[d]	x				L,O,P	L,P	
SC-Machinery[e]	x		x		O,Q,R	Q,R	
SC-Appliances[f]	x		x		O,Q,R	Q,R	
SC-Metal Furniture	x		x		O,Q,R	Q,R	
SC-Auto/Truck[g]	x		x		O,R,S	S,R	
SC-Fabrics	x				O,Q,R,T	D,K,Q,R,T	
SC-Cans[h]	x				O,Q,U	Q,U	
SC-Paper, Tapes, Labels	x				O,Q,T	B,I,Q,T	
Magnetic Tape Coating	x				F,Q,T	I,Q,T	
SC-Electrical Insulation	x				O,Q	Q	
SC-Marine Vessels[i]	x		x				Q
Vinyl & Acrylic Coatings[j]	x				O,L,P	L,P	
SC-Wood Furniture	x				O,R,S,T	S,R,T	
SC-Trans. Vehicles[k]	x		x		R,S	R,S	
Machine Lubricants	x						Q
Rubber Tire Manufacturing	x				F	I,V,W	

Source Key

A - bath evaporation
B - solvent transfer
C - ventilation
D - waste solvent disposal
E - washer
F - drying
G - still, filtration

I - solvent storage
J - pipes, flanges, pumps
K - transfer areas
L - rollers
M - ink fountains
N - condenser
O - oven

Q - application area
R - flashoff area
S - spray booth
T - solvent/coating mixing
U - quench area
V - green tire spraying
W - sidewall/tread end/undertreated cementing

[a] References 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 13, 26, 27, 76.
[b] Category includes flexography, lithography, offset printing, and textile printing.
[c] SC: surface coating.
[d] Category includes coating of other flat stock.
[e] Category includes coating of misc. metal parts, machinery, and equipment.
[f] Category includes all categories of appliances: Large and small.
[g] Category includes coating of automobiles and light-duty trucks.
[h] Category includes surface coating of coils, cans, containers, and closures.
[i] Category includes coating and maintenance of marine vessels.
[j] Category includes vinyl, acrylic, and nitrocellulose coatings.
[k] Category includes coating of trucks, buses, railroad cars, airplanes, etc.

include large and undefined emission sources such as waste treatment lagoons, raw material storage piles, roads, etc.

The sources listed in this manual generate emissions; however, a definitive statement as to whether they emit a HAP cannot be made. As in the case of identifying the potential HAPs emitted at a specific facility, communication with the owner/operator is useful in identifying each source that emits a HAP. The listings found in this section are not all-inclusive; a specific facility may have an emission-producing operation that is not common to its industry and, thus, the source may not be included here.

2.2.1 Solvent Usage Operations

Solvent usage operations are defined as manufacturing processes that use solvents, including such processes as surface coating operations, dry cleaning, solvent degreasing, waste solvent reclaiming, and graphic arts. The majority of solvent usage operations falls under SIC codes 2842, 2865, 2869, 2899, and 2911; and SCC codes 4-90-001-xx, 4-90-900-xx, and 4-90-999-xx. Table 2.1 lists source categories within this group of operations that have been identified as sources of volatile organic compound emissions that may include potential HAPs. As is shown by Table 2.1, all solvent usage operations generate organic vapor emissions. [**Note:** Some of the emission sources generate aerosols (i.e., organic particulate); however, the aerosols evaporate in a short time and the emissions normally are controlled as a vapor. Therefore, Table 2.1 does not indicate the presence of organic particulates.] Due to the large number of potential HAPs associated with these types of operations, the format of Table 2.1 prohibits the inclusion of compound-specific data. Potential HAPs that may be emitted by sources in Table 2.1 are summarized in Appendix A.3; this appendix lists both specific compounds and classes of compounds that may be emitted by sources within the

Example Case

As directed in Section 2.1., Appendix A.3 is used to determine the potential HAPs. The potential HAPs for paper coating operations are as follow:

Specific Compounds	Generic Compounds
toluene	mineral spirits
xylene	other aromatics
ethylene glycol	alcohols
acetone	cellusolves
methyl ethyl ketone	ketones
methyl isobutyl ketone	esters
ethyl acetate	

Upon reviewing data from the solvent vendor, the owner determined that only toluene is present in the solvent being evaporated by the ovens. Table 2.1 indicates that toluene is an organic compound, and it would be emitted as a vapor. This information is then listed on the "HAP Emission Stream Data Form" provided in Appendix C.1 (see Figure 2.1).

Also for the example case, the source (oven: a process point source) was identified. If the user were interested in the other emission-releasing processes at a paper coating operation, Table 2.1 indicates that the remaining sources include solvent transfer, solvent storage, application areas, and solvent/coating mixing.

category. Appendix A.3 can be used to make a preliminary determination of whether a particular solvent usage operation may emit a specific potential HAP or group of potential HAPs, as well as to determine potential solvent use operations that may emit a particular HAP. Table 2.1 presents the emission sources that may emit potential HAPs. Note that the same source may be given under a process point and a fugitive source, to account for different facilities.

2.2.2 Metallurgical Industries

The metallurgical industries can be broadly divided into primary, secondary, and miscellaneous metal production operations. The majority of this industry is covered under SIC Codes 331, 332, 333, 334 and 336 and SCC codes 3-03-001-xx through 3-03-010-xx and 3-04-001-xx through 3-04-010-xx. The term "primary metals" refers to production of the metal from ore. The secondary metals industry includes the recovery of metal from scrap and salvage and the production of alloys from ingots. The miscellaneous subdivision includes industries with operations that produce or use metals for final products. Table 2.2 contains the potential HAPs for these industries and the industry-specific emission sources. Given the array of potential sources, it is best to obtain specific information must be obtained from the permit applicant for this source category.

2.2.3 Synthetic Organic Chemical Manufacturing Industry (SOCMI)

The SOCMI is a large and diverse industry producing several thousand intermediate and end-product chemicals from a small number of basic chemicals. Most of the chemicals produced by this industry fall under SIC Code 286. Specific SCC codes for this source category are too numerous to list, but most fall under SCC code 3-01-xxx-xxx. Due to the complexity of the SOCMI, a general approach is used in this section to describe generic emission sources and specific emission source types. This approach is identical to the approach used by EPA in its efforts to develop new source performance standards for the SOCMI.

A large proportion of the emissions from the SOCMI occur as organic vapors. However, organic particulate emissions may be generated in some processes (usually during the manufacture of chemicals that exist as solids at ambient conditions). The emissions typically contain raw materials (including impurities) used in and intermediate and final products formed during the manufacturing process. Many of these emission streams may contain HAPs due to the great number of compounds manufactured in the SOCMI.

Potential emissions from this industry can be described generically as follows:

(a) storage and handling emissions,
(b) reactor process emissions,
(c) separation process emissions,
(d) fugitive emissions, and
(e) secondary emissions (e.g., from waste treatment).

Emissions can potentially occur from raw materials and product storage tanks as working and breathing losses through vents. Emissions from handling result during transportation or transfer of the volatile organic liquids. Reactor processes and separation processes are the two broad types of processes used in manufacturing organic chemicals. Reactor processes involve chemical reactions that alter the molecular structure of chemical compounds. A reactor process involves a reactor, or a reactor in combination with one or more product recovery devices. Product recovery devices include condensers, adsorbers, and absorbers. Emissions from reactor processes occur predominantly from venting of inert gases from reactors and product recovery devices, or from the release of organic compounds that cannot be recovered economically. Typical emission sources in reactor processes include point sources (e.g., vents on reactors and product recovery devices), process fugitive sources such as disposal of bottoms from the reactor or the product recovery devices, and area fugitive sources (e.g., pumps, valves, sampling lines, and compressors).

Separation processes often follow reactor processes and divide chemical product mixtures into distinct frac-

Table 2-2. Potential HAPs and Emission Sources for Metallurgical Industries

Source Category	Potential HAPs[a]				Potential Emission Sources		
	Organic		Inorganic				
	Vapor	Particulate	Vapor	Particulate	Process Point	Process Fugitive	Area Fugitive
Primary Aluminum Production			12,32,33	12,32,33	A,I,J,M,N,R	H,K,D	N,Q,U,Z
Primary Cadmium Production				9	J,E	O,P	N,Z
Metallurgical Coke	3,8,13,19,21,23, 26,27,28,30	18	4,29	1,5,6,7,9,14, 15,16,17,20,22	B	C,O,X	N,D,Q,U
Primary Copper Smelting		18	1,12,31	1,5,9,11,14, 15,17,20,24	F,J,T	G,H,K,O,P,X	N,Q,U,W,Z
Ferroalloy Production		18		9,10,11,14,16, 17,22,24	J	H,K,O,P	N,Q,W
Iron and Steel Production		18	12	6,9,10,11,14, 16,17,22,24	B,J,V	C,H,K,O,X	D,N,Q,U,W,Z
Primary Lead Smelting		18	1,12	1,5, 9,11,14,15,20	J,V	H,K,O,P	N,Q,U,W,Z
Primary Zinc Smelting		18	1,12	1,5,9,11,14,15 20,24	E,J,T,S	O	N,Q,U,W,Z
Manganese Production		18		16	J	H,K,M,P	N,Q,Z
Nickel Production		18	1,12	1,9,14,17,20,24	A,I,J,M,T	P	N,Q,Z
Secondary Aluminum Operations			12	12,17	J	H,K,P	U
Secondary Copper Operations (Brass and Bronze Production)		18	24	9,11,14,17,20,24	J	H,K,P	U
Gray Iron Foundries	2,3,13,19,21,23	18		1,6,7,9,10,11,14, 15,16,17,22,24,25	J,Y	H,K,G,P	U
Secondary Lead Smelting		18		1,14,16,20	J	H,K,P	U,Q
Steel Foundries				1,7,10,11,14, 16,17,24,25,34	J,Y	G,H,K,P	U
Secondary Zinc Processing			24	9,15,17,20,24	J,E,S	H,K,L,P	U
Lead Acid Battery Production			14	14		O,P	
Cadmium-Nickel Battery Production				9,14	V	N,O	
Dry Battery Production				16		M,N,O	
Misc. Lead Products			14	5,14		G,O,P	

Pollutant Key

1 - arsenic
2 - acrolein
3 - acetaldehyde
4 - ammonia
5 - antimony
6 - barium
7 - beryllium
8 - benzene
9 - cadmium
10 - chromium
11 - copper
12 - fluorides
13 - formaldehyde
14 - lead
15 - mercury
16 - manganese
17 - nickel
18 - polycyclic organic matter (POM)
19 - phenol
20 - selenium
21 - toluene
22 - vanadium
23 - xylene
24 - zinc
25 - iron
26 - cresols
27 - cyanides
28 - pyridine
29 - hydrogen sulfide
30 - methyl mercaptan
31 - sulfuric acid
32 - chloride
33 - hydrogen chloride

Source Key

A - calciner
B - coke oven
C - coke oven charging/pushing
D - coke quenching
E - condenser
F - converter
G - converter/charging etc.
H - furnace tapping
I - furnace material handling
J - furnace
K - furnace charging
L - galvanizing vessel
M - material crusher/mill
N - material storage and handling
O - material preparation
P - metal casting
R - reduction cell
S - retort
T - roaster
U - service road
V - sintering machine
W - slag dumping
X - vessel leakage
Y - foundry mold & core decomposition
Z - mining operations

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[a] References 6, 14, 15, 16, 17, 18, 19, 20, 21, 23, 24, 25, 28, 29, 30, 76.

tions. Emissions from separation processes are associated primarily with absorption, scrubbing, and distillation operations. Other separation processes that may contribute to emissions include drying, filtration, extraction, settling, crystallization, quenching, evaporation, ion exchange, dilution, and mixing/blending. One of the more commonly employed separation techniques is distillation. Depending on the type of distillation system used (i.e., vacuum or nonvacuum), typical emission points can include condensers, accumulators, hot wells, steam jet ejectors, vacuum pumps, and pressure relief valves. Emission points from a vacuum distillation system are shown in Figure 2.2.

Although fugitive emissions are listed as a separate group, they can occur from storage and handling, reactor processes, and separation processes. Area fugitive sources include groups of valves, pressure relief devices, pumps and compressors, cooling towers, open-ended lines, and sampling systems. Process fugitive sources include hotwells, accumulators, and process drains from reactors, product recovery devices, and separation equipment.

Table 2-3. Emission Sources for the SOCMI[a]

	Potential Emission Sources (Specific)		
Generic Source Category	Process Point	Process Fugitive	Area Fugitive[b]
Storage and Handling		A	B,C,D
Reactor Processes	E,F	G	C,D,H,I,J,K
Separation Processes	F,L	G,M,N	K
Fugitives		G,M,N	B,C,D,H,I J,K,M,N,O

Source Key

A - storage, transfer, and handling
B - spills
C - valves
D - flanges
E - reactors
F - product recovery devices (absorber, adsorber, condenser)
G - process drains
H - pumps
I - compressors
J - sampling lines
K - pressure relief devices
L - separation devices (distillation column, absorber, crystallizer, dryer, etc.)
M - hotwell
N - accumulator
O - cooling tower

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[a] References 12, 31, 32, 33, 34, 35 and 77.

[b] Groups of small point sources (e.g., valves, compressors, pumps, etc.) at a SOCMI plant are considered as area fugitive sources in this manual.

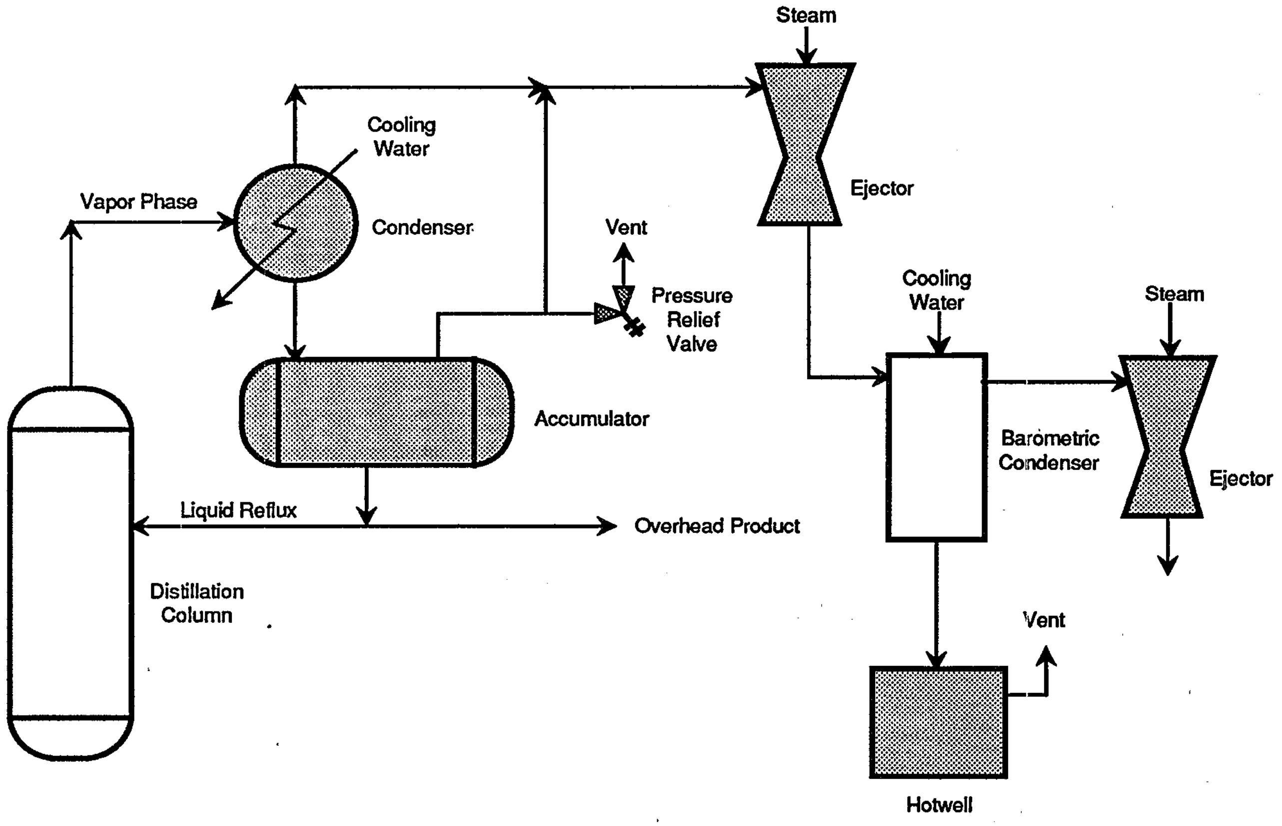

Figure 2.2. Potential emission points (shaded) from a vacuum distillation unit

Table 2.3 presents information on specific emission points and emission source types for each of the generic emission source groups. Using this information, the user can identify the potential emission sources pertaining to his specific situation. It is recommended that the user supplement this information with specific source data given the variability of this source category.

2.2.4 Inorganic Chemical Manufacturing Industry

This industry includes the manufacture of the basic inorganic chemicals before they are used in the manufacture of other chemical products. Most of the chemicals produced by this industry fall under SIC Code 281 and SCC codes 3-01-011-xx, 3-01-012-xx, 3-01-023-xx, 3-01-032-xx, and 3-01-035-xx through 3-01-039-xx. Potential emissions from these processes may be high, but because of economic reasons they are usually recovered. In some cases, the manufacturing operation is run as a closed system, allowing little or no emissions to escape to the atmosphere. Table 2.4 contains the potential HAPs and the industry-specific emission sources for these industries.

2.2.5 Chemical Products Industry

This industry includes the manufacture of chemical products, such as carbon black, synthetic fibers, synthetic rubber and plastics, which may be used in further manufacture. Also included are the manufacture of finished chemical products for ultimate consumption such as pharmaceutical, charcoal, soaps and detergents; or products to be used as materials or supplies in other industries such as paints, pesticides, fertilizers and explosives. Most of the chemical products are covered under SIC Codes 282, 283, 284, 285, 287 and 289. Specific SCC codes for this source category are too numerous to list. As in other chemical industries, the potential emissions from these processes may be high, but because of economic necessity they are usually recovered. Table 2.5 contains the potential HAPs and the industry-specific emission sources for this industry.

2.2.6 Mineral Products Industry

This industry involves the processing and production of various nonmetallic minerals. The industry includes cement production, coal cleaning and conversion, glass and glass fiber manufacture, lime manufacture, phosphate rock and taconite ore processing, as well as various other manufacturing processes. A majority of this industry falls under SIC Codes 142, 144, 145, 147, 148, 149, 321, 322, 323, 324, 325, and 327. Applicable SCC codes generally fall under 3-05-xxx-xx. Table 2.6 contains the potential HAPs and the industry-specific emission sources for this industry.

2.2.7 Wood Products Industry

The wood products industry involves industrial processes that convert logs to pulp, pulpboard, hardboard, plywood, particleboard, or related wood products and wood preserving. This industry falls under SIC Codes 242, 243, 249, and 261. Specific SCC codes for this source category included 3-07-007-xx, 3-07-008-xx, and 3-07-030-xx. Chemical wood pulping involves the extraction of cellulose from wood by dissolving the lignin that binds the cellulose fibers together. The principal processes used in chemical pulping are the kraft, sulfite, and neutral sulfite. Plywood production involves the manufacturing of wood panels composed of several thin wood veneers bonded together with an adhesive. The wood preserving process is one in which sawn wood products are treated by injection of chemicals that have fungistatic and insecticidal properties or impart fire resistance. Table 2.7 contains the potential HAPs and the industry-specific emission sources for this industry.

2.2.8 Petroleum Related Industries

In this manual, the petroleum related industries source category includes the oil and gas production industry, the petroleum refining industry, and the basic petrochemicals industry; these industries fall under SIC Codes 13 and 29. SCC codes for this source category include 3-06-xxx-xx, 3-01-001-xx, 3-01-002-xx, 3-01-004-xx, and 3-01-888-xx.

The oil and gas production industry includes the following processes: exploration and site preparation, drilling, crude processing, natural gas processing, and secondary or tertiary recovery. The principal products of this industry are natural gas and crude oil.

The petroleum refining industry involves various processes that convert crude oil into more than 2,500 products, including liquefied petroleum gas, gasoline, kerosene, aviation fuel, diesel fuel, a variety of fuel oils, lubricating oils, and feedstocks for the petrochemicals industry. The different processes involved in the petroleum refining industry are: crude separation, light hydrocarbon processing, middle and heavy distillate processing, and residual hydrocarbon processing.

In the basic petrochemicals industry, hydrocarbon streams from the oil and gas production and petroleum refining industries are converted into feedstocks for the organic chemical industry. These feedstocks include benzene, butylenes, cresol and cresylic acids, ethylene, naphthalene, paraffins, propylene, toluene, and xylene. The main processes used by this industry are separation, purification, and chemical conversion processes.

Table 2.8 contains the potential HAPs that may be emitted from these industries. More specific information is provided in Table 2.9 on potential emissions from the petroleum refining industry segment of this generic category. A large proportion of the emissions occur as organic vapors; for example, benzene, toluene, and xylenes are the principal organic vapor emissions. This is due to the chemical composition of the two starting materials used in these industries: crude oil and natural gas. Crude oil is composed chiefly of hydrocarbons (paraffins, naphthalenes, and aromatics) with small amounts of trace elements and organic compounds containing sulfur, nitrogen, and oxygen. Natural gas is largely saturated hydrocarbons (mainly methane). The remainder may include nitrogen, carbon dioxide, hydro-

Table 2-4. Potential HAPs for Inorganic Chemical Manufacturing Industry

Source Category	Potential HAPs[a]		Potential Emission Sources		
	Inorganic		Process Point	Process Fugitive	Area Fugitve
	Vapor	Particulate			
Aluminum chloride	4,10		X	X	
Aluminum fluoride	17		X	X	
Ammonia	1		B,D,E	K	J,S
Ammonium acetate	1		X	X	
Ammonium-nitrate, sulfate thiocyanate, formate, tartrate	1		C,F,I,L	Q	
Ammonium phosphate	1,17		X	X	
Antimony oxide	5		X	X	
Arsenic-disulfide, iodide pentafluoride, thioarsenate tribromide, trichloride, trifluoride, trioxide orthoarsenic acid	2	2	H,U	K,Q,T	J,S
Barium-carbonate, chloride hydroxide, sulfate, sulfide		6	C,E,G,I,L,U	N,P,Q,T	
Beryllium-oxide, hydroxide		7	X	X	
Boric acid and Borax		9	X	X	
Bromine	8,10		X	X	
Cadmium (pigment) - sulfide sulfoselenide, lithopone		15	X	X	
Calcium-carbide, arsenate phosphate	3,17	2	H	K,P	
Chlorine	10	25	H,C	K,R	J
Chlorosulfonic acid	19, 34		X	X	
Chromic acid	12	11,12	H	K,N,O,Q	J,S
Chromium-acetate, borides halides, etc.		11	X	X	
Chromium (pigment) - oxide		11	X	X	
Cobalt - acetate, carbonate halides, etc.		13	X	X	
Copper sulfate	14		X	X	
Fluorine	17		X	X	
Hydrazine	1,39		X	X	
Hydrochloric acid	10,20	20	B		
Hydrofluoric acid	17		B,G	K,R	
Iodine (crude)	10	38	X	X	
Iron chloride	10,20	20	X	X	
Iron (pigment) - oxide	40		X	X	
Lead-arsenate, halides hydroxides, dioxide, nitrate	3	2,21	G,L	P,Q	
Lead chromate	22		G,R	P,Q	
Lead (pigments) - oxide carbonate, sulfate		21	G,R	P,Q	
Manganese dioxide (Potassium permanganate)	24	23	G,L	Q,P,T	
Manganese sulfate		23	G,L	Q,P,T	
Mercury-halides, nitrates, oxides		25	X	X	
Nickel-halides, nitrates, oxides		26		P,Q	
Nickel Sulfate	27	26	L	Q,T	
Nitric acid	28	28	B,H	K,N,R	J,S
Phosphoric acid					
Wet process	10,17,18,30	30	H,C,W	K,N,P,T	J,S
Thermal process			B,G	K,N,R,T	J,S
Phosphorus	17		X	X	
Phosphorus oxychloride	10		X	X	
Phosphorus pentasulfide	29,31	29	X	X	
Phosphorus trichloride	32,10,29	29	X	X	
Potassium-bichromate, chromate	16	16	I		
Potassium hydroxide	10	25	X	X	
Sodium arsenate		2	H	K,P	
Sodium carbonate	1		I,L,V	P	
Sodium chlorate	10		X	X	
Sodium chromate-dichromate	16	16	G,I,L,M	P,Q	
Sodium hydrosulfide	18		X	X	

Table 2.4. Potential HAPs for Inorganic Chemical Manufacturing Industry (concluded)

Source Category	Potential HAPs[a] Inorganic Vapor	Potential HAPs[a] Inorganic Particulate	Potential Emission Sources Process Point	Potential Emission Sources Process Fugitive	Potential Emission Sources Area Fugitive
Sodium-siliconfluoride, fluoride	17	16	X	X	
Sulfuric acid	33,34	33	A,B,C,H	K,R	J,S
Sulfur monochloride-dichloride	10		X	X	
Zinc chloride	36,21	21	X	X	
Zinc chromate (pigment)	35		X	X	
Zinc oxide (pigment)	37		X	X	

Pollutant Key

1 - ammonia
2 - arsenic
3 - arsenic trioxide
4 - aluminum chloride
5 - antimony trioxide
6 - barium salts
7 - beryllium
8 - bromine
9 - boron salts
10 - chlorine
11 - chromium salts
12 - chromic acid mist
13 - cobalt metal fumes
14 - copper sulfate
15 - cadmium salts
16 - chromates (chromium)
17 - fluorine
18 - hydrogen sulfide
19 - hydrogen chloride
20 - hydrochloric acid
21 - lead
22 - lead chromate
23 - manganese salts
24 - manganese dioxide
25 - mercury
26 - nickel
27 - nickel sulfate
28 - nitric acid mist
29 - phosphorus
30 - phosphoric acid mist
31 - phosphorus pentasulfide
32 - phosphorus trichloride
33 - sulfuric acid mist
34 - sulfur trioxide
35 - zinc chromate
36 - zinc chloride fumes
37 - zinc oxide fumes
38 - iodine
39 - hydrazine
40 - iron oxide

Source Key

A - converter
B - absorption tower
C - concentrator
D - desulfurizer
E - reformer
F - neutralizer
G - kiln
H - reactor
I - crystallizer
J - compressor and pump seals
K - storage tank vents
L - dryer
M - leaching tanks
N - filter
O - flakers
P - milling/grinding/crushing
Q - product handling and packaging
R - cooler (cooling tower, condenser)
S - pressure relief valves
T - raw material unloading
U - purification
V - calciner
W - hot well
X - no information

[a] References 6, 17, 19, 20, 22, 23, 24, 25, 28, 36, 37, 38, 39, 40, 41, 42, 43, 45, 76.

gen sulfide, and helium. Organic and inorganic particulate emissions, such as coke fines or catalyst fines, may be generated in some processes.

The emission sources within each of the petroleum related industries are given in Table 2.10. Sources of potential HAP emissions from the oil and gas production industry include: blowouts during drilling operations; storage tank breathing and filling losses; wastewater treatment processes; and fugitive leaks in valves, pumps, pipes, and vessels. In the petroleum refining industry, potential HAP emission sources include: distillation/fractionating columns, catalytic cracking units, sulfur recovery processes, storage tanks, fugitives, and combustion units (e.g., process heaters). Fugitive emissions are a major source of emissions in this industry. Emission sources in the basic petrochemicals industry are similar to those from the petroleum refining industry and the SOCMI (see Section 2.2.3).

2.2.9 Combustion Sources

The fuel combustion industry encompasses a large number of combustion units generally used to produce electricity, hot water, and process steam for industrial plants; or to provide space heating for industrial, commercial, or residential buildings. The combustion units may differ in size, configuration, and type of fuel burned. Coal, fuel oil, and natural gas are the major fossil fuels burned, although other fuels such as wood and various waste (e.g., waste oil) or by-product fuels are burned in relatively small quantities. Industrial applications of both gasoline- and diesel-powered stationary internal combustion units such as generators, pumps, and well-drilling equipment are also included in this category. In general, emissions from combustion sources tend to be higher in inorganic HAPs rather than organic HAPs. A scrubber and/or particulate control device is often used for these sources. This industry falls under SIC code 4911. SCC codes applicable for this industry include 1-01-xxx-xx, 1-02-

Table 2.5. Potential HAPs and Emission Sources for the Chemical Products Industry

Source Category	Potential HAPs[a]				Potential Emission Sources		
	Organic		Inorganic		Process Point	Process Fugitive	Area Fugitive
	Vapor	Particulate	Vapor	Particulate			
Carbon black	14,15,16,21, 24,52,53,54,55	41	1,24,49,56	1,7,10,11, 28,29,37	B,H	G,K,L	I
Charcoal	4,23,30	41			E		
Explosives	9,23,42,46, 57,59,60,61,62,64,65		24,49,67		A,C,H	K	
Fertilizers	23,26,44,67		49,67	1	D,H, R,S,V	K,T	
Paint & varnish	16,22,31,46			6,28,43,48	N,O	L	
Pharmaceutical[b]	3,4,8,16,17, 18,31,34,46,66,68			28,58	A,H,U,W	G,L	F
Plastics[b]	23,33,35,39 42,50,51,52				A,P,V	K,L	F,I
Printing ink[b]	2,8,16,27,42 45,46,51,69			1,10,48,56	Q		
Pesticides[b]	2,3,8,9,16,17,18, 20,25,32,36,39, 47,57,66,69			1,10,63	A,H,O,X	G	F,I
Soap and detergents	4,8,22,34, 38,51,69,70	41	1	1,5,56	M,N,O	K,L	
Synthetic fibers	3,8,13,14,19,23, 24,32,38,40,42,46				A,H,J,O,U,V,X,Z	G,K	I
Synthetic rubber[b]	3,12,18,20,22,23, 33,34,35,36,46,49	41			A,H,O,P,X,Z	Y	F

Pollutant Key

1 - arsenic
2 - acrolein
3 - acrylonitrile
4 - acetic acid
5 - boron
6 - barium
7 - beryllium
8 - benzene
9 - cresols
10 - cadmium
11 - chromium
12 - chloroprene
13 - caprolactum
14 - carbon disulfide
15 - carbonyl sulfide
16 - carbon tetrachloride
17 - chloroform
18 - dichlorobenzene
19 - dimethylformamide
20 - dimethylamine
21 - ethylene
22 - ethylene dichloride
23 - formaldehyde
24 - hydrogen sulfide
25 - hexachlorocyclopentadiene
26 - hydrogen fluoride
27 - ketones
28 - mercury
29 - manganese
30 - methanol
31 - methyl chloroform (1,1,1 - trichloroethane)
32 - maleic anhydride
33 - butadiene, 1,3
34 - morpholine
35 - methylene chloride
36 - nitrosamines
37 - nickel
38 - perchloroethylene
39 - phosgene
40 - phtalic anhydride
41 - polycyclic organic matter
42 - phenols
43 - selenium
44 - silicontetrafluoride
45 - terpenes
46 - toluene
47 - xylene
48 - zinc
49 - ammonia
50 - vinyl chloride
51 - toluene diisocyanate
52 - pyridine
53 - acetylene
54 - hydrogen cyanide
55 - benzo(a)pyrent
56 - sulfuric acid
57 - acetaldehyde
58 - aluminum
59 - dinitrophenol,2-4
60 - dinitrotoluene
61 - diethyl phthalate
62 - hexachloroethane
63 - lead
64 - methyl ethyl ketone
65 - nitrobenzene
66 - dichlorophenoxy-acetic acid, 2,4-
67 - fluorides
68 - acetone
69 - dioxane
70 - methyl methacrylate

Source Key

A - reactor
B - furnace
C - concentrator
D - neutralizer
E - kiln
F - compressor and pump seals; valves, flanges, open ended lines, sampling lines
G - storage tank vents
H - dryer
I - spills
J - spin cell or bath
K - product handling, finishing, and packaging
L - raw material transport and unloading
M - spray dryer
N - kettle
O - mixing tank (blend tank)
P - polymerization vessel
Q - cooking vessel
R - prill tower
S - granulator
T - screen
U - distillation
V - cooler (condenser)
W - crystallizer
X - filter
Y - milling/blending/compounding
Z - flash tank

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[a] References 6, 18, 19, 28, 44, 45, 46, 47, 48, 49, 50, 51, 52, 53, 54, 76, 77.
[b] Number of compounds prevents complete listing here. See Reference 76 for a more complete list.

Table 2.6. Potential HAPs for the Mineral Products Industry

Source Category	Potential HAPs[a]				Potential Emission Sources		
	Organic		Inorganic		Process	Process	Area
	Vapor	Particulate	Vapor	Particulate	Point	Fugitive	Fugitive
Asbestos products	8,13,30,31, 32,33,34		23	3,10,11,17		D,N	I,L
Asphalt batching plants	2,8,13	18			B	F,J,M	I
Brick, ceramic, and related clay products			7,10,12, 21,26,35	7,10,12	B,E,C	D,F,N	I,L
Refractories			10,12	10,12	B,E	D,F,N	I
Cement manufacture		18	10,12,17,23	7,9,10,14, 15,17,24,25	E	F,G,N,S	I,L
Coal cleaning (dry)				22		M,N,R	I,L
Coal cleaning (wet)				1,5,6,7,9,10,11,14, 16,17,20,21,24	B,C	M,N	I,L
Coal conversion	8,19,27,28	18	4,23	1,5,7,9,14,16, 17,20,29	B,H	F,G,M,N	I,L
Glass fiber manufacturing	13,19	19	6,20,22		C,O	D,F,G,N,P	I
Frit manufacturing			12	12	B,C	S	I,L
Glass manufacturing			1,4,12,14,26	1,5,6,12,14, 20,21	C	D,F,M,N	I
Lime manufacturing			15	15	E,T	G,R,S	I,L
Mercury ore processing			15	15	C	G,N	I,L
Mineral wool manufacturing	12,13,19, 31,36,37		4,12,23	6	C,O	D,G,P	I,L
Perlite manufacturing			12	12	B,C	G,M,N,S	I,L
Phosphate rock processing			6,20,21	6,20,21	A,B,Q	F,M,N,R	I,L
Taconite ore processing				3	C,Q	F,M,N,R	I,L

Pollutant Key

1 - arsenic
2 - aldehydes
3 - asbestos
4 - ammonia
5 - antimony
6 - barium
7 - beryllium
8 - benzene
9 - cadmium
10 - chromium
11 - copper
12 - fluoride
13 - formaldehyde
14 - lead
15 - mercury
16 - manganese
17 - nickel
18 - polycyclic organic matter (POM)
19 - phenols
20 - selenium
21 - boron
22 - coal dust
23 - hydrogen sulfide
24 - zinc
25 - iron
26 - chlorine
27 - cresols
28 - toluene
30 - isopropanol
31 - methanol
32 - methyl ethyl ketone
33 - methyl chloroform
34 - xylene
35 - hydrogen fluoride
36 - acetone
37 - carbon tetrachloride

Source Key

A - calciner
B - dryer
C - furnace
D - end-product forming and finishing
E - kiln
F - raw material preparation/mixing
G - cooling
H - reactor
I - storage pile
J - saturator
L - mining operations
M - raw material handling/transport
N - raw material crusher/mill
O - oven
P - resin application
Q - washers
R - screening
S - end-product handling/grinding/bagging
T - hydrator

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[a] *References 6, 17, 18, 19, 20, 21, 22, 23, 24, 29, 38, 40, 41, 57, 58, 59, 60, 61, 62, 63, 64, 65, 76, 77.*

Table 2.7. Potential HAPs for the Wood Products Industry

Source Category	Potential HAPs[a]				Potential Emission Sources		
	Organic		Inorganic		Process	Process	Area
	Vapor	Particulate	Vapor	Particulate	Point	Fugitive	Fugitive
Chemical wood pulping							
Kraft pulp mill	i	e	k	a,b,c,d	A,B,C,D		
Sulfite pulp mill	h	e	f,k	a,b,c,d	A,B,C		
Neutral sulfite pulp mill		e	k	a,c,d	A,C,E		
Plywood, particleboard, and hardboard	h,l,o,p				G	F	
Wood preservative	j,g,m,n					F	

Pollutant Key

a - arsenic
b - asbestos
c - chromium
d - mercury
e - polycyclic organic matter (POM)
f - chlorine
g - chlorobenzene
h - formaldehyde

i - methyl mercaptan
j - dioxin
k - hydrogen sulfide
l - phenol
m - pentachlorophenol
n - cresols
o - abietic acid
p - pinene

Source Key

A - recovery furnace
B - digester
C - blow tank
D - lime kiln
E - fluidized bed reactor
F - resin and/or adhesive application
G - dryer

[a] References 4, 18, 19, 28, 49, 50, 76, 77.

Table 2.8. Potential HAPs for Petroleum Related Industries[a] (General Listing for Entire Source Category)

Potential HAPs			
Inorganic		Organic	
Vapor	Particulate	Vapor	Particulate
Paraffins (C_1-C_{10})	Coke fines	Sulfides (e.g., hydrogen sulfide, carbon disulfide, carbonyl sulfide)	Catalyst fines
Cycloparaffins (C_6-C_9)			
Aromatics (e.g., benzene, toluene, xylene)		Ammonia	
Phenols			
Sulfur containing compounds (e.g., mercaptans, thiophenes)			

[a] References 21, 68, 69, 70, 71, 72, and 76.

xxx-xx, 1-03-xxx-xx, 1-05-xxx-xx, 2-01-xxx-xx, 2-02-xxx-xx, 2-03-xxx-xx, and 2-04-xxx-xx.

The waste incineration category includes combustion processes whereby municipal solid wastes or sewage treatment sludges are disposed. Table 2.11 contains the potential HAPs and the facility-specific emission sources for these source types.

2.3 Identification of Key Emission Stream Properties

The emission stream physical properties needed to select the appropriate control technique(s) and to size the control device(s) for each identified HAP emission stream generated by a process source are identified in this section, be it either a process point source or a process fugitive source. Design and costing techniques for area fugitive emission control methodologies are outside the scope of this manual due to budget considerations; however, control techniques for vapor emissions and particulate emissions from area fugitive sources are discussed in Sections 3.1.4 and 3.2.2, respectively.

The actual/estimated values for the process emission stream properties should be obtained from the owner/operator or from available literature if the owner/operator cannot supply the necessary data. The values obtained are used in conjunction with the guidelines given in Chapter 3 to perform the control technique selection process. Table 2.12 lists the required information for organic vapor emissions, Table 2.13 for inorganic vapor emissions, and Table 2.14 for particulate emissions. After obtaining the values for the key physical properties for each HAP emission stream, record the data on the "HAP Emission Stream Data Form" found in Appendix C.1 (see Figure 2.1). Calculation procedures for determining the heat content of an emission stream are given in Appendix B.1.

Occasions will occur when the owner/operator should combine similar emission streams. For example, if two or more emission streams require the use of the same control technique, the more cost effective approach is to combine the streams and use just one control device as opposed to using a control device for each separate emission stream. If the owner/operator decides to combine emission streams, calculation procedures are provided in Appendix B.1 to determine the key effluent properties of combined emission streams.

Table 2.9. ***Potential HAPs for Petroleum Refining Industries***[a,b] ***(Specific Listing for Petroleum Refining Segment)***

Process	Potential HAPs			
	Organic		Inorganic	
	Vapor	Particulate	Vapor	Particulate
Crude separation	a,b,d,e,f,g,h,i,j,k,l,m,o, A,B,C,D,E,F,J	o	c,m,t,u,v,x,y,L	p,I,Q,R
Light hydrocarbon processing	g,h,i,n,N,O,P	R	t,v	G,H,Q
Middle and heavy distillate processing	a,d,e,f,g,h,i,j,k,l, F, J,K,O,P,S,T	o,R	m,t,u,v,x,y,L	p,q,G,H,I,Q,U
Residual hydrocarbon processing	a,d,e,f,g,h,i,j,k,l,n, F,J,M,N,P,S,T	o,R	m,s,t,u,v,x,y,L	p,q,G,H,I,Q,U
Auxiliary processes	a,b,d,e,f,g,h,i,j,k,l,n, A,B,C,D,J,K,M,T	o,R	c,m,s,u,y,L	p,q,r,z,I

Pollutant Key

a - maleic anhydride
b - benzoic acid
c - chlorides
d - ketones
e - aldehydes
f - heterocyclic compounds (e.g., pyridines)
g - benzene
h - toluene
i - xylene
j - phenols
k - organic compounds containing sulfur (sulfonates, sulfones)
l - cresols
m - inorganic sulfides
n - mercaptans
o - polynuclear compounds (benzo-pyrene, anthracene, etc.)
p - vanadium
q - nickel
r - lead
s - sulfuric acid
t - hydrogen sulfide
u - ammonia
v - carbon disulfide
x - carbonyl sulfide
y - cyanides
z - chromates

A - acetic acid
B - formic acid
C - methylethylamine
D - diethylamine
E - thiosulfide
F - methyl mercaptan
G - cobalt
H - molybdenum
I - zinc
J - cresylic acid
K - xylenols
L - thiophenes
M - thiophenol
N - nickel carbonyl
O - tetraethyl lead
P - cobalt carbonyl
Q - catalyst fines
R - coke fines
S - formaldehyde
T - aromatic amines
U - copper

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[a] *Source: Reference 21.*

[b] *Reference 76 contains additional HAP information for this industry.*

Table 2.10. ***Emission Sources for the Petroleum Related Industries***

Source Category	Potential HAP Emission Sources		
	Process Point	Process Fugitive	Area Fugitive
Oil and Gas Production			
Exploration, site preparation and drilling	A	C	D,E
Crude processing	G	F,H	
Natural Gas processing	G,J,K	H	I
Secondary and tertiary recovery techniques	G		I
Petroleum Refining Industry			
Crude separation	G,J,L	F,H,M,N	I
Light hydrocarbon processing	O,G	F,H	Q
Middle and heavy distillate processing	G,O,P,R	F,H	I
Residual hydrocarbon processing	B,G,K,O,R	H	I
Auxiliary processes	G	F,H	I
Basic Petrochemicals Industry			
Olefins production	G,K,O	F,H	I
Butadiene production	G,J,L,O,R	F,H,N	I
Benzene/toluene/xylene (BTX) production	G,K,O,R	F,Q	I
Naphthalene production	G,L,O	F,H	I
Cresol/cresylic acids production	G,L	F,H	I
Normal paraffin production	G,O	F,H	I

Source Key

A - blowout during drilling
B - visbreaker furnace
C - cuttings
D - drilling fluid
E - pipe leaks (due to corrosion)
F - wastewater disposal (process drain, blowdown, cooling water
G - flare, incinerator, process heater, boiler
H - storage, transfer, and handling
I - pumps, valves, compressors, fittings, etc.
J - absorber
K - process vent
L - distillation/fractionation
M - hotwells
N - steam ejectors
O - catalyst regeneration
P - evaporation
Q - catalytic cracker
R - stripper

Table 2.11. Potential HAPs and Emission Sources for Combustion Sources

Source Category	Potential HAPs[a]				Potential Emission Sources		
	Organic		Inorganic		Process	Process	Area
	Vapor	Particulate	Vapor	Particulate	Point	Fugitive	Fugitive
Coal combustion	3,14,19, 21,25,28	19	1,2,8,9,13, 17,27,31	1,2,5,6,8,9, 10,11,15,16, 18,20,22,24	A,B	I	H
Oil combustion	14	19	13,17,27	1,2,5,6,8,9, 10,11,15,16,29	A,B,E		
Natural gas combustion	14	19			A,B,E,F		
Gasoline combustion	12,14	12,19	17	15	G		
Diesel combustion	12	12,19		6,18	G		
Wood combustion	3,4,12,14,25	12,19	27	16,20	A,B,C		
Waste oil combustion	7,12,21,23,26	12,19		6,8,9,15,18	A,B,D		
Municipal refuse incineration	12	12,19	17,27	6,8,9,11, 15,16,18	D		
Sewage sludge incineration	12	12,19	17	1,6,8,9,15,16,18	D		
PCB incineration	12,21	12,19		30	D,B		

Pollutant Key

1 - arsenic
2 - antimony
3 - acetaldehyde
4 - acetic acid
5 - barium
6 - beryllium
7 - benzene
8 - cadmium
9 - chromium
10 - cobalt
11 - copper
12 - dioxin
13 - fluorides
14 - formaldehyde
15 - lead
16 - manganese
17 - mercury
18 - nickel
19 - polycyclic organic matter (POM)
20 - phosphorus
21 - polychlorinated biphenyls (PCB)
22 - radionuclides
23 - trichloroethylene
24 - zinc
25 - phenols
26 - ethyl benzene
27 - chlorine
28 - pyridine
29 - vanadium
30 - dibenzofuran

Source Key

A - furnace
B - boiler
C - woodstove/fireplace
D - incinerator
E - gas turbine
F - reciprocating engine
G - industrial engine and/or equipment
H - coal storage pile
I - ash handling system

[a] References 6, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 28, 29, 30, 31, 46, 65, 72, 74, 75, 76.

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Table 2.12. Key Properties for Organic Vapor Emissions

Emission Stream Properties (Preferred units of measure)	HAP Properties[a]
HAP content (ppm by volume)	Molecular weight
Organic content[b] (ppm by volume)	Vapor pressure
Heat content[c] (Btu/scf)	Solubility (graph)
Oxygen content (% by volume)	Adsorptive properties (isotherm plot)
Moisture content (% by volume)	
Halogen/metal content (yes or no)	
Flow rate (scfm)	
Temperature (°F)	
Pressure (mm Hg)	

[a] These properties pertain to the specific HAP or mixture of HAPs in the emission stream.

[b] Primary properties that affect control technique selection. Organic content is defined as organic emission stream combustibles less HAP emission stream combustibles.

[c] Heat content is determined from HAP/Organic Content (see Appendix B.1 for calculational procedures).

Table 2.13. Key Properties for Inorganic Vapor Emissions

Emission Stream Properties (preferred units of measure)	HAP Properties[a]
HAP content[b] (ppm by volume)	Molecular weight
Moisture content (% by volume)	Vapor pressure
Halogen/metal content (yes or no)	Solubility (graph)
Flow rate (scfm)	Adsorptive properties (isotherm plot)
Temperature (°F)	
Pressure (mm Hg)	

[a] These properties pertain to the specific HAP or mixture of HAPs in the emission stream.

[b] Primary properties that affect control technique selection.

Table 2.14. Key Properties for Particulate Emissions

Emission Stream Properties (preferred units of measure)	HAP Properties[a]
HAP content (% by mass)	(None)
Particulate content[b] (gr/dscf)	
Moisture content (% by volume)	
SO_3 content (ppm by volume)	
Flow rate (acfm)	
Temperature (°F)	
Particle mean diameter[c] (μm)	
Particle size distribution[c,d]	
Drift velocity[c] (ft/sec)	
Particle resistivity[c,d] (ohm-cm)	

[a] These properties pertain to the specific HAP or mixture of HAPs in the emission stream.

[b] Data include total particulate loading and principle particulate constituent.

[c] These properties are necessary only for specific control techniques.

[d] Some sources may not have this information.

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Chapter 3

Control Device Selection

3.1 Background

Guidelines that will enable the user to select the control technique(s) that can be used to control HAPs are presented in this chapter. The control techniques that can be applied to control HAP emissions from a specific emission source will depend on the emission source characteristics and HAP characteristics. Therefore, Section 3.2, Vapor Emissions Control, and Section 3.3, Particulate Emissions Control each pertain to specific HAP groups. The discussion of control technique selection within each section is according to type of HAP (organic or inorganic) and emission source (point, process fugitive, or area fugitive).

In the following sections, guidelines for selecting controls for point sources are discussed in detail. Point sources are typically controlled by add-on control devices. For each control technique, ranges of applicability with respect to emission stream characteristics, HAP characteristics, performance levels (e.g., removal efficiency), and other considerations that are important in control device selection are described in detail.

Work practices, including equipment modifications, play a key role in reducing emissions from process fugitive and area fugitive sources. These sources can also be controlled by add-on control devices if the emissions can be captured by hooding or enclosure or collected by closed vent systems and then transferred to a control device. Note that the overall performance of the control system will then be dependant on both the capture efficiency of the fugitive emissions and the efficiency of the control device.

To illustrate the control device selection process, several emission stream scenarios are presented throughout this chapter. The emission stream from the paper coating drying oven introduced in Chapter 2 is one of the scenarios presented. The data necessary for control device selection are recorded on the HAP emission Stream Data Form (see Figure 2.1).

3.2 Vapor Emissions Control

3.2.1 Control Techniques for Organic Vapor Emissions from Point Sources

The most frequent approach to point source control is the application of add-on control devices. These devices can be of two types: combustion and recovery. The combustion devices discussed in this manual include thermal incinerators, catalytic incinerators, flares, and boilers/process heaters. Applicable recovery devices include condensers, adsorbers, and absorbers. The combustion devices are the more commonly applied control devices, since they are capable of high removal (i.e., destruction) efficiencies for almost any type of organic vapor HAP although carbon adsorbers are also quite popular. Combustion devices serve as an ultimate control technique; that is, they destroy rather than collect pollutants. With carbon adsorbers and condensers, the VOC HAP must be dealt with after collection. The removal efficiencies of the recovery techniques generally depend on the physical and chemical characteristics of the HAP under consideration as well as the emission stream characteristics.

Applicability of the control techniques depends more on the individual emission stream under consideration than on the particular source category (e.g., degreasing vs. surface coating in solvent usage operations source category). Thus, selection of applicable control techniques for point source emissions is made on the basis of stream-specific characteristics and desired control efficiency. The key emission stream characteristics and HAP characteristics that affect the applicability of each control technique are identified in Table 3.1 and limiting values for each of these characteristics are presented.

Matching the specific characteristics of the stream under consideration with the corresponding values in Table 3.1 will help the user to identify those techniques that can potentially be used to control the emission stream. The list of potentially applicable control techniques will then be narrowed further depending on the capability of the

Table 3.1. Key Emission Stream and HAP Characteristics for Selecting Control Techniques for Organic Vapors From Point Sources

	Emission Stream Characteristics					HAP Characteristics [a]			
Control Device	HAP/Organics Content[b] (ppmv)	Heat Content (Btu/scf)	Moisture Content %	Flow Rate (scfm)	Temp. (°F)	Molecular Weight (lb/lb-mole)	Solubility	Vapor Pressure (mm Hg)	Adsorptive Properties
Thermal incinerator	>20; (<25% of LEL[c])			<50,000[d]					
Catalytic incinerator	50-10,000; (<25% of LEL[c])			<50,000					
Flare		>300[e]		<2,000,000[f]					
Boiler/ Process heater[g]		>150[h]		Steady					
Carbon adsorber	700-10,000 (<25% of LEL[c])		<50%[i]	300-200,000	≤130	45-130			Must be able to absorb on/ desorb from available adsorbents
Absorber	250-10,000			1,000-100,000			Must be readily soluble in water or other solvents		
Condenser	>5,000-10,000			<2,000				>10 (at room temperature)	

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[a] Refers to the characteristics of the individual HAP if a single HAP is present and to that of the HAP mixture if a mixture of HAPs is present.
[b] Determined from HAP/hydrocarbon content.
[c] For emission streams that are mixtures of air and VOC; in some cases, the LEL can be increased to 40 to 50 percent with proper monitoring and control (see Section 4.2 for definition of LEL).
[d] For packaged units; multiple-package or custom-made units can handle larger flows.
[e] Based on EPA's guidelines for 98 percent destruction efficiency.
[f] Units: lb/hr. Source: Reference 12.
[g] Applicable if such a unit is already available on site.
[h] Total heat content.
[i] Relative humidity. Applicable for HAP concentration less than about 1,000 ppmv.

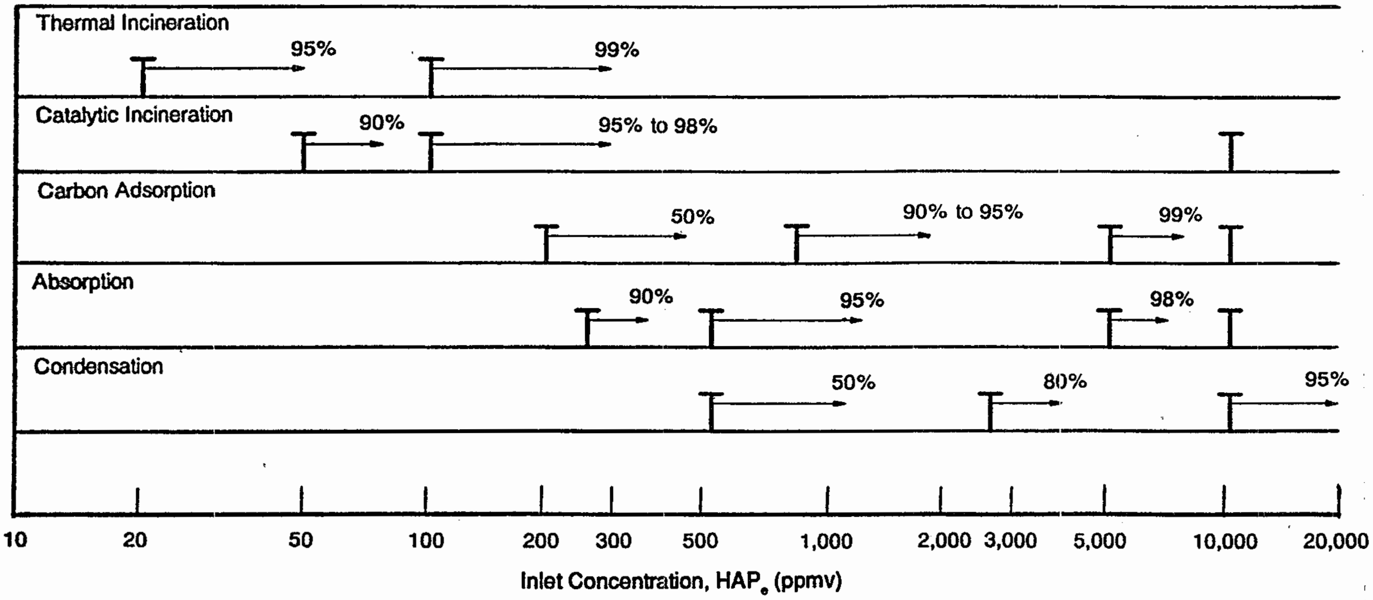


Figure 3.1. Approximate percent reduction ranges for add-on equipment

applicable control devices to achieve the required performance levels. The expected emission reduction from the application of each control technique on the basis of the total VOC concentration in the emission stream is identified in Figure 3.1. Very little data regarding control device removal efficiency for specific HAPs are available. Therefore, without actual source test data for a specific emission stream and control system, HAP removal efficiency is assumed to equal total volatile organic compound (VOC) removal efficiency.

3.2.1.1 Thermal Incinerators

Thermal incinerators are used to control a wide variety of continuous emission streams containing VOCs. Compared to the other techniques, thermal incineration is broadly applicable; that is, it is much less dependent on HAP characteristics and emission stream characteristics. Destruction efficiencies up to 99 + percent are achievable with thermal incineration. Although they accommodate minor fluctuations in flow, thermal incinerators are not well suited to streams with highly variable flow because the reduced residence time and poor mixing during increased flow conditions decreases the completeness of combustion. This causes the combustion chamber temperature to fall, thus decreasing the destruction efficiency.

Two types of thermal incinerators are commonly used. The thermal recuperative type uses a conventional heat exchanger to heat the incoming emission stream. The thermal regenerative type uses ceramic beds to heat the incoming stream. The discussion in Chapter 4 focuses on thermal recuperative incinerators. Thermal regenerative and thermal recuperative incinerators are discussed in Reference 19.

Thermal incineration typically is applied to emission streams that are dilute mixtures of VOC and air. In such cases, due to safety considerations, concentration of the VOCs generally is limited by insurance companies to 25 percent of the LEL (lower explosive limit) for the VOC in question (see Section 4.2.2 for more details). Thus, if the VOC concentration is high, dilution may be required.

When emission streams treated by thermal incineration are dilute (i.e., low heat content), supplementary fuel is required to maintain the desired combustion temperatures. Supplementary fuel requirements may be reduced by recovering the energy contained in the hot flue gases from the incinerator. For emission streams with high heat contents (e.g., >150 Btu/scf), the possibility of using the emission stream as fuel gas should be considered.

The performance of a thermal incinerator is largely dependent on the combustion chamber temperature. It is, therefore, recommended that continuous monitoring of this parameter be employed for control of HAPs.

Packaged single unit thermal incinerators are available in many sizes to control emission streams with flow rates from a few hundred up to about 50,000 scfm.

3.2.1.2 Catalytic Incinerators

Catalytic incinerators are similar to thermal incinerators in design and operation except that they employ a catalyst to enhance the reaction rate. Since the catalyst allows the reaction to take place at lower temperatures, significant fuel savings may be possible with catalytic incineration.

Catalytic incineration is not as broadly applicable as thermal incineration since performance of catalytic incinerators is more sensitive to pollutant characteristics and process conditions than is thermal incinerator performance. Materials such as phosphorus, bismuth, lead, arsenic, antimony, mercury, iron oxide, tin, zinc, sulfur, and halogens in the emission stream can poison the catalyst and severely affect its performance. (Note: Some catalysts can handle emission streams containing halogenated compounds.) Liquid or solid particles that deposit on the catalyst and form a coating also reduce the catalyst's activity by preventing contact between the VOCs and the catalyst surface. Catalyst life is limited by thermal aging and by loss of active sites by erosion, attrition, and vaporization. With proper operating temperatures and adequate temperature control, these processes are normally slow, and satisfactory performance can be maintained for 2 to 5 years before replacement of the catalyst is necessary.

Both fixed bed and fluid bed catalytic incinerators are encountered. The discussion in Chapter 4 focuses on fixed bed catalytic incinerators. For more information on fluid bed catalytic incineration, consult Reference 19.

Catalytic incineration can be less expensive than thermal incineration in treating emission streams with low VOC concentrations due to lower auxiliary fuel requirements. Emission streams with high VOC concentrations should not be treated by catalytic incineration without dilution since such streams may cause the catalyst bed to overheat and lose its activity. Also, fluctuations in the VOC content of the emission stream should be kept to a minimum to prevent damage to the catalyst.

Destruction efficiencies of 95 percent of HAPs can typically be achieved with catalytic incineration.[16,20] Higher destruction efficiencies (98 to 99 percent) are also achievable, but require larger catalyst volumes and/or higher temperatures, and are usually designed on a site specific basis.[20]

The performance of a catalytic incinerator is largely dependent on the temperature rise across the catalyst bed. This temperature rise is partially dependant on the amount of catalyst present which is indicated by the pressure drop across the catalyst bed. It is recommended that continuous monitoring of both these parameters be employed for control of HAPs.

Catalytic incinerators have been applied to continuous emission streams with flow rates up to about 50,000 scfm.

3.2.1.3 Flares

Flares are commonly used for disposal of waste gases during process upsets (e.g., start-up, shutdown) and emergencies. They are basically safety devices that are also used to destroy waste emission streams.

Flares can be used for controlling almost any VOC emission stream. They can be designed and operated to handle fluctuations in emission VOC content, inert content, and flow rate. There are several different types of flares including steam-assisted, air-assisted, and pressure head flares. Steam-assisted flares are very common and typically employed in cases where large volumes of waste gases are released. Air-assisted flares are generally used for moderate relief gas flows. Pressure head flares are small; they are used in arrays of up to 100 individual flares. Normally, only a few of the flares operate. The number of flares operating is increased as the gas flow increases.

Flaring is generally considered a control option when the heating value of the emission stream cannot be recovered because of uncertain or intermittent flow as in process upsets or emergencies. If the waste gas to be flared does not have sufficient heating value to sustain combustion, auxiliary fuel may be required.

Based on studies conducted by EPA, 98 percent destruction efficiency can be achieved by steam-assisted flares when controlling emission streams with heat contents greater than 300 Btu/scf.[3,12,17] Note that a stream with such a high heat content may serve as a fuel gas for an incinerator if one is employed at the site. Depending on the type of flare configuration (e.g., elevated or ground flares), the capacity of flares to treat waste gases can vary up to about 100,000 lb/hr for ground flares and 2 million lb/hr or more for elevated flares. The capacity of an array of pressure head flares depends on the number of flares in the array. For control of HAPs, it is recommended that a continuous monitoring system for the pilot flame be employed for flares controlling intermittent streams, and that the flare flame be continuously monitored for flares controlling continuous streams.

3.2.1.4 Boilers/Process Heaters

Existing boilers or process heaters can be used to control emission streams containing organic compounds. These are currently used as control devices for emission streams from several industries (e.g., refinery operations, SOCMI reactor processes and distillation operations, etc.)

Typically, emission streams are controlled in boilers or process heaters and used as supplemental fuel only if they have sufficient heating value (greater than about 150 Btu/scf). In some instances, emission streams with high heat content may be the main fuel to the process heater or boiler (e.g., process off-gas from ethylbenzene/styrene manufacturing). Note that emission streams with low heat content can also be burned in boilers or process heaters when the flow rate of the emission stream is small compared to the flow rate of the fuel/air mixture. When used as emission control devices, boilers or process heaters can provide destruction efficiencies of greater than 98 percent at small capital cost and little or no fuel cost. In addition, near complete recovery of the emission stream heat content is possible.

There are some limitations in the application of boilers or process heaters as emission control devices. Since these combustion devices are essential to the operation of a plant, only those emission streams that will not reduce their performance or reliability can be controlled using these devices. Variations in emission stream flow rate and/or heating value could adversely affect the performance of a boiler or process heater. By lowering furnace temperatures, emission streams with large flow rates and low heating values can cause incomplete combustion and reduce heat output. The performance and reliability of the process heater or boiler may also be affected by the presence of corrosive compounds in the emission stream; such streams are usually not employed with these devices.

3.2.1.5 Carbon Adsorbers

Carbon adsorption is commonly employed as a pollution control and/or a solvent recovery technique. It is applied to dilute mixtures of VOC and air. Although carbon (which comes in different grades) is the most widely used adsorption media, other adsorption media include silica gel and alumina. Carbon adsorption is the focus of this discussion. Removal efficiencies of 95 to 99 percent can be achieved using carbon adsorption. The maximum practical inlet concentration is usually about 10,000 ppmv but virtually all applications will have significantly lower concentrations. The inlet concentrations are typically limited by the adsorption capacity of the carbon bed or safety problems posed by high bed temperatures produced by heat of adsorption and presence of flammable vapors. Outlet concentrations around 50 ppmv can be routinely achieved with state-of-the-art systems; concentrations as low as 10 to 20 ppmv can be achieved with some compounds.[3,18] In contrast to incineration methods whereby the VOCs are destroyed, carbon adsorption provides a favorable control alternative when the VOCs in the emission stream are valuable.

High molecular-weight compounds that are characterized by low volatility are strongly adsorbed on carbon. The affinity of carbon for these compounds makes it difficult to remove them during regeneration of the carbon bed. Hence, carbon adsorption is not applied to such compounds (i.e., boiling point above 400° F; molecular weight greater than about 130). Highly volatile materials (i.e., molecular weight less than about 45) do not adsorb readily on carbon; therefore, adsorption is not typically used for controlling emission streams containing such compounds.

Carbon adsorption is relatively sensitive to emission stream conditions. The presence of liquid or solid particles, high boiling organics, or polymerizable substances may require pretreatment procedures such as filtration.

Dehumidification may be necessary if the emission stream concentration is less than 1,000 ppmv and the emission stream has a high humidity (relative humidity > 50 percent).[18] Cooling may be required if the emission stream temperature exceeds 120° - 130° F.

To prevent excessive bed temperatures resulting from the exothermic adsorption process and oxidation reactions in the bed, concentrations higher than 10,000 ppmv must frequently be reduced. This is usually done by condensation or dilution of the emission stream ahead of the adsorption step. Exothermic reactions may also occur if incompatible solvents are mixed in the bed, leading to polymerization. If flammable vapors are present, the VOC concentrations may be limited by insurance companies to less than 25 percent of the LEL. If proper controls and monitors are used, LEL levels up to 40 to 50 percent may be allowed. To ensure breakthrough does not occur, continuous monitoring of the outlet bed concentration is recommended.

3.2.1.6 Absorbers (Scrubbers)

Absorption is widely used as a raw material and/or a product recovery technique in separation and purification of gaseous streams containing high concentrations of VOCs. As an emission control technique, it is much more commonly employed for inorganic vapors (e.g., hydrogen sulfide, chlorides, etc.) than for organic vapors. Using absorption as the primary control technique for organic vapor HAPs is subject to several limitations and problems as discussed below.

The suitability of absorption for controlling organic vapor emissions is determined by several factors; most of these factors will depend on the specific HAP in question. For example, the most important factor is the availability of a suitable solvent. The pollutant in question should be readily soluble in the solvent for effective absorption rates and the spent solvent should be easily regenerated or disposed of in an environmentally acceptable manner.

Another factor that affects the suitability of absorption for organic vapor emissions control is the availability of vapor/liquid equilibrium data for the specific HAP/solvent system in question. Such data are necessary for design of absorber systems. For uncommon HAPs, these data are not readily available.

Another consideration involved in the application of absorption as a control technique is disposal of the absorber effluent (i.e., used solvent). If the absorber effluent containing the organic compounds is discharged to the sewer, pond, etc., the air pollution problem is merely being transformed into a water pollution problem. Hence, this question should be addressed (e.g., are there chemical/physical/biological means for treating the specific effluent under consideration?). In solvent recovery, used organic solvents are typically stripped (reverse of absorption) and recycled to the absorber for economic reasons. However, in HAP control applications, stripping requirements will often be very expensive because the residual organic concentrations in the solvent must be extremely low for it to be suitable for reuse. Also, if the VOCs in the effluent from the absorber have appreciable vapor pressure (e.g., > 0.1 mm Hg), the possibility of VOC emissions to the atmosphere should be considered.

In organic vapor HAP control applications, low outlet concentrations will typically be required. Trying to meet such requirements with absorption alone will lead to impractically tall absorption towers, long contact times, and high liquid-gas ratios that may not be cost effective. Therefore, absorbers will generally be effective when they are used in combination with other control devices such as incinerators or carbon adsorbers.

Removal efficiencies in excess of 99 percent can be achieved with absorption.

3.2.1.7 Condensers

Condensers are widely used as raw material and/or product recovery devices. They are frequently applied as preliminary air pollution control devices for removing VOC contaminants from emission streams prior to other control devices such as incinerators, adsorbers, or absorbers.

Condensers are also used by themselves for controlling emission streams containing high VOC concentrations (usually >5,000 ppmv). In these cases, removal efficiencies obtained by condensers can range from 50 to 90 percent although removal efficiencies at the higher end of this scale usually require HAP concentrations of around 10,000 ppmv or greater. The removal efficiency of a condenser is highly dependent on the emission stream characteristics including the nature of the HAP in question (vapor pressure-temperature relationship) and HAP concentration, and the type of coolant used. Note that a condenser cannot lower the inlet VOC concentration to levels below the saturation concentration (or vapor pressure) at the coolant temperature. When water, the most commonly used coolant, is employed, the saturation conditions represent high outlet concentrations. For example, condenser outlet VOC concentrations are often limited to above 10,000 to 20,000 ppmv due to the saturation conditions of most of the organic compounds at the temperature of the cooling water. Therefore, it is not possible for condensation with water as the coolant to achieve the low outlet concentrations that would be required in HAP control applications.
Removal efficiencies around 90 percent may be achieved if lower temperatures than those possible with cooling water are employed but this is generally only true if the HAP concentration is very high (e.g. >10,000-20,000 ppmv).[16] These low temperatures can be obtained with coolants such as chilled water, brine solutions, or chlorofluorocarbons. These refrigerated condenser systems are often sold as packaged units. However, for extremely low outlet HAP concentrations, condensation will usually be infeasible.

Depending on the type of condenser used, there may be potential problems associated with the disposal of the spent coolant. Therefore, using contact condensers that generate such effluents for controlling HAP emissions is not recommended.

Flow rates up to about 2,000 scfm can be considered as representative of the typical range for condensers used as emission control devices. Condensers for emission streams with flow rates above 2,000 scfm and containing high concentrations of noncondensibles will require prohibitively large heat transfer areas.

The temperature of the outlet steam is a fundamental indicator of performance for a condenser system. Therefore, continuous monitoring of this parameter is recommended for control of HAPs.

3.2.2 Control Techniques for Inorganic Vapor Emissions From Point Sources

Inorganic vapors make up only a small portion of the total HAPs emitted to the atmosphere. Potential sources of the various inorganic vapors found in the atmosphere are discussed in Chapter 2. Inorganic HAP vapors typically include gases such as ammonia, hydrogen sulfide, carbonyl sulfide, carbon disulfide, metals with hydride and carbonyl complexes, chloride, oxychloride, and cyanide.

In many cases, although the inorganic HAPs are emitted as vapors at the emission source, they may condense when passing through various ducts and form particulates. Prior to discharge to the atmosphere, these particulates are typically controlled by methods that will be discussed in Section 3.3. In this section, the discussion will be based on control techniques for HAPs that are emitted as vapors to the atmosphere.

Only a limited number of control methods are applicable to inorganic vapor emissions from point sources. The two most commonly used control methods are absorption (scrubbing) and adsorption. Absorption is the most widely used and accepted method for inorganic vapor control. Although combustion can be used for some inorganic HAPs (e.g., hydrogen sulfide, carbonyl sulfide, nickel carbonyl), typical combustion methods such as thermal and catalytic incineration are generally not applied. In some cases, for example, in controlling hydrogen sulfide emissions from gas wells and gas processing, flares are used.

Applicability of absorption and adsorption as control methods depends on the individual emission stream characteristics. The removal efficiencies that can be achieved will be determined by the physical and chemical properties of the HAP under consideration. Other factors (e.g., waste disposal, auxiliary equipment requirements), while not necessarily affecting the technical feasibility of the control device, may affect the decision to use that particular control method.

In the following two subsections, the applicability of absorption and adsorption for controlling inorganic vapor emissions will be discussed.

3.2.2.1 Absorbers (Scrubbers)

Absorption is the most widely used recovery technique for separation and purification of inorganic vapor emissions. The removal efficiency achievable with absorbers can be greater than 99 percent. It will typically be determined by the actual concentrations of the specific HAP in gas and liquid streams and the corresponding equilibrium concentrations. Table 3.2 summarizes the reported efficiencies for various inorganic vapors employing absorption as the control method.

As discussed in Section 3.2.1.6 for organic vapors, the suitability of absorption for controlling inorganic vapors in gaseous emission streams is dependent on several factors. The most important factor is the solubility of the pollutant vapor in the solvent. The ideal solvent should be nonvolatile, noncorrosive, nonflammable, nontoxic, chemically stable, readily available, and inexpensive. Typical solvents used by industry for inorganic vapor control include water, sodium hydroxide solutions, amyl alcohol, ethanolamine, weak acid solutions, and hypochlorite solutions. Other factors which may affect inorganic vapor absorption are similar to those for organic vapor absorption (see Section 3.2.1.6).

Water is the ideal solvent for inorganic vapor control by absorption. It offers distinct advantages over other solvents, the main one being its low cost. It is typically used on a once-through basis and then discharged to a wastewater treatment system. The effluent may require pH adjustment to precipitate metals and other HAPs as hydroxides or salts; these are typically less toxic and can be more easily disposed of.

3.2.2.2 Adsorbers

When the removal of inorganic vapors is especially difficult using absorption methods, adsorption may prove to be more effective. Adsorbents such as activated carbon, impregnated activated carbon, silica gel, and activated alumina are capable of adsorbing various inorganic vapors and gases. The degree of adsorption is dependent not only on the waste stream characteristics, but also on the different characteristics of the adsorbents.

Carbon adsorption, using conventional and chemically impregnated carbons, is widely used for controlling inorganic vapors such as mercury, nickel carbonyl, phosgene, and amines. For example, when mercury vapors are passed through a bed of sulfur-impregnated carbon, the mercury vapors react with sulfur to form a stable mercuric sulfide. Over 95 percent of the mercury removed in this way can be recovered for reuse.

Important factors to consider when choosing an adsorbent for inorganic vapor control are very similar to those for organic vapor control, which are discussed in Section 3.2.1.5. Some of these factors include the amount of adsorbent needed, temperature rise of the gas stream due to adsorption, ease of regeneration, and the useful life of the adsorbent. Most of the reported removal efficiencies for inorganic vapors are for activated carbon and impregnated activated carbon, and range from 90 to 100 percent. Table 3.2 summarizes removal efficiencies reported for various inorganic vapors controlled by adsorption.

Activated carbons are the most widely used adsorbents for inorganic vapor control. In several cases, they must be treated (i.e., impregnated with chemical) for effective application. Since activated carbons are relatively sensitive to emission stream conditions, pretreatment of the emission stream may be necessary. Pretreatment methods such as filtration, cooling, and dehumidification may be required depending on the emission stream conditions. Filtration is used to prevent plugging of the adsorber bed by any solids or particles which may be in emission stream. Ideal adsorption conditions for impregnated activated carbons are relative humidities less than 50 percent and gas stream temperatures below 130° F. Inorganic vapor concentrations are not recommended to exceed 1,000 ppmv (preferably, less than 500 ppmv) when activated carbon is used as an adsorbent.

3.2.3 Control Techniques for Organic/Inorganic Vapor Emissions from Process Fugitive Sources

Process fugitive emissions are defined in this handbook as emissions from a process or piece of equipment that are being emitted at locations other than the main vent or process stack. Process fugitive emissions include fumes or gases which escape from or through valves, pumps, compressors, access ports, and feed and/or discharge openings to a process. Examples include a pump in light liquid service, the open top of a vapor degreaser, the slag or metal tap opening on a blast furnace, and the feed chute on a ball mill. Process fugitive emission sources can also include vent fans from rooms or enclosures containing an emissions source. An example would be a vent fan on a perchloroethylene dry cleaner or the vent fan on a press room. Other examples of process fugitive sources include cooling towers and process drains.

Fugitive emissions of organic vapors occur in plants processing organic liquids and gases, such as petroleum refineries, chemical plants, and plants producing chemically based products such as plastics, dyes, and drugs. One group of emission sources found in plants of this type is commonly referred to as equipment leaks. Fugitive emissions of this type result from incomplete sealing of equipment at the point of interface of process fluid with the environment. Control techniques for equipment leaks include leak detection and repair programs and equipment installation or configuration. The following discussion contains information about control techniques for common types of processing equipment found in plants processing organic materials. Control techniques and control efficiencies for common types of processing equipment are summarized in Table 3.3.

Pumps. Several types of equipment or equipment configurations can be used to eliminate or capture all organic vapors leaking from pump seals. There are, first of all, leakless pumps, pumps designed with no interface between the process fluid and the environment, such as diaphragm seal, and canned pumps. These pumps effectively limit fugitive emissions. However, they are limited in application.

Sophisticated pump seals can also be used to capture or eliminate fugitive emissions. Dual seal systems with pressurized barrier fluids or low pressure systems vented to control devices may be used in some applications. Recent improvements by vendors have resulted in a greater array of pumps available for hazardous materials. These include pumps with new alloys and lining materials, and new magnetic and other sealless designs to reduce leaking. For more information, consult Reference 22. Another approach which may be used involves venting the entire seal area to a control device. Capture efficiencies should be virtually 100 percent in both systems vented to control devices. Then the overall control efficiency would be limited by the efficiency of the control device.

Table 3.2. Control Methods for Various Inorganic Vapors [a]

	Absorption		Adsorption	
Inorganic Vapor	Reported Removal Efficiency (%)	Solvent	Reported Removal Efficiency (%)	Adsorbent
Mercury (Hg)	95	Brine/hypochlorite solution	90	Sulfur-impregnated activated carbon
Hydrogen chloride (HCl)	95	Water		
Hydrogen sulfide (H_2S)	98	Sodium carbonate/water	100	Ammonia-impregnated activated carbon
Calcium fluoride (CaF_2)	95	Water		
Silicon tetrafluoride (SiF_4)	95	Water		
Hydrogen fluoride (HF)	85-95	Water	99	Calcined alumina
Hydrogen bromide (HBr)	99.95	Water		
Titanium tetrachloride ($TiCl_4$)	99	Water		
Chlorine (Cl_2)	90	Alkali solution		
Hydrogen cyanide (HCN)				Ammonia-impregnated active carbon

[a] References 1,3.

Another approach to reducing (but not eliminating) organic fugitive emissions from pumps is leak detection and repair programs. A leak detection and repair system modeled after the one EPA developed for the New Source Performance Standards (NSPS) of the synthetic organic chemical industry (SOCMI) should achieve about 60 percent control efficiency.[7] The efficiency of leak detection and repair programs is dependent on several factors such as frequency of monitoring, effectiveness of maintenance, action level, an underlying tendency to leak. These factors and their effect on control efficiency have been studied and discussed in References 7, 8, 9 and 10. Also, models are available for calculating the effectiveness of leak detection and repair programs (e.g., see Reference 11).

Valves. As with pumps, control of fugitive emissions from valves may be accomplished by installing equipment designed to isolate the process fluid from the environment. But also as with pumps, leakless valves such as diaphragm valves are limited in their application.

Leak detection and repair programs have been used to reduce fugitive emissions from valves. As indicated above for pumps, the control efficiency of a leak detection and repair program depends on the frequency of monitoring, the effectiveness of maintenance, the action level, the underlying tendency to leak, and other factors. A leak detection and repair program modeled after the one developed by EPA for the NSPS of the SOCMI should achieve a control efficiency of about 70 percent for valves in as service and about 50 percent for valves in light liquid service.[7]

Table 3.3. Summary of Control Effectiveness for Controlling Organic Process Fugitive Emission Sources [a]

Emission Source	Control Technique Equipment Modification	Control Effectiveness[6] (%)
Pumps	Monthly leak detection and repair	61
	Seamless pumps	100
	Dual mechanical seals	100
	Closed vent system[b]	100
Valves -Gas	Monthly leak detection and repair	73
	Diaphragm valves	100
-Light liquid	Monthly leak detection and repair	46
	Diaphragm valves	100
Pressure relief valves	Rupture disk	100
	Closed vent system[a]	100
Open-ended lines	Caps, plugs, blinds	100
Compressors	Mechanical seals with vented degassing reservoirs	100
	Closed vent system[a]	100
Sampling connections	Closed purge sampling	100

[a] Reference 7.

[b] Closed vent systems are used to collect and transfer the fugitive emissions to add-on control devices such as flares, incinerators, or vapor recovery systems.

Pressure Relief Valves. Fugitive emissions from pressure relief valves may be virtually eliminated through the use of rupture disks to prevent leakage through the seal. Fugitive emissions may also be added to gases collected in a flare system by piping the relief valve to a flare header. The control efficiency, then, depends on the destruction efficiency of the flare. If flares are operated in accordance with flare requirements established by EPA for sources complying with NSPS, at least 98 percent control efficiency should be achieved.

Open-ended Lines. Leakage of organic vapors through valve seats to the open ends of pipes can be eliminated by the installation of caps, plugs, or blind flanges. The control efficiency should be 100 percent as long as the plugs and caps remain in place.

Compressors. Fugitive emissions from compressor seals can be controlled by venting the seal area to a flare or other control device. Barrier fluid systems can also be used to purge the seal area and convey leakage to a control device. Capture efficiency should be 100 percent and, therefore, the overall control efficiency would depend on the efficiency of the control device.

Sampling Connections. Fugitive emissions from sampling connections can be controlled by returning the purged material to the process or by disposing of it in a control device. The practice of returning purged material to the process in a closed system should achieve almost 100 percent control efficiency. The control efficiency achieved by diverting the collected purge material to a control device depends on the efficiency of the device.

Some process fugitive sources can be controlled by add-on control devices once the emissions from the sources are captured by hooding, enclosures, or closed vent systems and then transferred to a control device. Because of the nature of the opening (e.g., for access or maintenance), the opening through which emissions escape cannot be totally enclosed or blanked off. Operators have to access the equipment or materials have to be fed or discharged from the process. For this reason, hoods or partial enclosures are used to control emissions from such openings.

Proper hood design requires a sufficient knowledge of the process or operations so that the most effective hood or enclosure can be installed to provide minimum exhaust volumes for effective contaminant control. In theory, hood design is based upon trying to enclose the process and keep all openings to a minimum and located away from the natural path of containment travel. Where possible, inspection and maintenance openings should be provided with doors. In practice, hoods are designed using the capture velocity principle which involves creation of and air flow past the source of containment sufficient to remove the highly contaminated air from around the source or issuing from that source and draw the air into an exhaust hood. The capture velocity principle is based on the fact that small dust particles travel very short distances (on the other of inches) when thrown or emitted from a source and therefore, can be assumed to follow air currents. Vapors and gases exhibit the same effects.

In practice, hood capture efficiency is very difficult to determine and therefore, when evaluating a hood, one of the few parameters that can be considered is the capture velocity. Standard design values of capture velocity are available from the American Conference of Government Industrial Hygienists in the Industrial Ventilation Manual (see Table 3.4).[2] Once a capture velocity has been determined, the volume of air required should be based on maintaining this capture velocity and should be sufficient to overcome any opposing air currents. (For additional information on hood design guidelines for several industries, see Reference 2.)

Very few measurements of hood capture efficiency have been conducted.[4,5] Hood capture efficiencies of between 90 and 100 percent are possible depending on the situation and the particular process fugitive sources being controlled. For sources where operator access is not needed and where inspection doors can be provided, efficiencies toward the upper end of the range are achievable. For sources where emissions are more diffused, for example, from printing presses, capture efficiencies of 90 percent may be difficult. In the flexible vinyl and printing industry, 90 percent is typically the upper bound for capture efficiency on coating presses.[4,21] In the publication rotogravure industry, capture efficiencies of 93 to 97 percent have been demonstrated based on material balances.[5]

Once the process fugitive emissions are captured, the selection of the control device will be dependent on the emission stream characteristics, HAP characteristics, and the required overall performance levels (e.g., removal efficiency). Note that the required performance level for the control device will be determined by the capture efficiency. The factors that affect the control device selection process are the same as for point sources; therefore, refer to Sections 3.2.1 and 3.2.2.

For process fugitive emission sources such as process drains, the control alternatives involve a closure or a seal. A common method involves the use of a P-leg in the drain line with a water seal. A less common, but more effective method, is a completely closed drain system. Several factors affect the performance of water-sealed drains in reducing organic emissions: drainage rate, composition and temperature of the liquid entering the drain, diameter of the drain, and ambient atmospheric conditions. Emission reductions from water-sealed drains will vary depending upon the specific application. In a completely closed drain system, the system may be pressured and purged to a control device to effectively capture all emissions. The control efficiency would then depend on the efficiency of the control device.

Process fugitive emissions from cooling towers have not been reliably quantified due to difficulties encountered in measuring them and no specific control guidelines have been developed.[6] Probably the best control technique currently available is close monitoring of heat exchangers and other equipment to detect small leaks as they occur.

Table 3.4. Range of Capture Velocities[a]

Condition of Contaminant Dispersion	Examples	Capture Velocity (fpm[b])
Released with practically no velocity into quiet air	Evaporation from tanks; degreasing, etc.	50-100
Released at low velocity into 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; booths; conveyor loading crushers	200-500
Released at high initial velocity into zone of very rapid air motion	Grinding; abrasive blasting; tumbling	500-2,000

In each category above, a range of capture velocities is shown. The proper choice of values depends on several factors:

Lower End of Range:
- Rome air currents minimal or favorable to capture.
- Contaminants of low toxicity or of nuisance value only.
- Intermittent, low production.
- Large hood-large air mass in motion.

Upper End of Range:
- Disturbing room air currents.
- Contaminants of high toxicity.
- High production, heavy use.
- Small hood-local control only.

[a] Reference 2.
[b] fpm = feet per minute.

3.2.4 Control Techniques for Organic/Inorganic Vapor Emissions from Area Fugitive Sources

The control measures that can be employed for controlling organic or inorganic vapor emissions from area fugitive sources are basically the same. Control techniques for organic and inorganic vapor emissions are discussed.

Area fugitive emission sources may include lagoons and ponds where liquid waste streams containing organic compounds are disposed of. Emissions and emission rates of organic vapors from such sources are not well documented, and such sources are not easily controlled. The best method currently available for reducing emissions from lagoons and ponds is enhancing upstream treatment processes, thereby minimizing the amount of organic material reaching the lagoons and/or ponds. Other emission control techniques include surface enclosures and impoundments.

Area fugitive emissions of inorganic vapors may be found in plants processing inorganic chemicals, metals, electronics, and other products. Although extensive work has not been done to quantify equipment leaks in plants processing inorganic chemicals, it is expected that they would be similar to equipment leaks encountered in plants processing organic chemicals. Therefore, plants processing highly volatile compounds such as hydrogen chloride or ammonia would be expected to benefit by the same control techniques applied to reduce or eliminate fugitive emissions containing organic compounds as discussed in Section 3.2.3. There are some differences to keep in mind, however. First, for those control techniques that employ a control device to treat collected vapors, the control device will probably differ. Instead of a combustion device, an absorber, condenser, or an adsorber may be a more appropriate choice. Another difference would be relevant to leak detection and repair programs. Leak detection and repair programs for organic vapors were developed using portable organic analyzers. Portable analyzers that respond to the inorganic vapors of concern would have to be used for leak detection of inorganic materials.

Controlling inorganic vapor emissions from area sources such as lagoons and/or ponds where liquid waste streams containing volatile organic compounds are disposed of is quite difficult. The best control method currently available is minimizing the quantity of inorganic compounds reaching the lagoon and/or pond by improving upstream treatment processes.

3.2.5 Control Device Selection for a Hypothetical Facility

This subsection illustrates the control device selection process discussed in the previous sections for a hypothetical facility with several emission streams. Assume that the owner/operator of this facility has requested assistance regarding the control of these emission streams. The data supplied by the owner/operator are presented in Figures 3.2 through 3.8.

Emission Stream 1 (see Figure 3.2). This stream is the same as that described in Chapter 2 in the Example Case. Assuming the HAP control requirement is 99 percent reduction, from Figure 3.1, the only applicable control technique for this level of performance at concentration levels of ~1000 ppmv is thermal incineration. The HAP concentration is less than 25 percent of the LEL for the HAP (see Table 4.2-1); hence, the concentration limit indicated in Table 3.1 will not be exceeded. Also, the flow rate of Emission Stream 1 falls in the range of application indicated for thermal incinerators in Table 3.1.

Emission Stream 2 (see Figure 3.3). Assume the HAP control requirement for Emission Stream 2 is 95 percent reduction. For this level of performance, the applicable control techniques for inlet concentrations of ~500 ppmv are thermal incineration, catalytic incineration, and absorption. If either of the incineration techniques are applied, the concentration limit indicated in Table 3.1 will not be exceeded since the HAP concentration is less than 25 percent of the LEL for the HAP (see Table 4.2-1). The flow rate of Emission Stream 2 falls in the range indicated as applicable in Table 3.1 for these control techniques. The final selection of the control technique should also be based on design and cost criteria (Chapter 4).

Emission Stream 3 (see Figure 3.4). Assume the HAP control requirement for Emission Stream 3 is 98 percent reduction. In this case, the inlet HAP concentration falls outside the range indicated in Figure 3.1; therefore, none of the control devices in this figure are applicable. Note that dilution air could be used to decrease the HAP concentration. Alternatively, this stream may warrant consideration as a fuel gas stream. However, for example purposes, assume this stream is to be flared. According to Section 3.2.1.3, flares can be used to control emission streams with high heat contents; hence, flaring can be considered an option. Also, if a boiler or a process heater is available on site, it can be used to control Emission Stream 3.

Emission Stream 4 (see Figure 3.5). Assume the HAP control requirement for Emission Stream 4 is 95 percent reduction. For this level of performance, the applicable control techniques for inlet concentrations of ~1,000 ppmv are thermal incineration, catalytic incineration, carbon adsorption, and absorption. If either of the incineration methods or carbon adsorption is applied, the concentration limit indicated in Table 3.1 will not be exceeded since the HAP concentration is less than 25 percent of the LEL (see Table 4.2-1). The flow rate of Emission Stream 4 falls in the range indicated as applicable in Table 3.1 for these control techniques. The final selection of the control technique should also be based on design and cost criteria (Chapter 4).

Emission Stream 5 (see Figure 3.6). Assume the HAP control requirement for Emission Stream 5 is 98 percent reduction. Since this emission stream contains inorganic HAPs, incineration techniques are not applicable. The only control technique that is applicable for this level of

Figure 3.2. Effluent characteristics for emission stream #1.

HAP EMISSION STREAM DATA FORM*

Company Glaze Chemical Company
Location (Street) 87 Octane Drive
(City) Somewhere
(State, Zip)

Plant Contact Mr. John Leake
Telephone No. (999) 555-5024
Agency Contact Mr. Efrem Johnson
No. of Emission Streams Under Review 7

A. Emission Stream Number/Plant Identification #1 / #3 Oven Exhaust

B.	HAP Emission Source	(a) paper coating oven	(b)	(c)
C.	Source Classification	(a) process point	(b)	(c)
D.	Emission Stream HAPs	(a) toluene	(b)	(c)
E.	HAP Class and Form	(a) organic vapor	(b)	(c)
F.	HAP Content (1,2,3)**	(a) 960 ppmv	(b)	(c)
G.	HAP Vapor Pressure (1,2)	(a) 28.4 mm Hg at 77° F	(b)	(c)
H.	HAP Solubility (1,2)	(a) insoluble in water	(b)	(c)
I.	HAP Adsorptive Prop. (1,2)	(a) provided	(b)	(c)
J.	HAP Molecular Weight (1,2)	(a) 92 lb/lb-mole	(b)	(c)

K. Moisture Content (1,2,3) 2% volume
L. Temperature (1,2,3) 120° F
M. Flow Rate (1,2,3) 15,000 scfm (max)
N. Pressure (1,2) atmospheric
O. Halogen/Metals (1,2) none/none

P. Organic Content (1) *** 100 ppmv CH_4
Q. Heat/O_2 Content (1) 4.1 scf/20.6 vol%
R. Particulate Content (3)
S. Particle Mean Diam. (3)
T. Drift Velocity/SO_3 (3)

U. Applicable Regulation(s)
V. Required Control Level
W. Selected Control Methods

* The data presented are for an emission stream (single or combined streams) prior to entry into the selected control method(s). Use extra forms if additional space is necessary (e.g., more than three HAPs) and note this need.

** The numbers in parentheses denote what data should be supplied depending on the data on lines C and E:
1 = organic vapor process emission
2 = inorganic vapor process emission
3 = particulate process emission

*** Organic emission stream combustibles less HAP combustibles shown on lines D and F.

performance and inlet HAP concentrations of ~20,000 ppmv is absorption. The flow rate of Emission Stream 5 falls in the range indicated as applicable for absorption.

***Emission Stream 6** (see Figure 3.7).* Assume the HAP control requirement for Emission Stream 6 is 90 percent. Also assume that the owner/operator has indicated his preference to recover the HAP in the emission stream. For this level of performance, the applicable control techniques for inlet concentrations of ~13,000 ppmv are absorption and condensation. The final selection among these types of techniques should also be based on design and cost criteria (Chapter 4).

***Emission Stream 7** (see Figure 3.8).* Assume the HAP control requirement for this stream is 90 percent, and that the stream originates from a Soil Vapor Extraction (SVE) system. In this case, carbon canister units are commonly used. Since the concentration of the stream is 700 ppmv, carbon canister systems are applicable. The final selection of the control techniques also should be based on design and cost criteria (Chapter 4).

3.3 Particulate Emissions Control

Section 3.3.1 discusses add-on particulate control devices, and presents guidelines that are used to determine the applicability of each control device. Section 3.3.2 discusses control techniques that are used to reduce fugitive particulate emissions.

3.3.1 Control Techniques for Particulate Emissions from Point Sources

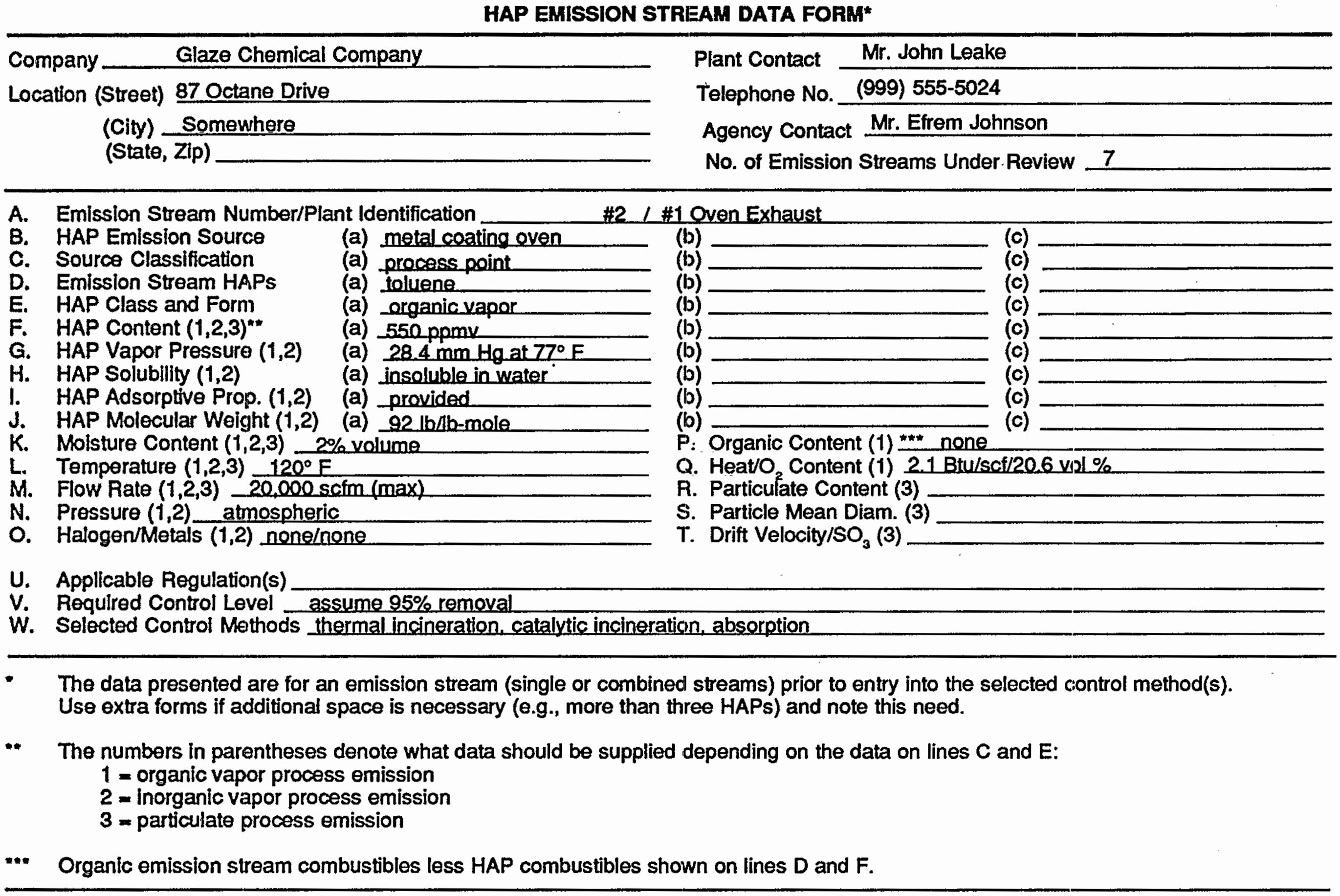
Three types of control devices applicable to particulate-laden emission streams from point sources are discussed below: fabric filters (baghouses), electrostatic precipitators (ESP), and venturi scrubbers.

The control efficiencies and applicability of these devices depend on the physical and/or chemical/electrical properties of the airborne particulate matter under consideration. Brief descriptions of each of these control devices appear in the subsections that follow.

Selection of the control devices themselves depends on the specific stream characteristics and the parameters (e.g., required collection efficiency) that affect the applicability of each control device.

Some key emission stream characteristics that affect the applicability of each device are identified in Table 3.5. Matching the characteristics of the emission stream under consideration with the corresponding information presented in Table 3.5 will identify those techniques most suited to control the stream. This does not imply that a given control device should be excluded at this point, however. In general, the parameters listed in Table 3.5

Figure 3.3. Effluent characteristics for emission stream #2.



HAP EMISSION STREAM DATA FORM*

Company Glaze Chemical Company
Location (Street) 87 Octane Drive
(City) Somewhere
(State, Zip)

Plant Contact Mr. John Leake
Telephone No. (999) 555-5024
Agency Contact Mr. Efrem Johnson
No. of Emission Streams Under Review 7

A. Emission Stream Number/Plant Identification #2 / #1 Oven Exhaust

B.	HAP Emission Source	(a) metal coating oven	(b)	(c)
C.	Source Classification	(a) process point	(b)	(c)
D.	Emission Stream HAPs	(a) toluene	(b)	(c)
E.	HAP Class and Form	(a) organic vapor	(b)	(c)
F.	HAP Content (1,2,3)**	(a) 550 ppmv	(b)	(c)
G.	HAP Vapor Pressure (1,2)	(a) 28.4 mm Hg at 77° F	(b)	(c)
H.	HAP Solubility (1,2)	(a) insoluble in water	(b)	(c)
I.	HAP Adsorptive Prop. (1,2)	(a) provided	(b)	(c)
J.	HAP Molecular Weight (1,2)	(a) 92 lb/lb-mole	(b)	(c)

K. Moisture Content (1,2,3) 2% volume
L. Temperature (1,2,3) 120° F
M. Flow Rate (1,2,3) 20,000 scfm (max)
N. Pressure (1,2) atmospheric
O. Halogen/Metals (1,2) none/none

P. Organic Content (1) *** none
Q. Heat/O_2 Content (1) 2.1 Btu/scf/20.6 vol %
R. Particulate Content (3)
S. Particle Mean Diam. (3)
T. Drift Velocity/SO_3 (3)

U. Applicable Regulation(s)
V. Required Control Level assume 95% removal
W. Selected Control Methods thermal incineration, catalytic incineration, absorption

* The data presented are for an emission stream (single or combined streams) prior to entry into the selected control method(s). Use extra forms if additional space is necessary (e.g., more than three HAPs) and note this need.

** The numbers in parentheses denote what data should be supplied depending on the data on lines C and E:
1 = organic vapor process emission
2 = inorganic vapor process emission
3 = particulate process emission

*** Organic emission stream combustibles less HAP combustibles shown on lines D and F.

are given as typical guidelines and should not be taken as absolute, definitive values. Gas stream pretreatment equipment can be installed upstream of the control device (i.e., cyclones, precoolers, preheaters) which enable the emission stream to fall within the parameters outlined in Table 3.5.

The temperature of the emission stream should be within 50 to 100° F above its dew point if the emission stream is to be treated (i.e., particulate matter collected) by an ESP or a fabric filter. If the emission stream temperature is below this range, condensation can occur; condensation can lead to corrosion of metal surfaces, blinding and/or deterioration of fabric filter bags, etc. If the emission stream is above this range, optimal HAP collection may not occur; by lowering the emission stream temperature, the vapor component of the HAP is reduced and, thus, an ESP or fabric filter will collect the HAP more effectively. Procedures for determining the dew point of an emission stream are provided in Appendix B.1; brief discussions of gas stream pretreatment equipment are presented in Appendix B.3.

General advantages and disadvantages for each particular control device are identified in Table 3.6. Table 3.6 is used to provide additional information on other considerations that, while not necessarily affecting the technical feasibility of the control device for the stream, may affect the overall desirability of using the device for a given emission stream can be provided by using Tables 3.5 and 3.6 together. Thus, guidelines to determine if a particular control device could and should be used for a given emission stream. Further design and cost criteria (Chapter 4) must be considered to enable a complete technical evaluation of the applicability of these devices to an emission stream.

Figure 3.9 provides the effluent characteristics for a hypothetical incinerator emission stream after exit from a heat exchanger. Assume the HAP control requirement is 99.9 percent, and that the HAP is cadmium. From Figure 3.9, note that the HAP content is 10 percent, the particulate content is 3.2 gr/acf, the particle mean diameter is 1μm, and the drift velocity is 0.31 ft/sec.

3.3.1.1 Fabric Filters

Fabric filters, or baghouses, are an efficient means of separating particulate matter entrained in a gaseous stream. A fabric filter is typically least efficient collecting particles in the range of 0.1 to 0.3 μm diameter although

Figure 3.4. **Effluent characteristics for emission stream #3.**

HAP EMISSION STREAM DATA FORM*

Company Glaze Chemical Company
Location (Street) 87 Octane Drive
(City) Somewhere
(State, Zip)
Plant Contact Mr. John Leake
Telephone No. (999) 555-5024
Agency Contact Mr. Efrem Johnson
No. of Emission Streams Under Review 7

A. Emission Stream Number/Plant Identification #3 / Acetaldehyde Manufacturing Absorber Vent

B.	HAP Emission Source	(a) absorber vent	(b)	(c)
C.	Source Classification	(a) process plant	(b)	(c)
D.	Emission Stream HAPs	(a) methylene chloride	(b)	(c)
E.	HAP Class and Form	(a) organic vapor	(b)	(c)
F.	HAP Content (1,2,3)**	(a) 44,000 ppmv	(b)	(c)
G.	HAP Vapor Pressure (1,2)	(a) 436 mm Hg of 77° F	(b)	(c)
H.	HAP Solubility (1,2)	(a) insoluble in water	(b)	(c)
I.	HAP Adsorptive Prop. (1,2)	(a) not given	(b)	(c)
J.	HAP Molecular Weight (1,2)	(a) 85 lb/lb-mole	(b)	(c)

K. Moisture Content (1,2,3) none
L. Temperature (1,2,3) 100° F
M. Flow Rate (1,2,3) 30,000 scfm expected
N. Pressure (1,2) atmospheric
O. Halogen/Metals (1,2) none / none
P. Organic Content (1) *** 17.8% vol CH_4
Q. Heat/O_2 Content (1) 180 Btu/scf/none
R. Particulate Content (3)
S. Particle Mean Diam. (3)
T. Drift Velocity/SO_3 (3)

U. Applicable Regulation(s)
V. Required Control Level assume 98% removal
W. Selected Control Methods flare, boiler, process heater

* The data presented are for an emission stream (single or combined streams) prior to entry into the selected control method(s). Use extra forms if additional space is necessary (e.g., more than three HAPs) and note this need.

** The numbers in parentheses denote what data should be supplied depending on the data on lines C and E:
1 = organic vapor process emission
2 = inorganic vapor process emission
3 = particulate process emission

*** Organic emission stream combustibles less HAP combustibles shown on lines D and F.

Table 3.5. **Key Characteristics for Particulate Emission Streams** [a]

Control Device	Achievable Efficiency Range	Particle Size Limitation	Temperature	Corrosiveness/ Resistivity	Moisture Content
Baghouse	Up to 99+%	Least efficient with particles 0.1 µm to 0.3 µm diameter.	Dependent on fiber type but not exceeding 550° F without a precooler	Special fiber types necessary to resist corrosion.	Poor efficiency with emission streams of high moisture content, very sensitive changes in moisture content of an emission stream.
ESP	Up to 99+%	Generally least efficient with particles around 1 µm diameter, but not as sensitive to particle size as other two devices.	Generally up to 1,000° F.	Corrosion resistant materials required. May require conditioning agents for highly resistive particles. Additionally, ESPs are not used to control organic matter since this constitutes a fire hazard.	Can control streams with relatively high moisture content (i.e., 34% vol) if so designed, but sensitive to moisture changes of an emission stream.
Venturi scrubber	Up to 99+%	Generally operates best with particles >0.5 µm diameter.	No general limitations.	Special construction may be required for corrosive emission streams particularly for throat section.	Not sensitive to changes in moisture content of an emission stream.

[a] Characteristics given are designed to provide general, not definitive, guidance.

Figure 3.5. Effluent characteristics for emission sream #4.

HAP EMISSION STREAM DATA FORM*

Company Glaze Chemical Company
Location (Street) 87 Octane Drive
(City) Somewhere
(State, Zip)

Plant Contact Mr. John Leake
Telephone No. (999) 555-5024
Agency Contact Mr. Efrem Johnson
No. of Emission Streams Under Review

A. Emission Stream Number/Plant Identification #4 / #1 Printing Press

B.	HAP Emission Source	(a) printing press	(b)	(c)
C.	Source Classification	(a) process point	(b)	(c)
D.	Emission Stream HAPs	(a) toluene	(b)	(c)
E.	HAP Class and Form	(a) organic vapor	(b)	(c)
F.	HAP Content (1,2,3)**	(a) 1,000 ppmv	(b)	(c)
G.	HAP Vapor Pressure (1,2)	(a) 28.4 mm Hg at 77° F	(b)	(c)
H.	HAP Solubility (1,2)	(a) insoluble in water	(b)	(c)
I.	HAP Adsorptive Prop. (1,2)	(a) provided	(b)	(c)
J.	HAP Molecular Weight (1,2)	(a) 92 lb/lb-mole	(b)	(c)

K. Moisture Content (1,2,3) 40% rel. humidity
L. Temperature (1,2,3) 90° F
M. Flow Rate (1,2,3) 15,000 scfm (max)
N. Pressure (1,2) atmospheric
O. Halogen/Metals (1,2) none / none

P. Organic Content (1)*** none
Q. Heat/O_2 Content (1) 4.2 Btu/scf/20.6% vol
R. Particulate Content (3)
S. Particle Mean Diam. (3)
T. Drift Velocity/SO_3 (3)

U. Applicable Regulation(s)
V. Required Control Level assume 95% removal
W. Selected Control Methods thermal incineration, catalytic incineration, carbon adsorption, and absorption

* The data presented are for an emission stream (single or combined streams) prior to entry into the selected control method(s). Use extra forms if additional space is necessary (e.g., more than three HAPs) and note this need.

** The numbers in parentheses denote what data should be supplied depending on the data on lines C and E:
1 = organic vapor process emission
2 = inorganic vapor process emission
3 = particulate process emission

*** Organic emission stream combustibles less HAP combustibles shown on lines Dand F.

efficiencies can still be quite high for this particle range. Fabric filters used to control emissions containing HAPs should have a closed, negative-pressure (suction) configuration to prevent accidental release of the gas stream and captured HAPs.

Fabric filters using mechanical shaking, reverse air, and pulse-jet cleaning are fundamentally different from ESPs and venturi scrubbers in that they are not "efficiency" devices. A properly designed and operated fabric filter using one of these two cleaning methods will yield a relatively constant outlet particle concentration, regardless of inlet load changes. The typical outlet particle concentration range is between 0.003 to 0.01 grains/scf (gr/scf), averaging around 0.005 grains/scf.[3,23] These numbers can be used to ascertain an expected performance level. This is not meant to be an absolute, definitive performance level. A vendor should assist in any attempt to quantify an actual performance level. Variables important to achieve a given performance (i.e., air-to-cloth ratio, cleaning mechanism, fabric type) are discussed in detail in Section 4.9.

Fabric filters are sensitive to emission stream temperature and a precooler or preheater may be required, as discussed previously. Fabric filters operate at low pressure drops, giving them low operating costs. Opacity monitors located in the stack are often used to monitor performance. In addition, the pressure drop across a fabric filter is a basic indicator of performance. For control of HAPs, it is recommended that this parameter be monitored continuously in conjunction with opacity monitors. Fabric filters are generally not a feasible choice to control emission streams with a high moisture content unless pretreatment is performed.

3.3.1.2 Electrostatic Precipitators

Electrostatic precipitator particle removal occurs by charging the particles, collecting the particles, and transporting the collected particles into a hopper. ESPs are less sensitive to particle size than the other two devices and in fact can control submicron particles quite well, but are very sensitive to those factors that affect the maximum electrical power (voltage) at which they operate. These are principally the aerosol density (grains/scf) and the electrical resistivity of the material although wet ESPs are much more insensitive to particle resistivity than dry ESPs. The electrical resistivity of the particles influences the drift velocity, or the attraction between the particles and the collecting plate. A high resistivity will cause a low

Figure 3.6. Effluent characteristics for emission stream #5.

HAP EMISSION STREAM DATA FORM*

Company Glaze Chemical Company
Location (Street) 87 Octane Drive
(City) Somewhere
(State, Zip)
Plant Contact Mr. John Leake
Telephone No. (999) 555-5024
Agency Contact Mr. Efrem Johnson
No. of Emission Streams Under Review 7

A. Emission Stream Number/Plant Identification #5 / Urea Evaporator Off-gas Exhaust

B.	HAP Emission Source	(a) evaporator off-gas	(b)	(c)
C.	Source Classification	(a) process point	(b)	(c)
D.	Emission Stream HAPs	(a) ammonia	(b)	(c)
E.	HAP Class and Form	(a) inorganic vapor	(b)	(c)
F.	HAP Content (1,2,3)**	(a) 20,000 ppmv	(b)	(c)
G.	HAP Vapor Pressure (1,2)	(a) 8.46 atm at 68° F	(b)	(c)
H.	HAP Solubility (1,2)	(a) provided	(b)	(c)
I.	HAP Adsorptive Prop. (1,2)	(a) not given	(b)	(c)
J.	HAP Molecular Weight (1,2)	(a) 17 lb/lb-mole	(b)	(c)

K. Moisture Content (1,2,3) 2% vol	P. Organic Content (1) ***
L. Temperature (1,2,3) 85° F	Q. Heat/O_2 Content (1)
M. Flow Rate (1,2,3) 3,000 scfm (max)	R. Particulate Content (3)
N. Pressure (1,2) atmospheric	S. Particle Mean Diam. (3)
O. Halogen/Metals (1,2) none / none	T. Drift Velocity/SO_3 (3)

U. Applicable Regulation(s)
V. Required Control Level assume 98% removal
W. Selected Control Methods absorption

* The data presented are for an emission stream (single or combined streams) prior to entry into the selected control method(s). Use extra forms if additional space is necessary (e.g., more than three HAPs) and note this need.

** The numbers in parentheses denote what data should be supplied depending on the data on lines C and E:
1 = organic vapor process emission
2 = inorganic vapor process emission
3 = particulate process emission

*** Organic emission stream combustibles less HAP combustibles shown on lines D and F.

drift velocity which may decrease the overall collection efficiency. A low resistivity indicates that it is difficult to charge the particles and will tend to decrease the collection efficiency, all other things being equal. Electrostatic precipitators are discussed further in Section 4.10.

An ionizing wet scrubber (IWS) may also be used for particulate collection. An IWS uses an electrostatic field followed by a packed bed for two stage collection. These devices are more insensitive to particle resistivity than dry ESPs and can also scrub the gas stream for further pollutant removal. See Section 4.10 for a further discussion.

3.3.1.3 Venturi Scrubbers

Venturi scrubbers use an aqueous stream to remove particulate matter from an emissions stream. The performance of a venturi scrubber is not affected by sticky, flammable, or corrosive particles. Venturi scrubbers are more sensitive to particle size distribution than either ESP or fabric filters. In general, venturi scrubbers perform most efficiently for particles above 0.5 um in diameter (see Section 4.11 for further detail). Venturi scrubbers have a lower initial cost than either fabric filters or ESPs, but the high pressure drop required for high collection efficiencies contributes to high operating costs.

3.3.2 Control Techniques for Particulate Emissions from Fugitive Sources

Fugitive emission sources may be broken down into two source categories: process sources and area sources, as defined in Section 2.2. The methods used to control process sources of fugitive particulate emissions are generally different from those applied to area sources. Basically, process fugitive sources can employ conventional measures (i.e., capture techniques and add-on control devices) while area fugitive sources either cannot use conventional measures or the use of conventional measures is precluded due to cost. For example, fugitive emissions from unpaved roads cannot use conventional control measures, but fugitive emissions from area sources such as pumps and valves can be captured and ducted to a control device, although the costs may be prohibitive. Area sources are often controlled by preventive techniques rather than capture/control techniques.

Section 3.2.3 discusses methods of hooding and capture of process emissions. The remaining fugitive particulate emission control methodologies (i.e., nonconventional techniques) can be applied to multiple fugitive emission sources - both for process and area sources.

Example Case

Assume a facility is required to achieve an emission limit for particulate emissions from a municipal waste incinerator. The emissions stream particles consist primarily of fly ash; however, 10 percent of these particles is a HAP: cadmium. The characteristics of the emission stream after exiting a heat exchanger are shown in Figure 3.9. From Figure B.1-1 (Appendix B), t the dew point of an emission stream containing 200 ppmv SO_3 and 5 percent moisture is approximately 327° F. Thus, the emission stream temperature (400° F) is within 50 to 100° F above its dew point, thus minimizing the amount of the HAP in vapor form and eliminating condensation problems. Calculate the al

$$\frac{110{,}000\text{ acf}}{\text{min}} \times \frac{3.2\text{ gr}}{\text{acf}} \times \frac{\text{lb}}{7{,}000\text{ gr}} \times \frac{60\text{ min}}{\text{hr}} = 3{,}017\,\frac{\text{lb}}{\text{hr}}$$

$$3{,}017\,\frac{\text{lb}}{\text{hr}} \times (1 - 0.999) = 3.017\,\frac{\text{lb}}{\text{hr}}$$

Since the HAP constitutes 10 percent of the total particulate matter, the outlet concentration of the HAP is:

$$0.10 \times 3.017\,\frac{\text{lb}}{\text{hr}} = 0.3017\,\frac{\text{lb HAP}}{\text{hr}}$$

This value assumes that the HAP is in particulate form and that it is collected as efficiently as the other particles. A fabric filter will generally control particles to a limit of about 0.003 gr/scf. Converting gr/scf to lb/hr yields:

$$\frac{0.003\text{ gr}}{\text{scf}} \times \frac{110{,}000\text{ acf}}{\text{min}} \times \frac{530°\text{ R-scf}}{(400 + 460)\text{ °R-acf}}$$

$$\times \frac{60\text{ min-lb}}{7000\text{ gr-hr}} = 1.7\,\frac{\text{lb}}{\text{hr}}$$

To calculate the HAP outlet emission rate:

$$1.7\,\frac{\text{lb}}{\text{hr}} \times 0.10 = 0.17\,\frac{\text{lb HAP}}{\text{hr}}$$

This value again is decided by assuming that the HAP is in particulate form and that it is collected as efficiently as the other gas stream particles. The calculated HAP emission rate from a fabric filter is less than the allowable rate, indicating that use of a fabric filter is an appropriate control technique for this emission stream.

In general, an electrostatic precipitator can achieve control efficiencies of 99.9 percent, provided the particle resistivity is not "high." The drift velocity of the particles (0.31 ft/sec) is indicative of particles with an "average" resistivity (see Section 4.10.3.1); therefore, an ESP can probably be used to control this stream and, thus, it also is an appropriate control technique for this emission stream.

Venturi scrubber particles below 0.5 μm diameter are difficult to control with. The emission stream presented contains particles generally above this limit; therefore, a venturi scrubber may be an acceptable control device for this example and, thus, all three particulate control devices are approptriate control techniques for this emission stream. To determine the basic design parameters and actual applicability of each control device, Section 4.9 (Fabric Filter), Section 4.10 (ESPs), and Section 4.11 (Venturi Scrubbers) must be examined.

The following subsections discuss the different types of fugitive particulate emission control techniques that can be applied to general process and area fugitive particulate emission sources (i.e., sources common to many industries).

An extensive review of available literature on fugitive emissions revealed that a specific reference included almost all necessary information pertinent to the scope of this manual. Consequently, most of the following subsections are taken directly from the following document: "Technical Guidance for Control of Industrial Process Fugitive Particulate Emissions."[14] Reference 15 also provides the reader with a comprehensive view of this subject.

Throughout the discussions, control efficiencies are stated for many of the control techniques. It is important to note that the efficiency values are estimates. The ability to quantify accurately the emission rates from a fugitive emission source has not yet been fully realized.

3.3.2.1 Process Fugitive Particulate Emission Control

Control of HAP process fugitive emissions may be accomplished by capturing the particulate material and venting it to an add-on control device (i.e., venturi scrubbers, fabric filters, and ESP's). Venting emissions is accomplished by exhausting particle-laden air through fixed or movable ducting under negative pressure. The airflow into the ducting must be sufficient to maintain

Figure 3.7. Effluent characteristics for emission stream #6.

HAP EMISSION STREAM DATA FORM*

Company Glaze Chemical Company
Location (Street) 87 Octane Drive
(City) Somewhere
(State, Zip)

Plant Contact Mr. John Leake
Telephone No. (999) 555-5024
Agency Contact Mr. Efrem Johnson
No. of Emission Streams Under Review 7

A. Emission Stream Number/Plant Identification #6 / Styrene Recovery Condenser Unit
B. HAP Emission Source (a) condenser vent (b) (c)
C. Source Classification (a) process point (b) (c)
D. Emission Stream HAPs (a) styrene (b) (c)
E. HAP Class and Form (a) organic vapor (b) (c)
F. HAP Content (1,2,3)** (a) 13,000 ppmv (b) (c)
G. HAP Vapor Pressure (1,2) (a) provided (b) (c)
H. HAP Solubility (1,2) (a) insoluble in water (b) (c)
I. HAP Adsorptive Prop. (1,2) (a) not given (b) (c)
J. HAP Molecular Weight (1,2) (a) 104 lb/lb-mole (b) (c)
K. Moisture Content (1,2,3) negligible
L. Temperature (1,2,3) 90° F
M. Flow Rate (1,2,3) 2,000 scfm (max)
N. Pressure (1,2) atmospheric
O. Halogen/Metals (1,2) none / none
P. Organic Content (1)*** none
Q. Heat/O_2 Content (1) 61.5 Btu/scf/20.7% vol
R. Particulate Content (3)
S. Particle Mean Diam. (3)
T. Drift Velocity/SO_3 (3)
U. Applicable Regulation(s)
V. Required Control Level assume 90% removal
W. Selected Control Methods absorption, condensation

* The data presented are for an emission stream (single or combined streams) prior to entry into the selected control method(s). Use extra forms if additional space is necessary (e.g., more than three HAPs) and note this need.

** The numbers in parentheses denote what data should be supplied depending on the data on lines C and E:
1 = organic vapor process emission
2 = inorganic vapor process emission
3 = particulate process emission

*** Organic emission stream combustibles less HAP combustibles shown on lines D and F.

particle size capture velocity and to overcome opposing air currents. The effect of opposing air currents can be eliminated by complete enclosure, or can be reduced by minimizing the opening of capture enclosures, or by utilizing curtains or partitions to block room air currents. If enclosure or installation of fixed hoods is not feasible due to space limitations or operational procedures, movable hoods may be a viable alternative. Movable hoods can be placed over the fugitive emission source as the production cycle permits. For example, movable hoods can be placed over the filling hatch in some types of trucks and rail cars during loading. Movable hoods have also been applied in the production of coke, whereby a movable hood follows quench cars during coke pushing. Another alternative is to evacuate an enclosed building to a control device.

Once the emissions are captured, the selection of the control device will be dependent on the emission stream characteristics, HAP characteristics, and the required performance levels (i.e., removal efficiency). It is important to remember that the required performance level for the control device is influenced by the efficiency of the capture system. The factors that affect the control device selection process are the same as for point sources, and are discussed in Section 3.3.1.

3.3.2.2 Area Fugitive Emission Control from Transfer and Conveying

Loss of material from conveyors is primarily at the feeding, transfer, and discharge points and occurs due to spillage or windage. The majority of particulate emissions are generally from spillage and mechanical agitation of the material at uncovered transfer points. However, emissions from inadequately enclosed systems can be quite extensive. Table 3.7 presents control techniques applicable to these emission sources.

Control by wet suppression methods includes the application of water, chemicals, and foam. The point of application is most commonly at the conveyor feed and discharge points, with some applications at conveyor transfer points. Wet suppression with water only is a relatively inexpensive technique; however, it has the inherent disadvantage of being short-lived. Control with chemicals (added to water for improved wetting) or foam is longer lasting but more expensive than water alone. Foam is effective in dust suppression because small particles (in the range of 1 to 50 μm diameter) break the surface of the bubbles in the foam when they come in contact, thereby wetting the particles. Particles larger than 50 um only move the bubbles away. The small wetted particles then must be brought together or brought

Table 3.6. Advantages and Disadvantages of Particulate Control Devices.

	Advantages	Disadvantages
Baghouse	— Very efficient at removing fine particulate matter from a gaseous stream; control efficiency can exceed 99 percent for most applications. — Lower system pressure drop than venturi scrubber when controlling fine particulates; i.e., 5" to 20" H_2O compared with ≥ 40" H_2O. — Can collect electrically resistive particles. — With mechanical shaking, reverse air cleaning, or low pressure pulse-jet, control efficiency is generally independent of inlet loading. — Simple to operate.	— Cannot control high temp stream (>550° F) without a precooler, or special fabric types. — Cannot effectively control stream with high moisture content. — Highly erosive particles can damage the filter. — Mechanical collectors generally required upstream if significant amounts of large particulates (>20 µm) are present. — Needs special or selected fabrics to control corrosive streams. — Least efficient with particles between 0.1µm to 0.3 µm diameter.
ESP	— Can control very small (0.1 µm) particles with high efficiency. — Low operating costs with very low system pressure drop (5" H_2O) — Can collect corrosive or tar mists. — Power requirements for continuous operation are low. — Wet ESPs can collect gaseous pollutants and are less sensitive to particle resistivity.	— High initial capital investment. — Not readily adaptable to changing conditions. — Conditioning agents may be necessary to control resistive particles. — Dry ESPs are more sensitive to particle loading, size distribution, and resistivity than other two devices. — Space requirements may be greater than that for a fabric filter or venturi scrubber.
Venturi scrubber	— Low initial investment. — Takes up relatively little space. — Can control sticky, flammable, or corrosive matter with few problems. — Can simultaneously collect particulates and gaseous matter. — Control efficiency is independent of particle resistivity. — Simple to operate, few moving parts.	— High operating cost due to high pressure drop (40" H_2O or greater), particularly for smaller (<1µm) particles. — Has wastewater and cleaning/disposal costs. — Least efficient with particles less than 0.5 µm diameter.

in contact with larger particles to achieve agglomeration. If foam is injected into free-falling aggregate at a transfer point, the mechanical motion provides the required particle to bubble contact and subsequent particle-to-particle contact. Highly diluted chemical wetting agents are applied by water jets ahead of any points in the conveying system where dusting occurs. The wetting agent breaks down the surface tension of the water, allowing it to spread further, penetrate deeper, and wet the small particles better than untreated water. With mechanical agitation of the material, the small particles agglomerate. For effective control, the spray should be applied at each point where the particles might be fractured, allowed to free fall, or subjected to strong air currents.

3.3.2.3 Area Fugitive Emission Control from Loading and Unloading

Loading and unloading bulk material is common to many processing industries. Loading and unloading operations can be either for external transportation of material to or from a facility or for internal transportation within a facility (for example, internal transportation might consist of loading of a mining haul truck with ore via a front-end loader for subsequent unloading to a crushing process). Appendix A.8 should also be consulted for industry-specific information on loading and unloading for internal transportation.

Various control technology applications for loading and unloading operations are presented in Table 3.8. These techniques can be used alone or at times in various combinations. Generally, the simultaneous use of more than one technique will provide increased levels of control.

Rail Car and Truck Loading. To minimize particulate emissions from rail car and truck loading, the entire operation can be enclosed by the use of doors on the loading shed. This prevents a wind tunnel effect and allows dust emitted in the enclosure to settle to the ground within the enclosure. By venting the entire enclosure to a control device, dust leakage around the doors and any other openings can be prevented, thus ensuring near 100 percent control.

Exhausting the car or truck body to a dust removal device reduces emissions if the body is fairly well enclosed. In open type rail or truck bodies this technique is not too effective.

Choke-feed eliminates free fall of material into the car or truck. In this technique the mouth of the feed tube is immersed in the material being unloaded. This technique only works for fairly free-flowing dry material. A telescopic chute or spout also essentially eliminates the free-fall distance of the material being loaded. This type of system can be used on all types of material. Both the choke-feed and telescopic chute methods are only partially effective in eliminating emissions since the surface of the loaded material is constantly disturbed by new

Figure 3.8. Effluent characteristics for emission stream #7.

HAP EMISSION STREAM DATA FORM*

Company Glaze Chemical Company

Location (Street) 87 Octane Drive

(City) Somewhere

(State, Zip)

Plant Contact Mr. John Leake

Telephone No. (999) 555-5024

Agency Contact Mr. Efrem Johnson

No. of Emission Streams Under Review 7

A. Emission Stream Number/Plant Identification #7 / Soil Vapor Extraction (SVE) Vent

B.	HAP Emission Source	(a) SVE vent	(b)	(c)
C.	Source Classification	(a) process point	(b)	(c)
D.	Emission Stream HAPs	(a) acetone	(b)	(c)
E.	HAP Class and Form	(a) organic vapor	(b)	(c)
F.	HAP Content (1,2,3)**	(a) 700 ppmv	(b)	(c)
G.	HAP Vapor Pressure (1,2)	(a) provided	(b)	(c)
H.	HAP Solubility (1,2)	(a) micisible in water	(b)	(c)
I.	HAP Adsorptive Prop. (1,2)	(a) provided	(b)	(c)
J.	HAP Molecular Weight (1,2)	(a) 58 lb/lb-mole	(b)	(c)

K. Moisture Content (1,2,3) 40% rel humidity

L. Temperature (1,2,3) 90° F

M. Flow Rate (1,2,3) 2,000 scfm (max)

N. Pressure (1,2) atmospheric

O. Halogen/Metals (1,2) none / none

P. Organic Content (1)*** none

Q. Heat/O_2 Content (1) 1.34 Btu/scf/20.6% vol

R. Particulate Content (3)

S. Particle Mean Diam. (3)

T. Drift Velocity/SO_3 (3)

U. Applicable Regulation(s)

V. Required Control Level assume 90%

W. Selected Control Methods carbon adsorption canister system

* The data presented are for an emission stream (single or combined streams) prior to entry into the selected control method(s). Use extra forms if additional space is necessary (e.g., more than three HAPs) and note this need.

** The numbers in parentheses denote what data should be supplied depending on the data on lines C and E:
1 = organic vapor process emission
2 = inorganic vapor process emission
3 = particulate process emission

*** Organic emission stream combustibles less HAP combustibles shown on lines D and F.

material. This surface is subject to wind and dust entrainment.

Movable hoods exhausted to a dust removal system can be placed over the filling hatch in some types of trucks and railcars during loading. By keeping other openings on the body closed, any dust generated in loading must be emitted through the single open hatch. A hood with sufficient airflow mounted around this opening could capture most of the dust generated.

Wet suppression techniques, when applied to loading operations, can reduce airborne dust to some extent. The loading process naturally breaks up surface coatings, but some small dust particles will adhere to larger pieces so as not to become entrained. Many materials cannot be readily wetted and this technique could not be used for these materials.

Barge and Ship Loading. Due to their larger size, barge and ship loading present unique problems for dust control. However, a number of control techniques have been developed and utilized, especially at some of the larger shipping terminals.

The use of tarpaulins or similar covers over hatches on ships and enclosed barges reduces airborne emissions by preventing their escape. Air, displaced by the material being loaded, causes the hold to become slightly pressurized during loading, and the hold must be vented at some point if the hatches are air-tight. Thus, a more effective control system incorporates an exhaust system for the hold. This exhaust system is connected to a dust control system such as fabric filter with the collected material being returned to the hold. Such a system can practically eliminate loading emissions if carefully maintained and properly operated. The use of a canopy hood and exhaust system over the loading boom is less effective than a totally enclosed system, but can still reduce emissions and is a viable alternative for open barges. Effective utilization of this technique requires some type of wind break to increase the hood capture efficiency. Choke feed and telescopic chutes or spouts as previously described can also be used for loading both enclosed and open ships or barges. Wet suppression techniques may also help reduce airborne emissions if the product specifications do not prohibit use of this technique.

Figure 3.9. ***Effluent characteristics for a municipal incinerator emission stream***

HAP EMISSION STREAM DATA FORM*

Company Incineration, Inc.
Location (Street) 123 Main Street
(City) Somewhere
(State, Zip)

Plant contact Mr. Phil Brothers
Telephone No. (999) 555-5024
Agency Contact Mr. Ben Hold
No. of Emission Streams Under Review 1

A. Emission Stream Number/Plant Identification #1 / Incineration

B.	HAP Emission Source	(a) municipal incinerator	(b)		(c)	
C.	Source Classification	(a) process point	(b)		(c)	
D.	Emission Stream HAPs	(a) cadmium	(b)		(c)	
E.	HAP Class and Form	(a) inorganic particulate	(b)		(c)	
F.	HAP Content (1,2,3)**	(a) 10%	(b)		(c)	
G.	HAP Vapor Pressure (1,2)	(a)	(b)		(c)	
H.	HAP Solubility (1,2)	(a)	(b)		(c)	
I.	HAP Adsorptive Prop. (1,2)	(a)	(b)		(c)	
J.	HAP Molecular Weight (1,2)	(a)	(b)		(c)	

K. Moisture Content (1,2,3) 5% vol
L. Temperature (1,2,3) 400° F
M. Flow Rate (1,2,3) 110,000 acfm
N. Pressure (1,2) atmospheric
O. Halogen/Metals (1,2) none / none

P. Organic Content (1) ***
Q. Heat/O_2 Content (1)
R. Particulate Content (3) 3.2 gr/acf, flyash
S. Particle Mean Diam. (3) 1.0 um
T. Drift Velocity/SO_3 (3) 0.31 ft/sec/200 ppmv

U. Applicable Regulation(s)
V. Required Control Level assume 99.9% removal
W. Selected Control Methods fabric filter, ESP, venturi scrubber

* The data presented are for an emission stream (single or combined streams) prior to entry into the selected control method(s). Use extra forms if additional space is necessary (e.g., more than three HAPs) and note this need.

** The numbers in parentheses denote what data should be supplied depending on the data on lines C and E:
1 = organic vapor process emission
2 = inorganic vapor process emission
3 = particulate process emission

*** Organic emission stream combustibles less HAP combustibles shown on lines D and F.

Rail Car and Truck Unloading. Many of the unloading dust control techniques are identical to the loading techniques. When a rail car or truck is tilted and materials are dumped into an underground chamber through a grating, exhausting air from this chamber through a control device will effectively reduce emissions. By causing air to flow down through the grating, dust emissions are contained. The face velocity of air through the grating is a critical design parameter in this technique. Unloading cars with a screw conveyor causes less distribution of the material and thereby less dust. Problems of material handling and time requirements limit the application of this technique. Pneumatic unloading of very fine materials is an effective and widely used technique that practically eliminates dust emissions. With this system, careful maintenance of hose fittings and the fabric filter through which the conveying air exhausts is required.

Barge and Ship Unloading. Control of barge and ship unloading requires enclosure of the receiving point on the shore and possibly exhausting of that enclosure to a control device. A good enclosure with an exhaust system can provide essentially 100 percent capture. For open ships and barges which use buckets and conveyors, a partially enclosed bucket will reduce windblown dust. When observation of the bucket by the operator is re-

Table 3.7. Control Technology Applications for Transfer and Conveying Sources.

Emission Points	Control Procedure
Conveyor system (belt, bucket elevator, etc.)	Enclosure 1. Top covered (marginal control) 2. Sides and top covered (good control) 3. Completely enclosed (excellent control) Wet suppression (water, chemical, foam) at conveyor feed points. Belt scrapers and wipers Mechanical belt turnovers Replacement with pneumatic system or screw conveyor
Transfer and transition points	Enclosure Hoods, covers, or canopies with exhaust to removal equipment (fabric filters, and wet-collectors) Wet suppression (water, chemical, foam)

Table 3.8. ***Control Technology Applications for Loading and Unloading Operations***

Emission Points	Control Procedures Loading Operations	 Unloading Operations
Railcar, truck	— Drive-through enclosure with doors at ends — Exhaust of entire enclosure to dust removal equipment — Movable hood over hatch opening — Exhaust of car hopper to dust removal equipment — Choke-feed or telescopic chute to confine and limit free-fall distance (gravity loading) — Wet suppression (water, chemicals)	— Drive-through enclosure with doors at both — Exhaust of enclosure to dust removal equipment — Exhaust air from below grating of receiving hopper to removal equipment — Chock-feed to receiving pit (hopper car and hopper truck). — Unloading with screw conveyor (box car) — Wet suppression (water, chemicals) — Use of pneumatic unloading system
Barge, ship	— Use of tarpaulins or covers over the holds — Canopy and exhaust system over the loading boom, with attached tarps around the hatch — Exhaust of ship hold to dust removal equipment — Choke-feed or telescopic chute to confine and limit free-fall distance — For tanker types, use of gravity filler spouts with concentric outer exhaust — Wet suppression (water, chemicals)	— Enclosure of top of clamshell bucket with transparent material and maintenance of closure seals and teeth on bottom of bucket — Enclosure of shoreside receiving hopper — Exhaust of enclosed shoreside receiving hopper to dust removal equipment

quired, a transparent heavy plastic sheet can be used as a cover. This system is only partially effective and must usually be supplemented with other controls, such as tighter fitting covers, wind breaks, or possibly wet suppression.

3.3.2.4 Area Fugitive Emission Control from Paved and Unpaved Roads

Dust on the surface of paved roads is deposited by such processes as mud track-out on vehicle tires, atmospheric fallout, spillage or leakage from trucks, pavement wear and decomposition, runoff or wind erosion from adjacent land areas, deposition of biological debris, wear from tires and brake linings, and wear of anti-skid compounds. This material is reentrained by contact with tires and by the air turbulence created by passing vehicles.

On unpaved roads, the road base itself serves as the main source of dust. As with paved roads, the dust becomes airborne by contact with vehicles' tires and by air turbulence from passing vehicles. Also, some of the fugitive dust from unpaved roads is attributed to wind erosion. On both paved and unpaved roads, traffic movement causes the continuing mechanical breakdown of large particles on the road surface, thus providing new material in the suspended particulate size range. Available procedures for reducing emissions from plant roads and their estimated efficiencies are presented in Table 3.9.

Paved streets and roads in a plant area can be cleaned on a frequent schedule to reduce the amount of particulate material on the surface that is available for reentrainment. Flushers and vacuum-type motorized street cleaners are both quite effective in removing surface material and thereby reducing emission rates from vehicles using the cleaned streets. Because raw material accumulates rapidly on the streets, the overall effectiveness of a street-cleaning measure is a function of the frequency of cleaning and the removal efficiency of the equipment.

For plants with small amounts of paved roads, industrial vacuum sweepers or contracted sweeping programs (such as many shopping centers use) would be more appropriate than the larger vacuum street cleaning equipment used on public streets. Mechanical broom sweepers have been shown to be ineffective from an air pollution control standpoint in that they redistribute material into the active traffic lanes of the streets and they remove almost none of the fine material (less than 43 um) that is subject to reentrainment.

Many street sweepers depend upon the material being concentrated in the gutter in order to achieve good collection efficiency, and therefore cannot be used on streets without curbs and gutters. However, the smaller

Table 3.9. ***Control Technology Applications for Plant Roads***

Emission Points	Control Procedure	Efficiency
Paved streets	Street cleaning	No Estimate
	Housecleaning programs to reduce deposition of material on streets	No estimate
	Vacuum street sweeping[2] (daily)	25%[15]
	Speed reduction	Variable
Unpaved roads	Paving	85%
	Chemical stabilization	50%
	Watering	50%
	Speed reduction	Variable
	Oiling and double chip surface	85%
Road shoulders	Stabilization	80%

industrial sweepers are usually designed for use in warehouse and storage areas that are not curbed. A factor which might limit the applicability of street flushers in plants is that unpaved areas adjacent to the streets would be wet by the water spray and then become subject to mud track-out onto the streets by equipment and vehicles driving through these areas.

Good housekeeping practices include the rapid removal of spills on roadways and at conveyor transfer points. Preventive measures include covering of truck beds to prevent windage losses, cleaning of truck tires and undercarriages to reduce mud track-out onto paved roads, and minimizing the pick-up of mud by trucks.

The paving of unpaved roadways is the most permanent of the various types of controls. However, the degree of effectiveness of this technique is highly dependent on prevention of excessive surface dust loading.

Watering of unpaved roads is effective only when carried out on a regular basis. The schedule depends on climate, type of surface material, vehicle use, and type of vehicles.

Oiling unpaved roads is more effective than watering and needs to be applied less often. However, special precautions must always be taken so as not to add to surface water runoff problems.

3.3.2.5 Area Fugitive Emission Control From Storage Piles

Most dust arises from stockpile areas as the material is dumped from the conveyor or chute onto the pile, and as bulldozers move the pile. During periods with high wind speeds [greater than about 6 m/sec (13 mph)] or low moisture, wind erosion of a non-weathered surface may also cause emissions. Applicable control techniques for open storage piles are presented in Table 3.10.

Table 3.10. Control Technology Applications for Open Storage Piles

Emission Points	Control Procedure	Efficiency
Loading onto piles	Enclosure	70-99%
	Chemical wetting agents or foam	80-90%
	Adjustable chutes	75%
Movement of pile	Enclosure	95-99%
	Chemical wetting agents	90%
	Watering	50%
	Traveling booms to distribute material	No estimate
Wind erosion	Enclosure	95-99%
	Wind screens	Very low
	Chemical wetting agents or foam	90%
	Screening of material prior to storage, with fines sent directly to processing or to a storage silo	No estimate
Loadout	Water spraying	50%
	Gravity feed onto conveyor	80%
	Stacker/reclaimer	25-50%

Enclosing materials in storage is generally the most effective means of reducing emissions from this source category because it allows the emissions to be captured. However, storage bins or silos may be very expensive. Storage buildings must be designed to withstand wind and snow loads and to meet requirements for interior working conditions. One alternative to enclosure of all material is to screen the material prior to storage, sending the oversize material to open storage and the fines to silos.

Wind screens, or partial enclosure of storage piles, can reduce wind erosion losses but do not permit capture of the remaining storage pile fugitive emissions. Earthen berms, vegetation, or existing structures can serve as wind screens.

Telescoping chutes, flexible chute extensions, and traveling booms are used to minimize the free fall of material onto the pile and resulting emissions. Similarly, emissions due to loadout can be reduced by reclaiming the material from the bottom of the pile with a mechanical plow or hopper system. The use of telescoping chutes and flexible chute extensions for piles with high material flow rates may require closer control of operations because of the possibility of jamming. Traveling or adjustable booms can handle high flow rates, but have greater operating costs.

Wetting agents or foam that are sprayed onto the material during processing or at transfer points retain their effectiveness in subsequent storage operations. Wetting agents retain surface moisture for extended periods, thereby preventing dusting. Spraying of the material prior to storage may not be possible in cases where product contamination could result (e.g., Portland cement clinker) or where the material is water soluble. However, such materials are generally not placed in open storage anyway. Steam has also been found to be an effective dust suppressant for some short-term storage operations.

3.3.2.6 Area Fugitive Emission Control from Waste Disposal Sites

Fugitive dust can occur anywhere dusty waste material is dumped for disposal. This includes overburden piles, mining spoils, tailings, fly ash, bottom ash, catch from air pollution control equipment, process overload discharges, building demolition wastes, contaminated product, etc. Like open storage, emissions come from dumping and from wind erosion across unprotected surfaces. Since waste piles are generally not disturbed after dumping, there are no emissions from an activity comparable to loading out of the storage pile. However, there may be emissions from transporting the waste material on-site (if it is dry when it is produced) or from a reclamation process such as landfill covering associated with the waste disposal operation. If the surface of the waste material does not include a compound that provides cementation upon weathering, or if the surface is not compacted, or if an area of very little rainfall, wind erosion of fines can occur withwinds greater than about

21 km per hour (13 mph). Table 3.11 presents control techniques for waste disposal sites.

Table 3.11. Control Technology Applications for Waste Disposal Sites

Emission Points	Control Procedure	Efficiency
Handling	Keep material wet	100
	Cover or enclosure hauling	No estimate
	Minimize free fall of material	No estimate
Dumping	Spray bar at dump area	50%
	Minimal free fall of material	No estimate
	Semi-enclose bin	No estimate
Wind erosion	Cover with dirt or stable material	100%
	Chemically stabilize	80%
	Revegetate	25%-100%
	Rapidly reclaim newly filled areas	No estimate
Grading	Water	50%

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Chapter 4

Design and Cost of HAP Control Techniques

4.1 Background

The procedures used to calculate the basic design and operating variables of HAP control techniques are described and illustrated in terms of commonly employed design principles and values. For each technique, (a) a brief description of how the technique works, (b) definitions of input data required, (c) a step-by-step calculation procedure showing where each number used in the procedure originates and how it is to be used, and (d) capital and annual cost methodologies utilizing the design variables calculated earlier are provided. The procedures described in this handbook will result in conservatively designed control systems. In instances in which less conservatively designed control systems might achieve the target control level, more detailed calculation procedures requiring compound-specific data would be needed. This level of specificity is beyond the scope of this handbook.

The format of Chapter 4 in this revision differs from the 1986 Handbook. Sections 4.2 through 4.11 are designed to be self-contained and to integrate the design and cost information previously contained in separate chapters. This arrangement is used to enable the reader to obtain a study- type cost estimate (±30 percent) for a given control device without having to extract specific cost information from the general cost algorithm that was presented in the 1986 manual. The design methodologies have been updated where applicable to reflect recent advances in calculation techniques. The cost information has been updated for all techniques. The cost of auxiliary equipment is common to all techniques and therefore, the auxiliary equipment cost procedures are provided in Section 4.12. The reader should note that the cost data presented in some sections may need to be escalated to reflect current costs. Table 4.12-1 contains appropriate escalation factors. For purposes of this manual, cost information that is given in May 1988 dollars - January 1990 dollars is considered current and does not need to be escalated. Cost information that is more dated should be escalated to reflect current costs.

In working with this revision, the reader may note that some control technique sections contain more information than others. This level of detail is primarily a reflection of the popularity some control techniques enjoy resulting in more available information for the more popular techniques. For the most popular techniques, a more detailed calculational approach was included where possible and when appropriate for the design and cost variables. This detail was included to incorporate recently published information relevant to that technique, and to provide a more detailed calculational approach for the permit reviewer for those techniques he is more likely to encounter. In addition, a given permit may have multiple controls on a single emission stream. As an example, a fixed bed carbon absorber using hot air as a desorbent can be placed upstream of an incinerator. The carbon absorber in effect increases the HAP concentration in the emission stream to the incinerator, allowing for a more economical and possibly more efficient operation. Such control techniques used in tandem are not discussed per se, and the reader should attempt to obtain specific information on these systems before performing a design and cost analysis.

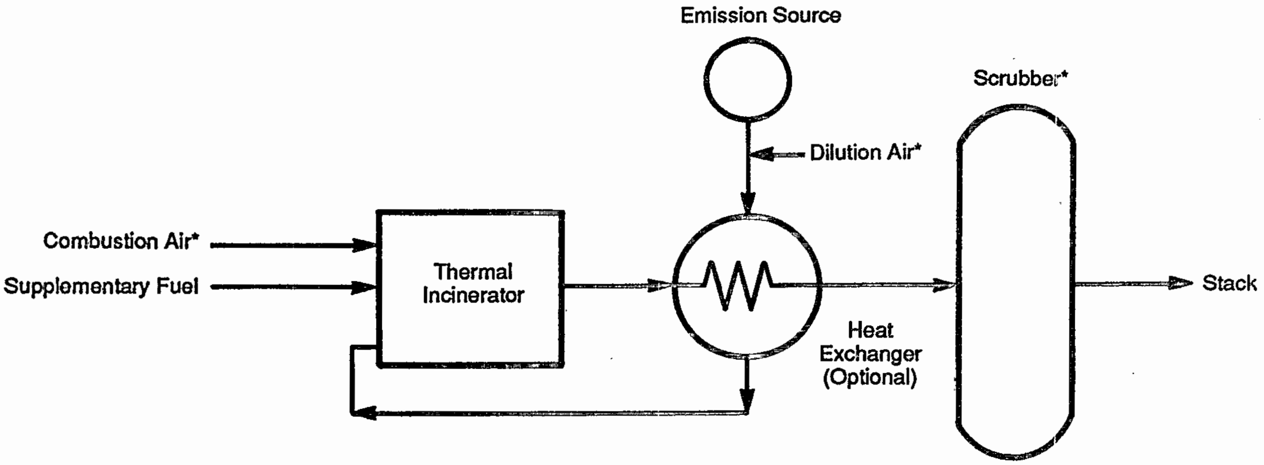
The data for the HAP emission stream to be controlled are taken from the HAP Emission Stream Data Form given in Chapter 2. In case of a permit evaluation, however, these data should be supplied by the applicant. The reviewer may wish to confirm the completeness of the applicant's data by referring to Chapters 2 and 3.

The step-by-step calculation procedures are illustrated for each control technique using data based on Emission Streams 1 through 8 described in Chapter 3. In permit reviews, the calculated values are compared to the values in the permit application to determine the adequacy of the applicant's proposed design. Appendices C.3 through C.12 contain blank calculation sheets to use in applying the calculations described for each control technique. Numbering of the calculation sheets in these appendices is consistent with the section numbers to which they apply in this chapter.

4.2 Thermal Incineration

Thermal incineration (Figure 4.2-1) is a widely used air pollution control technique whereby organic vapors are oxidized at high temperatures. Incineration (both thermal and catalytic) is considered an ultimate disposal method in that pollutant compounds in a waste gas

Figure 4.2-1. Schematic diagram of a thermal incinerator.



*Required for specific situations.

stream are converted rather than collected. A major advantage of incineration is that virtually any gaseous organic stream can be incinerated safely and cleanly, given proper design, engineering, installation, operation, and maintenance. Also, high (99 + percent) destruction efficiencies are possible with a wide variety of emission streams. A methodology is provided in this section to quickly estimate thermal incinerator design and cost variables.

The approach taken in this section is somewhat less detailed than the approach given in other EPA references, but it allows for a relatively quick calculational procedure. This approach enables the reader to obtain a general indication of design and cost parameters without resorting to more detailed and complex calculations. For a more detailed design procedure refer to the OAQPS Control Cost Manual (OCCM)[1].*

The two main types of thermal incinerators employed are thermal recuperative and thermal regenerative. The thermal recuperative type is the most common and nearly always employs a heat exchanger to preheat a gaseous stream prior to incineration. Regenerative type incinerators are newer and employ ceramics to obtain a more complete transfer of heat energy. The discussion below focuses on the more common recuperative type incineration. A detailed discussion of regenerative thermal incinerators is provided in Reference 1.

The most important variables to consider in recuperative thermal incinerator design are the combustion temperature and residence time because these design variables determine the incinerator's destruction efficiency. This efficiency also assumes that adequate oxygen is present in the combustion chamber so that combustion air is not required. Further, at a given combustion temperature and residence time, destruction efficiency is also affected by the degree of turbulence, or mixing of the emission stream and hot combustion gases, in the incinerator. In addition, halogenated organics are more difficult to oxidize then unsubstituted organics; hence, the presence of halogenated compounds in the emission stream requires higher temperatures and longer residence times for complete oxidation. Thermal incinerators can achieve a wide range of destruction efficiencies. This discussion focuses on efficiencies of 98 to 99 + percent.

The incinerator flue gases are discharged at high temperatures and contain valuable heat energy. Therefore, a strong economic incentive exists for heat recovery. Typical recovery methods include heat exchange between the flue gases and the emission stream and/or combustion air and use of the available heat for process heat requirements (e.g., recycling flue gases to the process, producing hot water or steam, etc.). In most thermal incinerator applications, the available enthalpy in the flue gases is used for preheating the emission stream. This discussion will be based on a thermal incineration system where the emission stream is preheated.

The incineration of emission streams containing organic vapors with halogen or sulfur components may create additional control requirements. For example, if sulfur

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*Appropriate references are given at the end of each section.

and/or chlorine are present in the emission stream, the resulting flue gas will contain sulfur dioxide (SO_2) and/or hydrogen chloride (HCl). Depending upon the concentrations of these compounds in the flue gas and the applicable regulations, scrubbing may be required to reduce the concentrations of these compounds. The selection and design of scrubbing systems are discussed in Section 4.7.

In this subsection, the calculation procedure will be illustrated using Emission Stream 1 described in Chapter 3. Appendix C.3 contains worksheets for design and cost calculations.

4.2.1 Data Required

The data necessary to perform the calculations consist of HAP emission stream characteristics previously compiled on the HAP Emission Stream Data Form and the required HAP control as determined by the applicable regulations.

Example Case

Maximum flow rate, Q_e = 15,000 scfm
Temperature, T_e = 120°F
Heat content, h_e = 55.4 Btu/lb or 4.1 Btu/scf
Oxygen content, O_2 = 20.6%
Halogenated organics: Yes __ No _X_

Based on the control requirements for the emission stream: Required destruction efficiency, DE = 99%

Note: To convert to Btu/scf, multiply Btu/lb by the density of the emission stream at standard conditions (typically, 0.0739 lb/ft^3).

If dilution air is added to the emission stream upon exit from the process, the data that will be used in the calculations are the resulting characteristics after dilution.

In the case of permit review for a thermal incinerator, the data outlined below should be supplied by the applicant; the calculations in this section will then be used to check the applicant's values.

Thermal incinerator system variables at standard conditions (77°F, 1 atm):

Reported destruction efficiency, $DE_{reported}$, %
Temperature of the emission stream entering the incinerator, T_e,°F (if no heat recovery);
T_{he}, °F (if a heat exchanger is employed)
Combustion temperature, T_c °F
Residence time, t_r, sec
Maximum emission stream flow rate, Q_e, scfm
Fuel heating value (assume natural gas), h_f, Btu/lb
Combustion chamber volume, V_c, ft^3
Flue gas flow rate, Q_{fg}, scfm

4.2.2 Pretreatment of the Emission Stream: Dilution Air Requirements

In HAP emission streams containing oxygen/air and flammable vapors, the concentration of flammable vapors is generally limited to less than 25 percent of the lower explosive limit (LEL) to satisfy safety requirements imposed by insurance companies. (**Note**: The LEL for a flammable vapor is defined as the minimum concentration in air or oxygen at and above which the vapor burns upon contact with an ignition source and the flame spreads through the flammable gas mixture). In some cases, flammable vapor concentrations up to 40-50 percent of the LEL are permitted if on-line monitoring of VOC concentrations and automatic process control and shutdown are provided. The LELs of some common organic compounds are provided in Table 4.2-1.

In general, emission streams treated by thermal incineration are dilute mixtures of VOC and air, and typically do not require further dilution. For emission streams with oxygen concentrations less than 20 percent and heat contents greater than 176 Btu/lb or 13 Btu/scf (in most cases corresponding to flammable vapor concentrations of approximately 25 percent of LEL), the calculation procedure in this handbook assumes that dilution air is required. (See Appendix B.2 for calculation of dilution air requirements and Appendix C.2 for a calculation worksheet.) Equation 4.2-1 can be used to obtain a value for dilution air, Q_d:

$$Q_d = [(h_e/h_d)-1]\,Q_e \qquad (4.2\text{-}1)$$

where:

Q_d = dilution air required, scfm
h_e = heat content of emission stream, Btu/scf
h_d = desired heat content of emission stream, ≤ 13 Btu/scf

Note that this will change emission stream parameters. Appendix B.2 provides the necessary equations to calculate the changed stream parameters while Appendix C.2 provides a corresponding worksheet.

Example Case

Since O_2 = 20.6% and h_e = 4.1 Btu/scf, no dilution air is required.

4.2.3 Design Variables, Destruction Efficiency, and Typical Operational Problems

Table 4.2-2 contains suggested combustion temperature and residence time values for thermal incinerators to achieve a given destruction efficiency. Two sets of values are shown in the table, one set for nonhalogenated emission streams and another set for halogenated emission streams. The combustion temperature and residence time values listed are conservative and assume adequate mixing of gases in the incinerator and adequate oxygen in the combustion chamber. The criteria in this table are

Table 4.2-1. Flammability Characteristics of Combustible Organic Compounds in Air [a,b]

Compounds	Mol.Wt.	LEL,[c] % Vol.	UEL,[d] % Vol.
Methane	16.04	5.0	15.0
Ethane	30.07	3.0	12.4
Propane	44.09	2.1	9.5
n-Butane	58.12	1.8	8.4
n-Pentane	72.15	1.4	7.8
n-Hexane	86.17	1.2	7.4
n-Heptane	100.20	1.05	6.7
n-Octane	114.28	0.95	3.2
n-Nonane	128.25	0.85	2.9
n-Decane	142.28	0.75	5.6
n-Undecane	156.30	0.68	
n-Dodecane	170.33	0.60	
n-Tridecane	184.36	0.55	
n-Tetradecane	208.38	0.50	
n-Pentadecane	212.41	0.46	
n-Hexadecane	226.44	0.43	
Ethylene	28.05	2.7	36
Propylene	42.08	2.4	11
Butene-1	56.10	1.7	9.7
cis-Butene-2	56.10	1.8	9.7
Isobutylene	56.10	1.8	9.6
3-Methyl-Butene-1	70.13	1.5	9.1
Propadiene	40.06	2.6	
1,3-Butadiene	54.09	2.0	12
Acetylene	2.5	100	
Methylacetylene	1.7		
Benzene	78.11	1.3	7.0
Toluene	92.13	1.2	7.1
Ethylbenzene	106.16	1.0	6.7
o-Xylene	106.16	1.1	6.4
m-Xylene	106.16	1.1	6.4
p-Xylene	106.16	1.1	6.6
Cumene	120.19	0.88	6.5
p-Cumene	134.21	0.85	6.5
Cyclopropane	42.08	2.4	10.4
Cyclobutane	56.10	1.8	
Cyclopentane	70.13	1.5	
Cyclohexane	84.16	1.3	7.8
Ethylcyclobutane	84.16	1.2	7.7
Cycloheptane	98.18	1.1	6.7
Methylcyclohexane	98.18	1.1	6.7
Ethylcyclopentane	98.18	1.1	6.7
Ethylcyclohexane	112.21	0.95	6.6
Methyl alcohol	32.04	6.7	36
Ethyl alcohol	46.07	3.3	19
n-Propyl alcohol	60.09	2.2	14
n-Butyl alcohol	74.12	1.7	12
n-Amyl alcohol	88.15	1.2	10
n-Hexyl alcohol	102.17	1.2	7.9
Dimethyl ether	46.07	3.4	27
Diethyl ether	74.12	1.9	36
Ethyl propyl ether	88.15	1.7	9
Diisopropyl ether	102.17	1.4	7.9
Acetaldehyde	44.05	4.0	36
Propionaldehyde	58.08	2.9	14
Acetone	58.08	2.6	13
Methyl ethyl ketone	72.10	1.9	10
Methyl propyl ketone	86.13	1.6	8.2
Diethyl ketone	86.13	1.6	
Methyl butyl ketone	100.16	1.4	8.0

[a] Reference 1.
[b] Reference 2.
[c] LEL—lower explosive limit.
[d] UEL—upper explosive limit.

not the only conditions for achieving the specified destruction efficiencies. For a given destruction efficiency, HAP emission streams may be incinerated at lower temperatures with longer residence times. However, the values provided in Table 4.2-2 reflect temperatures and residence times found in industrial applications. Based on the required destruction efficiency (DE), select appropriate values for T_c and t_r from Table 4.2-2. For more information on temperature requirements vs. destruction efficiency, consult Appendix D of Reference 6.

Since the performance of a thermal incinerator is highly related to the combustion chamber and outlet gas temperature, any thermal incinerator system used to control HAPs should be equipped with a continuous temperature monitoring system. Most vendors routinely equip thermal incinerators with such a system.[4] However, some older units may not have a continuous temperature monitoring system. In this case, the permit reviewer should request a retrofit installation of such a system. To obtain an indication of the combustion chamber volume corresponding to a given residence time, refer to Section 4.2.4.3.

In addition to temperature and residence time, correct mixing of the gas streams is essential for proper operation. Unfortunately, mixing cannot be measured and quantified as a design variable. Typically, mixing is improved and adjusted in an incinerator after start-up. It is ultimately the responsibility of the user to ensure correct operation and maintenance of a thermal incinerator after start-up.

Example Case

The required destruction efficiency is 99 percent and the HAP emission stream is nonhalogenated, therefore:

T_c = 1,800°F (Table 4.2-2)
t_r = 0.75 sec (Table 4.2-2)

A continuous monitoring system should ensure operation at 1800°F.

In a permit evaluation, if the reported values for T_c and t_r are sufficient to achieve the required DE (compare the applicant's values with the values from Table 4.2-2), proceed with the calculations. If the reported values for T_c and t_r are not sufficient, the applicant's design is unacceptable. The reviewer may wish to use the values for T_c and t_r from Table 4.2-2. (**Note**: If DE is less than 98 percent, obtain information from the literature and incinerator vendors to determine appropriate values for T_c and t_r.)

Table 4.2-3 contains theoretical combustion chamber temperatures for 99.99 percent destruction efficiencies for various compounds with a residence time of 1 second. Note that the theoretical temperatures in Table 4.2-

Table 4.2-2. Thermal Incinerator System Design Variables[a]

Required Destruction Efficiency DE(%)	Nonhalogenated Stream		Halogenated Stream	
	Combustion Temperature T_c(°F)	Residence Time t_r (sec)	Combustion Temperature T_c(°F)	Residence Time t_r (sec)
98	1,600	0.75	2,000	1.0
99	1.800	0.75	2,200	1.0

[a]Reference 3.

3 are considerably lower than those given in Table 4.2-2. This difference is because the values in Table 4.2-3 are theoretical values for specific compounds, while the values given in Table 4.2-2 are more general values designed to be applicable to a variety of compounds and are conservatively high. Table 4.2-3 is provided to indicate that certain specific applications may not require as high a combustion chamber temperature as those given in Table 4.2-2. Since the values given in Table 4.2-3 are theoretical, they may not be as accurate as the values given in Table 4.2-2.

Table 4.2-3. Theoretical Combustion Temperatures Required for 99.99 Percent Destruction Efficiencies[a]

Compound	Combustion Temperature (°F)	Residence Time (Sec)
Acrylonitrile	1,344	1
Allyl chloride	1,276	1
Benzene	1,350	1
Chlorobenzene	1,407	1
1,2-dichloroethane	1,368	1
Methyl chloride	1,596	1
Toluene	1,341	1
Vinyl chloride	1,369	1

[a] Reference 1.

As a practical matter, a specific temperature to provide a specific destruction efficiency cannot be calculated *a priori*. Typically, incinerator vendors can provide general guidelines for destruction efficiency based on extensive experience. Tables 4.2-2 and 4.2-3 are presented to show a range of difference between theoretical and general values. In essence, these tables are used as a substitute for design equations relating destruction efficiency to equipment parameters, since design equations are seldom used in hand analysis.

Most operational problems with thermal incinerators concern the burner. Typical problems encountered include low burner firing rates, poor fuel atomization (oil-fired units), poor air/fuel ratios, inadequate air supply, and quenching of the burner flame.[5] These problems lead to lower destruction efficiencies for HAPs. Symptoms of these problems include obvious smoke production or a decrease in combustion chamber temperature as indicated by the continuous monitoring system. If a thermal incinerator system begins to exhibit these symptoms, the facility operator should take immediate action to correct any operational problems.

4.2.4 Determination of Incinerator Operating Variables

4.2.4.1 Supplementary Fuel Requirements

Supplementary fuel is added to the thermal incinerator to attain the desired combustion temperature (T_c). For a given combustion temperature, the quantity of heat needed to maintain the combustion temperature in the thermal incinerator is provided by: (a) the heat supplied from the combustion of supplementary fuel, (b) the heat generated from the combustion of hydrocarbons in the emission stream, (c) the sensible heat contained in the emission stream as it leaves the emission source, and (d) the sensible heat gained by the emission stream through heat exchange with hot flue gases.

In general, emission streams treated by thermal incineration are dilute mixtures of VOC and air, and typically do not require additional combustion air. For purposes of this handbook, it is assumed that the streams treated will have oxygen contents greater than 20 percent in the waste gas stream, which is typical of the majority of cases encountered. Use the following simplified equation for dilute streams to calculate supplementary heat requirements (based on natural gas):

$$Q_f = \frac{D_e (Q_e) [Cp_{air} (1.1\ T_c - T_{he} - 0.1\ T_r) - h_e]}{D_f [h_f - 1.1\ Cp_{air} (T_c - T_r)]} \qquad (4.2\text{-}2)$$

where:

Q_f = natural gas flow rate, scfm
D_e = density of flue gas stream, lb/scf (usually 0.0739 lb/scf)
D_f = density of fuel gas, 0.0408 lb/scf for methane
Q_e = emission stream flow rate, scfm
Cp_{air} = mean heat capacity of air between T_c and T_r, Btu/lb-°F (See Table C.8-1)

T_c = combustion temperature, °F
T_{he} = emission stream temperature after heat recovery, °F
T_r = reference temperature, 77°F
h_e = heat content of flue gas, Btu/lb
h_f = lower heating value of natural gas, 21,600 Btu/lb

Calculate T_{he} using the following expression if the value for T_{he} is not specified:

$$T_{he} = (HR/100)T_c + [1 - (HR/100)]\ T_e$$

where:

HR = heat recovery in the exchanger, %
T_e = temperature of emission stream, °F

Assume a value of 70 percent for HR if no other information is available.

The factor 1.1 in Equation 4.2-2 is to account for an estimated heat loss of 10 percent in the incinerator. Supplementary heat requirements are based on maximum emission stream flow rate, and hence will lead to a conservative design.

Example Case

Using Equation 4.2-2:

Since the emission stream is very dilute and has an oxygen content greater than 20 percent, Equation 4.2-2 is applicable. The values to be inserted in the equation are:

D_e = 0.0739 lb/scf
D_f = 0.0408 lb/scf
Q_e = 15,000 scfm
Cp_{air} = 0.269 Btu/lb-°F for interval 77°F-1800°F
T_{he} = 1296°F
T_c = 1800°F
T_r = 77°F
h_f = 21,600 Btu/lb
h_e = 55.4 Btu/lb

$$Q_f = \frac{(0.0739)\ (15{,}000)\ [0.269\ (1980 - 1296 - 7.7) - 55.41}{0.0408\ [21{,}600 - 1.1\ (0.269\ (1800 - 77)]}$$

Q_f = 163 scfm

4.2.4.2 Flue Gas Flow Rate

Flue gas is generated as a result of the combustion of supplementary fuel and the emission stream. Use the following equation to calculate flue gas flow rate:

$$Q_{fg} = Q_e + Q_f + Q_d \qquad (4.2\text{-}3)$$

where:

Q_{fg} = flue gas flow rate, scfm
Q_e = emission stream flow rate, scfm
Q_f = natural gas flow rate, scfm
Q_d = dilution air requirement, scfm

Example Case

Using Equation 4.2-3:

Q_{fg} = 15,000 + 163 + 0
Q_{fg} = 15,200 scfm (rounded to three places)

4.2.4.3 Combustion Chamber Volume

To obtain an indication of the residence time, the combustion chamber volume (V_c) should be calculated. First, the emission stream flow rate of actual conditions should be calculated from Equation 4.2-4:

$$Q_{fg,a} = Q_{fg}\ [(T_c + 460)/537] \qquad (4.2\text{-}4)$$

where:

$Q_{fg,a}$ = actual flue gas flow rate, acfm
Q_{fg} = flue gas flow rate, scfm (from Eq. 4.2.-3)

The combustion chamber volume, V_c, is determined from the residence time t_r from Table 4.2-2 and $Q_{fg,a}$ obtained above.

$$V_c = [(Q_{fg,a}/60)\ t_r] \times 1.05 \qquad (4.2\text{-}5)$$

The factor of 1.05 is used to account for minor fluctuations in the flow rate, and follows industry practice.

Example Case

Q_{fg} = 15,200
$Q_{fg,a}$ = 15,200 [(1,800 + 460)/537] = 64,000 acfm
V_c = [(64,000/60) 0.75] x 1.05
V_c = 840 ft³

The combustion chamber volume for the proposed thermal incinerator should therefore have a value that is approximately 840 ft³.

4.2.5 Evaluation of Permit Application

Using Table 4.2-4, compare the results from the calculations and the values supplied by the permit applicant. The calculated values in the table are based on the example. The flue gas flow rate, Q_{fg} is determined from the emission stream flow rate (Q_e), dilution air requirement (Q_d), and supplementary fuel requirement (Q_f). Therefore, any differences between the calculated and

Table 4.2-4. Comparison of Calculated Values and Values Supplied by the Permit Applicant for Thermal Incineration

	Calculated Value (Example Case)[a]	Reported Value
Continuous monitoring of combustion temperature	yes	...
Supplementary fuel flow rate, Q_f	163 scfm	...
Dilution air flow rate, Q_d	0	...
Flue gas flow rate, Q_{fg}	15,200 scfm	...
Combustion chamber volume, V_c	840 ft²	...

[a] Based on Emission Stream 1.

Table 4.2-5. Costs for Thermal Incinerators[a]

Thermal Incinerator Cost TC (April 1988$)	Heat Exchanger Efficiency, HR
$TC = 10{,}294\ Q_{fg}^{0.2355}$	HR = 0%
$TC = 13{,}149\ Q_{fg}^{0.2609}$	HR = 35%
$TC = 17{,}056\ Q_{fg}^{0.2502}$	HR = 50%
$TC = 21{,}342\ Q_{fg}^{0.2500}$	HR = 70%

[a] Reference 1.

reported values for Q_{fg} will be dependent on the differences between the calculated and reported values for Q_d and Q_f. If the calculated values for Q_d and Q_f differ from the reported values for these variables, the differences may be due to the assumptions involved in the calculations. Therefore, further discussions with the permit applicant will be necessary to find out about the details of the design and operation of the proposed thermal incinerator system.

If the calculated values and the reported values are not different, then the design and operation of the proposed thermal incinerator system may be considered appropriate based on the assumptions used in this handbook.

4.2.6 Capital and Annual Costs of Thermal Incinerators

Procedures for estimating the capital and annual costs of a thermal-recuperative type incinerator are presented in this section.

4.2.6.1 Thermal Incinerator Capital Costs

The capital cost of a thermal incinerator is estimated as the sum of the equipment cost and the installation cost. The equipment cost is a function of the incinerator equipment cost and the cost of auxiliary equipment. For thermal incinerators auxiliary equipment includes the cost of ductwork and dampers. Equations to estimate the equipment cost of thermal incinerators based on Q_{fg} and heat exchanger efficiency are provided in Table 4.2-5. These costs include instrumentation. The equations given in Table 4.2-5 are to be used for flow rates from 500 scfm to 50,000 scfm and will yield equipment costs in April 1988 $. These equations should not be extrapolated outside this range. Refer to Section 4.12 to obtain costs of auxiliary equipment. The factors given in Table 4.2-6 are then used to obtain the purchased equipment cost (PEC).

After obtaining the purchased equipment cost, the total capital cost is estimated using the factors presented in Table 4.2-6.

Example Case

Q_{fg} = 15,200 scfm
HR = 70 percent

From Table 4.2-5,

TC = $21{,}342\ (15{,}200)^{0.2500}$
TC = $237,000

Assume auxiliary equipment costs obtained from Section 4.12 are $10,000. Instrumentation is included with the TC. Use Table 4.2-6 to obtain the purchased equipment cost (PEC).

TC + auxiliary equipment = $247,000
Sales tax = ($247,000)(0.03) = $ 7,400
Freight = ($247,000)(0.05) = $ 12,300

PEC = $247,000 + $7,400 + $12,300
PEC = $267,000

After obtaining the PEC, simply use the factors provided in Table 4.2-6 to obtain the total capital cost. These example case costs are presented in Table 4.2-7.

4.2.6.2 Thermal Incinerator Annual Costs

The total annual cost (TAC) of a thermal incinerator consists of direct and indirect annual costs. Table 4.2-8 contains the appropriate factors to estimate total annual costs, while the discussion below details the information necessary to obtain a TAC estimate.

Direct Annual Cost. These costs include fuel, electricity, operating and supervisory labor, and maintenance labor and materials.

Fuel usage is calculated in Section 4.2.4.1. Once this value is calculated, multiply it by 60 to obtain scfh and multiply this by the annual operating hours to obtain the annual fuel usage. Then simply multiply the annual fuel usage by the cost of fuel provided in Table 4.2-8 to obtain this annual cost.

Table 4.2-6. Capital Cost Factors for Thermal Incinerators[a]

Cost Item	Factor
Direct Costs	
Purchased equipment costs	
Incinerator (TC) + auxiliary equipment, EC	As estimated, EC
Instrumentation[b]	0.10 EC
Sales taxes	0.03 EC
Freight	0.05 EC
Purchased Equipment Cost, PEC	PEC =1.18 EC
Direct installation costs	
Foundations & supports	0.08 PEC
Handling & erection	0.14 PEC
Electrical	0.04 PEC
Piping	0.02 PEC
Insulation for ductwork[c]	0.01 PEC
Painting	0.01 PEC
Direct Installation Cost	0.30 PEC
Site preparation	As required, SP
Buildings	As required, Bldg.
Total Direct Cost, DC	1.30 PEC + SP + Bldg.
Indirect Costs (installation)	
Engineering	0.10 PEC
Construction and field expenses	0.05 PEC
Contractor fees	0.10 PEC
Start-up	0.02 PEC
Performance test	0.01 PEC
Contingencies	0.03 PEC
Total Indirect Cost, (IC)	0.31 PEC
Total Capital Costs (TCC) = DC + IC	1.61 PEC + SP + Bldg.

[a] Reference 1.

[b] Instrumentation and controls often furnished with the incinerator, and thus often included in the EC.

[c] If ductwork dimensions have been established, cost may be estimated based on \$10 to \$12/ft^2 of surface for field application. Fan housings and stacks may also be insulated.

Electricity costs are associated primarily with the fan needed to move the gas through the incinerator. Use Equation 4.2-6 to estimate the power requirements for a fan, assuming a fan motor efficiency of 65 percent and a fluid specific gravity of 1.0. The fan is assumed to be installed downstream of the incinerator.

$$F_p = 1.81 \times 10^{-4} (Q_{fg,a})(P)(HRS) \qquad (4.2\text{-}6)$$

where:

F_p = power needed for fan, kWh/yr
$Q_{fg,a}$ = actual emission stream flow rate, acfm
P = system pressure drop, in. H_2O (from Table 4.2-9)
HRS = operating hours per year, hr/yr

Operating labor requirements are estimated as 0.5 hours per 8-hour shift. The operator labor wage rate is provided in Table 4.2-8. Supervisory costs are estimated as 15 percent of operator labor costs.

Maintenance labor requirements are estimated as 0.5 hours per 8-hour shift with a slightly higher labor rate (see Table 4.2-8) to reflect increased skill levels. Maintenance materials are estimated as 100 percent of maintenance labor. The wage rates provided in Table 4.2-8 reflect typical values. A given situation may have wage rates different from these values.

Indirect Annual Costs. These costs include the capital recovery cost, overhead, property taxes, insurance, and administrative charges. The capital recovery cost is based on an estimated 10-year equipment life, while overhead, property taxes, insurance, and administrative costs are percentages of the total capital cost. Table 4.2-8 contains the appropriate factors for these costs.

Table 4.2-7. Example Case Capital Costs

Cost Item	Factor	Cost ($)
Direct Costs		
Purchased equipment costs (PEC)		
Incinerator (TC) + auxiliary equipment, EC		$247,000
Instrumentation	Included	0
Sales tax	0.03	7,400
Freight	0.05	12,300
Purchased Equipment Cost	1.08	$267,000
Direct installation costs		
Foundation and supports	0.08 PEC	$ 21,400
Handling and erection	0.14 PEC	37,400
Electrical	0.04 PEC	10,700
Piping	0.02 PEC	5,300
Insulation for ductwork	0.01 PEC	2,700
Painting	0.01 PEC	2,700
Direct Installation Cost	0.30 PEC	$ 80,200*
Site preparation		As required, SP
Building		As required, Bldg.
Total Direct Cost, DC		$267,000 + $80,200 + SP + Bldg.
Indirect Costs		
Engineering	0.10 PEC	$ 26,700
Construction and field expense	0.05 PEC	13,400
Contractor fees	0.10 PEC	26,700
Start-up	0.02 PEC	5,300
Performance test	0.01 PEC	2,700
Contingencies	0.03 PEC	8,000
Total Indirect Cost, IC	0.31 PEC	$ 82,800

Total Capital Cost = DC + IC
= $267,000 + $80,200 + $82,800 + SP + Bldg.

Total Capital Cost (TCC) = $430,000 + SP + Bldg.

* In this and subsequent tables, added values may vary from "factor" values due to rounding.

Table 4.2-8. Annual Cost Factors for Thermal Incinerators[a]

Cost Item	Factor
Direct Annual Costs, DAC[b]	
Utilities	
Fuel (natural gas)[c]	$3.30/1,000 ft^3
Electricity	$0.059/kwh
Operating Labor	
Operator	$12.96/hr
Supervisor	15% of operator labor
Maintenance	
Labor	$14.26/hr
Material	100% of maintenance labor
Indirect Annual Cost, IAC	
Overhead	0.60 (Operating labor and maintenance costs)
Administrative 2% of TCC	
Property taxes	1% of TCC
Insurance	1% of TCC
Capital recovery	0.1628 (TCC)

[a] Reference 1. Costs given above are typical, not definitive.
[b] 1988 $.
[c] The fuel cost may vary from this value. If possible, obtain a value more appropriate for the situation.
[d] The capital recovery factor is calculated as: $i(1+i)^n/(1+i)^n -1$
where: i = interest rate, 10 percent
n = equipment life, 10 yrs

Table 4.2-9. Typical Pressure Drops for Thermal Incinerators[a,b]

Equipment Type	Heat Recovery (HR)	Pressure Drop P (in. H_2O)
Thermal incinerator	0	4
Heat exchanger	35	4
Heat exchanger	50	8
Heat exchanger	70	15

[a] Reference 1.
[b] The pressure drop is calculated as the sum of the incinerator and heat exchanger pressure drops.

Example Case

Direct Annual Costs

Fuel usage $= 163$ scfm (60 min/hr) (6000 hr/yr)
$= 58.7 \times 10^6$ ft^3/yr

Fuel cost $= \dfrac{(58.7 \times 10^6 \text{ ft}^3)}{1{,}000 \text{ ft}^3} = \$194{,}000/\text{yr}$

Electricity usage is estimated from Eq. 4.2-6 and Table 4.2-6:

$F_p = 1.81 \times 10^{-4} (15{,}200) (4+15) (6000 \text{ hr/yr})$
$= 31.4 \times 10^4$ kWh/yr

Electricity cost $=$ \$0.059 (31.4×10^4)
$=$ \$18,500

Operating labor costs are estimated as:

[(0.5 hr/shift)/(8 hr/shift)] 6000 hrs/yr = 375 hr/yr
375 hr/yr (\$12.96/hr) = \$4,900

Supervisory costs are taken as 15 percent of this value or \$700.

Maintenance labor costs are estimated as:

[(0.5 hr/shift)/(8 hr/shift)] 6000 hrs/yr = 375 hr/yr
375 hr/yr (\$14.20/hr) = \$5,300

Maintenance materials are taken as 100 percent of this value, or \$5,300.

Total Direct Costs = \$194,000 + \$18,500 + \$4,900 + \$700 + \$5,300 + \$5,300 = \$229,000

Indirect Annual Costs

These costs are obtained from the factors presented in Table 4.2-7, and the example case costs estimated above.

Overhead = 0.60 (\$4,900 + \$700 + \$5,300+ \$5,300)= \$9,700
Administrative = 0.02 (\$430,000) = \$8,600
Property taxes = 0.01 (\$430,000) = \$4,300
Insurance = 0.01 (\$430,000) = \$4,300
Capital recovery = 0.1628 (\$430,000)= \$70,000

Total Indirect Costs = \$9,700 + \$8,600 + \$4,300 + \$4,300 + \$70,000 = \$96,900

Total Annual Costs = \$229,000 + \$96,900 = \$326,000

4.2.7 References

1. U.S. EPA. OAQPS Control Cost Manual. Fourth Edition, EPA 450/3-90-006 (NTIS PB90-169954). January 1990.

2. Handbook of Chemistry and Physics, 60th ed., Cleveland: The Chemical Rubber Company, 1980.

3. U.S. EPA. Handbook: Control Technologies for Hazardous Air Pollutants. EPA 625/6-86-014. Cincinnati, OH. September 1986 (NTIS PB91-228809).

4. PES, Inc., Research Triangle Park, NC. Company data for the evaluation of continuous compliance monitors.

5. Memorandum with attachments. Carlos Nunez, U.S. EPA, AEERL, to Michael Sink, PES. Research Triangle Park, NC. October 1989.

6. U.S. EPA. Handbook: Guidance on Setting Permit Conditions and Reporting Trial Burn Results. EPA 625/6-89-019. Cincinnati, OH. January 1989.

4.3 Catalytic Incineration

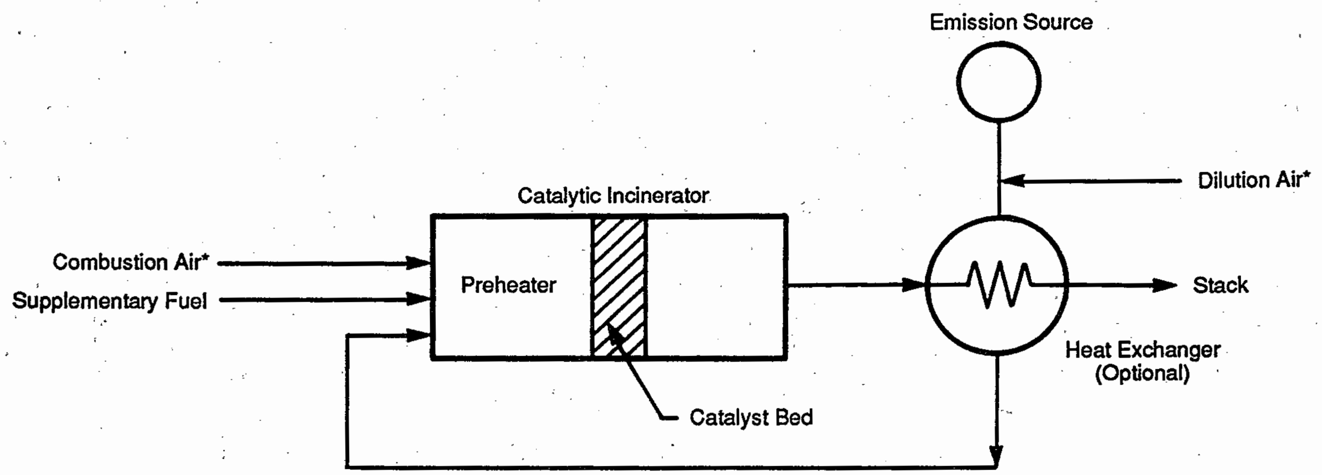
Catalytic Incineration (Figure 4.3-1) is an air pollution control technique whereby VOCs in an emission stream are oxidized with the help of a catalyst. A catalyst is a substance that accelerates the rate of a reaction at a given temperature without being appreciably changed during the reaction. Catalysts typically used for VOC incineration include platinum and palladium; other formulations are also used, including metal oxides for emission streams containing chlorinated compounds. The catalyst bed (or matrix) in the incinerator is generally a metal mesh-mat, ceramic honeycomb, or other ceramic matrix structure designed to maximize catalyst surface area. The catalysts may also be in the form of spheres or pellets. Before passing through the catalyst bed, the emission stream is preheated, if necessary, in a natural gas-fired preheater and/or via heat exchange with the flue gas.

Recent advances in catalysts have broadened the applicability of catalytic incineration. Catalysts now exist that are relatively tolerant of compounds containing sulfur or chlorine. These new catalysts are often single or mixed metal oxides and are supported by a mechanically strong carrier. A significant amount of effort has been directed towards the oxidation of chlorine-containing VOCs. These compounds are widely used as solvents and degreasers, and are often encountered in emission streams. Catalysts such as chrome/alumina, cobalt oxide, and copper oxide/manganese oxide have been demonstrated to control emission streams containing chlorinated compounds. Platinum-based catalysts are often employed for control of sulfur containing VOCs but are sensitive to chlorine poisoning.

Despite catalyst advances, some compounds simply do not lend themselves well to catalytic oxidation. These include compounds containing atoms such as lead, arsenic, and phosphorous. Unless the concentration of such compounds is sufficiently low, or a removal system is employed upstream, catalytic oxidation should not be considered in these cases.

The performance of a catalytic incinerator is affected by several factors including: (a) operating temperature, (b) space velocity (reciprocal of residence time), (c) VOC composition and concentration, (d) catalyst properties, and as mentioned above, (e) presence of poisons/

Figure 4.3-1. Schematic diagram of a catalytic incinerator system.



*Required for specific situations.

inhibitors in the emission stream. In catalytic incinerator design, the important variables are the operating temperature at the catalyst bed inlet, the temperature rise across the catalyst bed, and the space velocity assuming adequate oxygen is present. The operating temperature for a particular destruction efficiency is dependent on the concentration and composition of the VOC in the emission stream and the type of catalyst used.

Space velocity is defined as the volumetric flow rate of the combined gas stream (i.e., emission stream + supplemental fuel + combustion air) entering the catalyst bed divided by the volume of the catalyst bed. As such, space velocity also depends on the type of catalyst used. At a given space velocity, increasing the operating temperature at the inlet of the catalyst bed increases the destruction efficiency. At a given operating temperature, as space velocity is decreased (i.e., as residence time in the catalyst bed increases), destruction efficiency increases. Catalytic incinerators can achieve overall HAP destruction efficiencies of about 95 percent with space velocities in the range of 30,000 - 40,000 hr^{-1} using precious metal catalysts, or 10,000 - 15,000 hr^{-1} using base metal catalysts.[9] However, greater catalyst volumes and/or higher temperatures required for higher destruction efficiencies (i.e., 99 percent) may make catalytic incineration uneconomical. This discussion will be based on HAP destruction efficiencies of 95 percent.

The performance of catalytic incinerators is sensitive to pollutant characteristics and process conditions (e.g. flow rate fluctuations). In the following discussion, it is assumed that the emission stream is free from poisons/inhibitors such as phosphorous, lead, bismuth, arsenic, antimony, mercury, iron oxide, tin, zinc, sulfur, and halogens. (Note: some catalysts can handle emission streams containing halogenated compounds as discussed above.) It is also assumed that the fluctuations in process conditions (e.g., changes in VOC content) are kept to a minimum.

After oxidation of the emission stream, the energy in the flue gases leaving the catalyst bed may be recovered in several ways including: (a) use of a recuperative heat exchanger to preheat the emission stream and/or combustion air, or (b) by use of the available energy for process heat requirements (e.g., recycling flue gases to the process, producing hot water or steam, etc.). In recuperative heat exchange, only a limited preheat is possible due to the temperature rise across the catalyst bed as a result of the combustion of VOC in the emission stream. High preheat temperatures accompanied by a temperature increase across the catalyst bed lead to high temperatures at the catalyst bed, causing the catalyst bed to overheat and eventually lose its activity.[5,6]

The following discussion will be based on fixed bed catalytic incinerator systems with no heat recovery and with recuperative heat exchange (i.e., preheating the emission stream). Throughout this section, it is assumed that adequate oxygen is present in the emission stream so that combustion air is not required (i.e. $O_2 \geq 20$ percent). The calculation procedure will be illustrated using Emission Stream 2 described in Chapter 3. Appendix C.4 provides worksheets for calculations.

4.3.1 Data Required

The data necessary to perform the calculations consist of HAP emission stream characteristics previously compiled on the HAP Emission Stream Data Form and the required HAP control as determined by the applicable regulations.

Example Case

Maximum flow rate, Q_e = 20,000 scfm
Temperature, T_e = 120°F
Heat content, h_e = 24.8 Btu/lb or 2.1 Btu/scf
Oxygen content, O_2 = 20.6%

Based on the control requirements for the emission stream:
Required destruction efficiency, DE = 95%

If dilution air is added to the emission stream upon exit from the process, the data that will be used in the calculations are the resulting characteristics after dilution.

In the case of a permit review for a catalytic incinerator, the following data should be supplied by the applicant. The calculations in this section will then be used to check the applicant's values.

Catalytic incineration system variables at standard conditions (77°F, 1 atm):

Reported destruction efficiency, $DE_{reported}$, %

Temperature of the emission stream entering the incinerator, T_e, °F (if no heat recovery); T_{he}, °F (if emission stream is preheated)

Temperature of flue gas leaving the catalyst bed, T_{co}, °F

Temperature of combined gas stream (emission stream + supplementary fuel combustion products) entering the catalyst bed, T_{ci},°F

Space velocity through catalyst bed, SV, hr^{-1}

Supplementary fuel gas flow rate, Q_f, scfm

Flow rate of combined gas stream entering the catalyst bed, Q_{com}, scfm (Note that if no supplementary fuel is used (i.e., Q_f=0) the value of Q_{com} will equal the emission stream flow rate)

Dilution air flow rate, Q_d, scfm

Catalyst bed requirement, V_{bed}, ft^3

Fuel heating value, h_f, Btu/lb

4.3.2 Pretreatment of the Emission Stream: Dilution Air Requirements

In general, catalytic incineration is applied to dilute emission streams. If emission streams with high VOC concentrations (i.e., heat content above 10 Btu/scf for air + VOC mixtures and above 15 Btu/scf for inert + VOC mixtures) are treated by catalytic incineration, they may generate enough heat upon combustion to deactivate the catalyst. Therefore, dilution of the emission stream with air is necessary to reduce the concentration of the VOCs. These cut-off values are taken from a previous EPA publications.[1]

Typically, the concentration of flammable vapors in HAP emission streams containing air is limited to less than 25 percent of the LEL (corresponding to a heat content of 176 Btu/lb or 13 Btu/scf) for safety requirements. To convert from Btu/lb to Btu/scf, multiply Btu/lb by the density of the emission stream at standard conditions, 0.0739 lb/scf. Table 4.2-1 contains a listing of LELs for common organic compounds. In order to meet the safety requirements and to prevent damage to the catalyst bed, it is assumed in this handbook that catalytic incineration is applicable if the heat content of the emission stream (air + VOC) is less than or equal to 10 Btu/scf. For emission streams that are mixtures of inert gases and VOC (i.e., containing no oxygen), it is assumed that catalytic incineration is applicable if the heat content of the emission stream is less than or equal to 15 Btu/scf.[1] Otherwise, dilution air will be required to reduce the heat content to levels below these cut-off values (i.e., 10 and 15 Btu/scf). For emission streams that cannot be characterized as air + VOC or inert + VOC mixtures, apply the more conservative 10 Btu/scf cut-off value for determining dilution air requirements. The dilution air requirements can be calculated from Equation 4.3-1 given below which is also provided in Appendix B.2. Note that dilution air will change the emission stream parameters. Appendix B.2 provides the necessary equations to calculate the stream parameters, while Appendix C.2 provides a blank worksheet.

$$Q_d = [(h_e/h_d) - 1]\, Q_e \qquad (4.3\text{-}1)$$

where:

Q_d = dilution air requirement, scfm
h_e = heat content of emission stream, Btu/scf
h_d = desired heat content of emission stream, Btu/scf

Example Case

Since the heat content of the emission stream (h_e) is 2.1 Btu/scf (or 28.4 Btu/lb), no dilution is necessary.

4.3.3 Design Variables, Destruction Efficiency, and Typical Operational Problems

Table 4.3-1 presents suggested values and limits for the design variables of a fixed bed catalytic incinerator system to achieve a 95 percent destruction efficiency. Most catalytic incinerators currently sold are designed to achieve an efficiency of 95 percent.[9] In selected instances, catalytic incinerators can achieve efficiencies on the order of 98 to 99 percent, but general guidelines for space velocities at these efficiencies could not be found. For specific applications, other temperatures and space velocities may be appropriate depending on the type of catalyst employed and the emission stream characteristics (i.e., composition and concentration). For example, the temperature of the flue gas leaving the catalyst bed may be lower than 1,000°F for emission streams containing easily oxidized compounds and still achieve the desired destruction efficiency. (See Reference 3 or 4, for data on temperatures typically required for specific destruction efficiency levels for several compounds.)

The destruction efficiency for a given compound may vary depending on whether the compound is the only VOC in the emission stream, or it is part of a mixture of VOCs.[4] The destruction efficiency for a given compound in different VOC mixtures may also vary with mixture composition. (See Reference 4 for compound-specific destruction efficiency data for two different VOC mixtures.) Based on the required destruction efficiency (DE), specify the appropriate ranges for T_{ci}, T_{co}, and select the value for SV from Table 4.3-1.

The performance of a catalytic incinerator system depends greatly on both the temperature and pressure differential across the catalyst bed assuming a correct operating temperature at the catalyst bed inlet. The temperature differential or rise across the catalyst bed is the fundamental performance indicator for a catalytic incinerator system, as it directly indicates VOC oxidation. The pressure differential across the catalyst bed serves as an indication of the volume of catalyst present.[7] The pressure drop decreases over time as bits of catalyst become entrained in the gas stream. To ensure proper performance of the system, it is recommended that both the temperature rise across the catalyst bed and the pressure drop across the catalyst bed be monitored continuously. Currently, most vendors routinely include continuous monitoring of these parameters as part of catalytic incinerator system package.[7] However, some older units may not be so equipped; in this case the reviewer should ensure the incinerator is equipped with both continuous monitoring systems.

In addition to catalyst loss, catalyst deactivation and blinding occur over time and limit performance. Catalyst deactivation is caused by the presence of materials that react with the catalyst bed. Blinding is caused by the accumulation of particulate matter on the catalyst bed surface which decrease the effective surface area of the catalyst.[6,9] For these reasons, vendors recommend replacing the catalyst every two to three years. Symptoms of catalyst loss include a decrease in pressure drop across the catalyst bed and a decrease in the temperature rise across the catalyst bed. Symptoms of deactivation and blinding include a decrease in the temperature rise across the catalyst bed. If a catalytic incinerator system exhibits these symptoms, the facility should take immediate action to correct these operational problems.

Example Case

The required destruction efficiency is 95%; therefore:

T_{ci} (minimum) = 600°F
T_{co} (minimum) = 1,000°F
T_{co} (maximum) = 1,200°F
SV = 30,000 hr^{-1} (assume precious metal catalyst)

In a permit evaluation, determine if the reported values for T_{ci}, T_{co}, and SV are appropriate to achieve the required destruction efficiency by comparing the applicant's values with the values in Table 4.3-1. However, it is important to keep in mind that the values given in Table 4.3-1 are approximate and a given permit may

Table 4.3-1. Catalytic Incinerator System Design Variables[9]

Required Destruction Efficiency DE (%)	Temperature at the Catalyst Bed Inlet[a] T_{ci}(°F)	Temperature at the Catalyst Bed Outlet[b] T_{co} (°F)	Space Velocity SV (hr^{-1})	
			Base Metal	Precious Metal
95	600	1,000 - 1,200	10,000 - 15,000[c]	30,000 - 40,000[c]
98-99	600	1,000 - 1,200	[d]	[d]

[a] Minimum temperature of combined gas stream (emission stream + supplementary fuel combustion products) entering the catalyst bed is designated as 600°F to ensure an adequate initial reaction rate.

[b] Minimum temperature of the flue gas leaving the catalyst bed is designated as 1,000°F to ensure an adequate overall reaction rate to achieve the required destruction efficiency. Note that this is a conservative value; it is in general a function of the HAP concentration (or heat content) and a temperature lower than 1,000°F may be sufficient to achieve the required destruction level. Maximum temperature of flue gas leaving the catalyst bed is limited to 1,200°F to prevent catalyst deactivation by overheating. However, base metal catalysts may degrade somewhat faster at these temperatures than precious metal catalysts.

[c] The space velocities given are designed to provide general guidance not definitive values. A given application may have space velocities that vary from these values. These values are quoted for monolithic catalysts. Pellet-type catalysts will typically have lower space velocities.

[d] In general, design of catalytic incinerator systems in this efficiency range is done relative to specific process conditions.

differ slightly from these values. The reported value for T_{ci} should equal or exceed 600°F in order to obtain an adequate initial reaction rate. To ensure that an adequate overall reaction rate can be achieved to give the desired destruction efficiency without damaging the catalyst, check whether T_{co} falls in the interval 1,000° - 1,200°F. (This temperature range is somewhat higher than the range provided in Reference 5 to ensure a high HAP destruction efficiency). Then check if the reported value for SV is equal to or less than the value in Table 4.3-1. If the reported values are appropriate, proceed with the calculations. In some cases it may be possible to achieve the desired destruction efficiency at a lower temperature level. If a permit applicant uses numbers significantly different from Table 4.3-1, documentation indicating the rationale for this variance should accompany the application. In this case, the permit values should take precedence over those values given in Table 4.3-1. Otherwise, the applicant's design is considered unacceptable. In such a case, the reviewer may then wish to use the values in Table 4.3-1.

4.3.4 Determination of Incineration Operating Variables

4.3.4.1 Supplementary Fuel Requirements

Supplementary fuel is added to the catalytic incinerator system to provide the heat necessary to bring the emission stream up to the required catalytic oxidation temperature (T_{co}) for the desired level of destruction efficiency. For a given T_{co}, the quantity of supplementary heat needed is provided by: (a) the heat supplied from the combustion of supplementary fuel, (b) the sensible heat contained in the emission stream as it enters the catalytic incinerator system, and (c) the sensible heat gained by the emission stream through heat exchange with hot flue gases. If recuperative heat exchange is not practiced at a facility, then item (c) will be zero.

Since emission streams treated by catalytic incineration are dilute mixtures of VOC and air, they typically do not require additional combustion air. For purposes of this handbook, it is assumed that no additional combustion air is required if the emission stream oxygen content (O_2) is greater than or equal to 20 percent.

Before calculating the supplementary heat requirements, the temperature of the flue gas leaving the catalyst bed (T_{co}) should be estimated to ensure that an adequate overall reaction rate can be achieved to give the desired destruction efficiency without damaging the catalyst. In other words, check whether T_{co} falls in the interval 1,000° - 1,200°F to ensure a high destruction efficiency without catalyst damage. Use Equation 4.3-2 to calculate T_{co}. This equation assumes a 50°F temperature increase for every 1 Btu/scf of heat content:

$$T_{co} = T_{ci} + 50\ h_e \qquad (4.3\text{-}2)$$

where:

h_e = heat content of the emission stream, Btu/scf

In this expression, it is assumed that the heat content of the emission stream and the combined gas stream is the same. First, insert a value of 600°F for T_{ci} in equation 4.3-2. Then determine if T_{co} is in the range of 1,000° - 1,200°F. If this is true then the initial value of T_{ci} is satisfactory. If T_{co} is less than 1,000°F, use the following equation to determine an appropriate value for T_{ci} (above 600°F) and use this new value of T_{ci} in the calculations below:

$$T_{ci} = 1{,}000 - 50\ h_e \qquad (4.3\text{-}3)$$

The value of T_{ci} obtained from Equation 4.3-3 is then used in Equation 4.3-4.

(Note: Emission streams with high heat contents will be diluted based on the requirements discussed in Section 4.3.2. Therefore, values for T_{co} exceeding 1,200°F should not occur.)

For catalytic incinerators, a 50 percent efficient heat exchanger is assumed, while for thermal incineration a 70 percent efficient exchanger is assumed. A 70 percent efficient heat exchanger for catalytic oxidation can result in excessive catalyst bed temperatures. Therefore, a 50 percent efficient heat exchanger is assumed for purposes of this report, although 70 percent efficient heat exchangers may be found on some streams.

To calculate supplementary heat requirements (based on natural gas as the fuel), use the following simplified equation for dilute emission streams that require no additional combustion air:

$$Q_f = \frac{D_e\ Q_e\ [Cp_{air}\ (1.1\ T_{ci} - T_{he} - 0.1\ T_r)]}{D_f\ [h_f - (1.1\ Cp_{air}\ (T_{ci} - T_r)]} \qquad (4.3\text{-}4)$$

where:

Q_f = fuel gas flow rate, scfm
D_e = density of emission stream, lb/ft^3 (typically, 0.0739 lb/ft^3)
D_f = density of fuel gas (0.0408 lb/ft^3 for methane at 77°F)
Q_e = emission stream flow rate, scfm
Cp_{air} = average specific heat of air over a given temperature interval, Btu/lb-°F (See Table C.8-1)
T_{ci} = temperature of combined gas stream entering the catalyst bed, °F
T_r = reference temperature, 77°F
T_{he} = emission stream temperature after heat recovery, °F
h_f = lower heating value of natural gas, 21,600 Btu/lb

Note that for the case of no heat recovery, $T_{he} = T_e$. The factor 1.1 attempts to account for an estimated heat loss of 10 percent in the incinerator. Supplementary heat requirements are based on maximum emission flow rate, and hence will lead to a conservative design. In contrast to thermal incineration, there is no minimum supplementary heat requirement specified for catalytic incineration since no fuel is needed for flame stabilization. Depending on the HAP concentration, emission stream temperature, and level of heat recovery, supplementary heat requirements may be zero when heat recovery is employed.

Calculate T_{he} using the following expression if the value for T_{he} is not specified.

$$T_{he} = (HR/100)\, T_{co} + [1 - (HR/100)]\, T_e \qquad (4.3\text{-}5)$$

Example Case

Using Equations 4.3-2, -3, and -4

Since the emission stream is dilute (h_e = 2.1 Btu/scf) and has an oxygen concentration greater than 20 percent, these equations are applicable.

a. Determine if T_{co} falls in the range 1,000° - 1,200°F:

T_{ci} = 600°F
h_e = 2.1 Btu/scf (input data)
T_{co} = 600 + (50 x 2.1) = 705°F

Since T_{co} is less than 1,000°F, use Equation 4.3-3 to calculate an appropriate value for T_{ci}:

T_{ci} = 1,000 - (50 x 2.1) = 895°F

Note that this inlet temperature results in T_{co} = 1,000°F

b. Determine Q_f (assume recuperative heat recovery will be employed):

Q_e = 20,000 scfm
T_r = 77°F
T_{he} = 560°F (based on HR of 50 percent)
Cp_{air} = 0.253 Btu/lb °F
D_e = 0.0739 lb/scf
D_f = 0.0408 lb/scf
h_f = 21,6000 Btu/lb

$$Q_f = \frac{0.0739\,(20{,}000)\,[0.253\,(984 - 560 - 7.7)]}{0.0408\,[21{,}600 - (1.1\,(0.253)(895 - 77))]}$$

Q_f = 179 scfm

4.3.4.2 Flow Rate of Combined Gas Stream Entering the Catalyst Bed

To calculate the quantity of catalyst required, the flow rate of the combined gas stream (emission stream + supplementary fuel combustion products) at the inlet to the catalyst bed has to be determined. Use the following equation:

$$Q_{com} = Q_e + Q_f + Q_d \qquad (4.3\text{-}6)$$

where:

Q_{com} = flow rate of the combined gas stream, scfm
Q_e = flow rate of emission stream, scfm
Q_f = natural gas flow rate, scfm
Q_d = dilution air requirement, scfm

Example Case

Using Equation 4.3-6:

Q_e = 20,000 scfm
Q_d = 0 (since h_e < 15 Btu/scf)
Q_{com} = 20,000 + 179 + 0
Q_{com} = 20,200 scfm (rounded to 3 places)

4.3.4.3 Flow Rate of Flue Gas Leaving the Catalyst Bed

In order to determine costs for incinerators, the flow rate of flue gas leaving the catalyst bed must be determined.

Assume that the flow rate of the combined gas stream entering the catalyst bed is approximately equal to the flow rate of the flue gas leaving the catalyst bed at standard conditions. The volume change across the catalyst bed due to the combustion of the HAP in the mixed gas stream is small, especially when dilute emission streams are treated. Therefore,

$$Q_{fg} = Q_{com}$$

where:

Q_{fg} = flow rate of the flue gas leaving the catalyst bed, scfm

When calculating costs, assume that catalytic incinerators are designed for a minimum Q_{fg} of 2,000 scfm.[1] Therefore, if Q_{fg} is less than 2,000 scfm, define Q_{fg} as 2,000 scfm.

In some instances, operating costs are based on the flue gas flow rate at actual conditions. (The cost procedures detailed later in this section use scfm.) However, if necessary the following equation can be used to convert from scfm to acfm:

$$Q_{fg,a} = Q_{fg}[(T_{co} + 460)/537] \qquad (4.3\text{-}7)$$

where:

$Q_{fg,a}$ is the flue gas flow rate at actual conditions (acfm)

Example Case

Using Equation 4.3-7:

$Q_{fg} = Q_{com} = 20{,}200$ scfm

$T_{co} = 1{,}000°F$

$Q_{fg,a} = 20{,}200\ [(1{,}000 + 460)/537]$

$Q_{fg,a} = 54{,}900$ acfm

4.3.5 Catalyst Bed Requirement

The total volume of catalyst required for a given destruction efficiency is determined from the design space velocity as follows:

$$V_{bed} = 60\ Q_{com}/SV \qquad (4.3\text{-}8)$$

where:

V_{bed} = volume of catalyst bed required, ft³

Example Case

Using Equation 4.3-8:

$Q_{com} = 20{,}200$ scfm

$SV = 30{,}000\ hr^{-1}$ (Table 4.3-1)

$V_{bed} = 60 \times 20{,}200/30{,}000$

$V_{bed} = 40\ ft^3$

4.3.6 Evaluation of Permit Application

Compare the results from the calculations and the values supplied by the permit applicant using Table 4.3-2. The calculated values in the table are based on the example case.

If the calculated values agree with the reported values, then the design and operation of the proposed catalytic incinerator system may be considered appropriate based on the assumptions used in this handbook.

4.3.7 Capital and Annual Costs of Catalytic Incinerators

This section presents procedures for estimating the capital and annual costs of a fixed bed catalytic incinerator.

4.3.7.1 Catalytic Incinerator Capital Costs

The capital cost of a catalytic incinerator is estimated as the sum of the equipment cost (EC) and the installation cost. The equipment cost is primarily a function of the total emission stream flow rate and the heat exchanger efficiency as well as the cost of auxiliary equipment. Table 4.3-3 provides equations to estimate the equipment cost of fixed bed catalytic incinerators based on Q_{com} and HR. Refer to Section 4.12 to obtain the auxiliary costs.

Table 4.3-2. Comparison of Calculated Values and Values Supplied by the Permit Applicant for Catalytic Incineration[a]

	Calculated Value (Example Case)[a]	Reported Value
Continuous monitoring of temperature rise and pressure drop across catalyst bed	yes	...
Supplementary fuel flow rate, Q_f	179 scfm	...
Dilution air flow rate, Q_d	0	...
Combined gas steam flow rate, Q_{com}	20,200 scfm	...
Catalyst bed volume, V_{bed}	40 ft³	...

[a] Based on Emission Stream 2.

The equations given in Table 4.3-3 are to be used for flow rates from 2,000 scfm to 50,000 scfm, and will yield costs in April 1988 dollars. These costs include instrumentation. These equations should not be extrapolated outside their range.

After obtaining equipment costs, the next step in the cost algorithm is to obtain the purchased equipment cost, PEC. The PEC is calculated as the sum of the equipment cost EC (incinerator and auxiliary equipment) and the cost of instrumentation, freight and taxes. Table 4.3-4 provides appropriate factors to estimate these costs. After obtaining the purchased equipment cost, PEC, the total capital cost (TCC) is estimated using the factors presented in Table 4.3-4.

Table 4.3-3. Equipment Costs for Fixed Bed Catalytic Incinerators[a]

Catalytic Incinerator Cost, CC (April 1988 $)	Heat Exchanger Efficiency, HR
$CC = 1{,}105\ Q_{com}^{0.5471}$	HR = 0%
$CC = 3{,}623\ Q_{com}^{0.4189}$	HR = 35%
$CC = 1{,}215\ Q_{com}^{0.5575}$	HR = 50%
$CC = 1{,}443\ Q_{com}^{0.5527}$	HR = 70%

[a] Reference 5.

Example Case

Q_{com} = 20,200 scfm
HR = 50 percent

From Table 4.3-3:

$CC = \$1,215 (20,200)^{0.5575}$
$CC = \$305,000$

Assume auxiliary equipment costs (i.e., ductwork and dampers) obtained from Section 4.12 are $10,000. Instrumentation is included with CC. Use Table 4.3-4 to obtain the purchased equipment cost, PEC.

EC + auxiliary equipment = $315,000
Sales tax = (315,000)(0.03) = $ 9,500
Freight = (315,000)(0.05) = $ 15,800

PEC = $315,000 + $9,500 + $15,800
PEC = $340,000

After obtaining the PEC, simply use the factors provided in Table 4.3-4 to obtain the total capital cost. These example case costs are presented in Table 4.3-5.

4.3.7.2 Catalytic Incinerator Annual Costs

The total annual cost (TAC) of a catalytic incinerator consists of direct and indirect annual costs. Table 4.3-6 contains appropriate factors used to estimate total annual costs, while the discussion below details the information necessary to correctly use these factors.

Direct Annual Cost. These costs include fuel, electricity, catalyst replacement operating and supervisory labor, and maintenance labor and materials.

Fuel usage is calculated in Section 4.3.4.2. Once this value is calculated, multiply it by 60 to obtain scfh and multiply this by the annual operating hours to obtain the annual fuel usage. Then simply multiply the annual fuel usage by the cost of fuel to obtain this annual cost.

Electricity costs are primarily associated with the fan needed to move the gas through the incinerator. Use Equation 4.3-9 to estimate the power requirements for a fan assuming a combined motor-fan efficiency of 65 percent and a fluid specific gravity of 1.0.

$$F_p = 1.81 \times 10^{-4} (Q_{fg,a}) (P) (HRS) \qquad (4.3\text{-}9)$$

Table 4.3-4. Capital Cost Factors for Catalytic Incinerators[a]

Cost Item	Factor
Direct Costs	
Purchased equipment costs	
Incinerator (CC) + auxiliary equipment, EC	As estimated, EC
Instrumentation[b]	0.10 EC
Sales taxes	0.03 EC
Freight	0.05 EC
Purchased Equipment Cost, PEC	PEC = 1.18 EC
Direct installation costs	
Foundations & supports	0.08 PEC
Handling & erection	0.14 PEC
Electrical	0.04 PEC
Piping	0.02 PEC
Insulation for ductwork[c]	0.01 PEC
Painting	0.01 PEC
Direct Installation Cost, DC	0.30 PEC
Site preparation	As required, SP
Buildings	As required, Bldg.
Total Direct Cost, DC	1.30 PEC + SP + Bldg.
Indirect Costs (installation)	
Engineering	0.10 PEC
Construction and field expenses	0.05 PEC
Contractor fees	0.10 PEC
Start-up	0.02 PEC
Performance test	0.01 PEC
Contingencies	0.03 PEC
Total Indirect Cost, IC	0.31 PEC
Total Capital Cost (TCC) = DC + IC	1.61 PEC + SP + Bldg.

[a] Reference 5.
[b] Instrumentation and controls often furnished with the incinerator, and thus often included in the EC.
[c] If ductwork dimensions have been established, cost may be estimated based on $10 to $12/ft² of surface for field application. Fan housings and stacks may also be insulated.

Table 4.3-5. Example Case Capital Costs

Cost Item	Factor	Cost ($)
Direct Costs		
Purchased Equipment Costs, PEC		
Incinerator (EC) + auxiliary equipment		$315,000
Instrumentation	Included	0
Sales Tax	0.03	9,500
Freight	0.05	15,800
Purchased Equipment Cost, PEC		$340,000
Direct installation costs		
Foundation and supports	0.08 PEC	$ 27,200
Handling and erection	0.14 PEC	47,700
Electrical	0.04 PEC	13,600
Piping	0.02 PEC	6,800
Insulation for ductwork	0.01 PEC	3,400
Painting	0.01 PEC	3,400
Direct Installation Cost	0.30 PEC	$102,000
Site preparation		As required, SP
Building		As required, Bldg.
Total Direct Cost, DC		$340,000 + $102,000 + SP + Bldg.
Indirect Costs		
Engineering	0.10 PEC	$ 34,000
Construction and field expense	0.05 PEC	17,000
Contractor fees	0.10 PEC	34,000
Start-up	0.02 PEC	6,800
Performance test	0.01 PEC	3,400
Contingencies	0.03 PEC	10,200
Total Indirect Cost, IC	0.31 PEC	$105,000

Total Capital Cost = DC + IC
= $340,000 + $102,000 + $105,000 + SP + Bldg.

Total Capital Cost = $547,000 + SP + Bldg.

where:

F_p = power needed for fan, kWh/yr

$Q_{fg,a}$ = total emission stream flowrate, acfm

P = system pressure drop, in. H_2O (from Table 4.3-7)

HRS = operating hours per year, hr/yr

In general, catalyst replacement costs are highly variable and depend on the nature of the catalyst, the amount of poisons and particulates in the emission stream, the temperature history of the catalyst, and the design of the unit. Given that these costs are so variable it is not possible to accurately predict the costs for a given application. However, for purposes of this report, it is assumed the catalyst has a life of two years. To estimate this cost, multiply the catalyst volume from section 4.3.5 by the appropriate capital recovery factor assuming a two year life and 10 percent interest rate (i.e, CRF = 0.5762). The catalyst replacement cost can be estimated as $650/ft^3 for base metal oxide catalysts, and $3,000/ft^3 for noble metal catalysts.[5] The initial catalyst cost used in estimating the capital recovery cost, can be obtained by multiplying the catalyst requirement by the catalyst cost.

Operating labor requirements are estimated as 0.5 hours per 8-hour shift. The operator labor wage rate is provided in Table 4.3-6. Supervisory costs are estimated as 15 percent of operator labor costs.

Maintenance labor requirements are estimated as 0.5 hours per 8-hour shift with a slightly higher labor rate (see Table 4.3-6) to reflect increased skill levels. Maintenance materials are estimated as 100 percent of maintenance labor.

Indirect annual costs. These costs include the capital recovery cost, overhead, property taxes, insurance, and administrative charges. The capital recovery cost is based on an estimated 10-year equipment life and subtracts out the initial catalyst cost, while overhead, property taxes, insurance, and administrative costs are percentages of the total capital cost. Table 4.3-6 contains the appropriate factors for these costs.

Example Case

Direct Annual Costs

Annual fuel usage = 179 (60 min/hr)(6000 hr/yr)
= 64.4×10^6

Annual fuel cost = \$3.30(64.4×10^6/1,000)
= \$213,000

Electricity:

F_p = 1.81×10^{-4} (20,200)(6+8) (6000 hr/yr)
= 3.07×10^5 kWh/yr

Annual electricity cost, AEC:

AEC = \$0.059 (3.07×10^5)
= \$18,100

Catalyst Replacement Cost, CRCT

V_{bed} = 40 ft^3

A precious metal catalyst is used, thus

CRCT = (40)(\$3,000)(0.5762)
= \$69,100

Operating labor costs are estimated as:

(0.5 hr/shift)/(8 hr/shift) x 6000 hr/yr = 375 hr/yr
375 hr/yr (\$12.96/hr) = \$4,900/yr

Supervisory costs are estimated as 15 percent of this cost, or \$700.

Maintenance labor costs are estimated as:

(0.5 hr/shift)/(8 hr/shift) x 6,000 hr/yr = 375 hr/yr
375 hr/yr (\$14.26/hr) = \$5,300/yr

Maintenance materials are estimated as 100 percent of this cost, or \$5,300.

Total Direct Costs: \$213,000 + \$18,100 + \$69,100 + \$4,900 + \$700 + \$5,300 + \$5,300 = \$316,000

Indirect Annual Costs

Overhead = 0.60 (\$4,900 + \$700 + \$5,300 + \$5,300) = \$9,700
Administrative = 0.02 (\$547,000) = \$10,900
Property taxes = 0.01 (\$547,000) = \$5,500
Insurance = 0.01 (\$547,000) = \$5,500
Capital recovery = 0.1628 (\$547,000 - 1.08 (\$120,000)) = \$69,500

Total Indirect Costs: \$9,700 + \$10,900 + \$5,500 + \$5,500 + \$69,100 = \$101,000

Total Annual Costs: \$316,000 + \$101,000 = \$417,000

Table 4.3-6. Annual Cost Factors for Catalytic Incinerators[a]

Cost Item	Factor
Direct Annual Cost (DAC)[b]	
Utilities	
Fuel (natural gas)[c]	\$3.30/1,000 ft^3
Electricity	\$0.059/kwh
Catalyst replacement	\$650/ft^3 base metal oxide \$3,000/ft^3 precious metal
Operating Labor	
Operator	\$12.96/hr
Supervisor	15% of operator labor
Maintenance	
Labor	\$14.26/hr
Material	100% of maintenance labor
Indirect Annual Cost (IAC)	
Overhead	0.60 (Operating labor and maintenance costs)
Administrative	2% of TCC
Property taxes	1% of TCC
Insurance	1% of TCC
Capital recovery[d]	0.1628 [TCC - 1.08 (Cat. cost)]

[a] Reference 5.

[b] 1988 dollars.

[c] The fuel cost may vary. When possible, obtain a value more appropriate for the situation.

[d] The capital recovery factor is calculated as: $i(1+i)^n/(1+i)^n - 1$
where: i = interest rate, 10 percent
n = equipment life, 10 yrs

Table 4.3-7. Typical Pressure Drops for Catalytic Incinerators[a]

Equipment Type	Heat Recovery HR (%)	Pressure Drop P (in. H_2O)
Catalytic Incinerator (Fixed-Bed)	0	6
Heat Exchanger	35	4
Heat Exchanger	50	8
Heat Exchanger	70	15

[a] The pressure drop is calculated as the sum of the incinerator and heat exchanger pressure drops.

4.3.8 References

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4.4 Flares

Open flames used for disposing of waste gases during normal operations and emergencies are called flares. They are typically applied when the heating value of the waste gases cannot be recovered economically because of intermittent or uncertain flow, or when the value of the recovered product is low. In some cases, flares are operated in conjunction with baseload gas recovery systems (e.g., condensers). Flares handle process upset and emergency gas releases that the baseload system is not designed to recover.

Several types of flares exist, the most common of which are steam-assisted, air-assisted, and pressure head flares. Typical flare operations can be classified as "smokeless," "nonsmokeless," and "fired" or "endothermic." For smokeless operation, flares use outside momentum sources (usually steam or air) to provide efficient gas/air mixing and turbulence for complete combustion. Smokeless flaring is required for destruction of organics heavier than methane. Nonsmokeless operation is used for organic or other vapor streams which burn readily and do not produce smoke. Fired, or endothermic, flaring requires additional energy in order to ensure complete oxidation of the waste streams such as for sulfur tail gas and ammonia waste streams.

In general, flare performance depends on such factors as flare gas exit velocity, emission stream heating value, residence time in the combustion zone, waste gas/oxygen mixing, and flame temperature. Since steam-assisted smokeless flares are the most frequently used, they will be the focus of this discussion. A typical steam-assisted flare system is shown in Figure 4.4-1. First, process off-gases enter the flare through the collection header. When water or organic droplets are present, passing the off-gases through a knockout drum may be necessary since these droplets can create problems. Water droplets can extinguish the flame and organic droplets can result in burning particles.

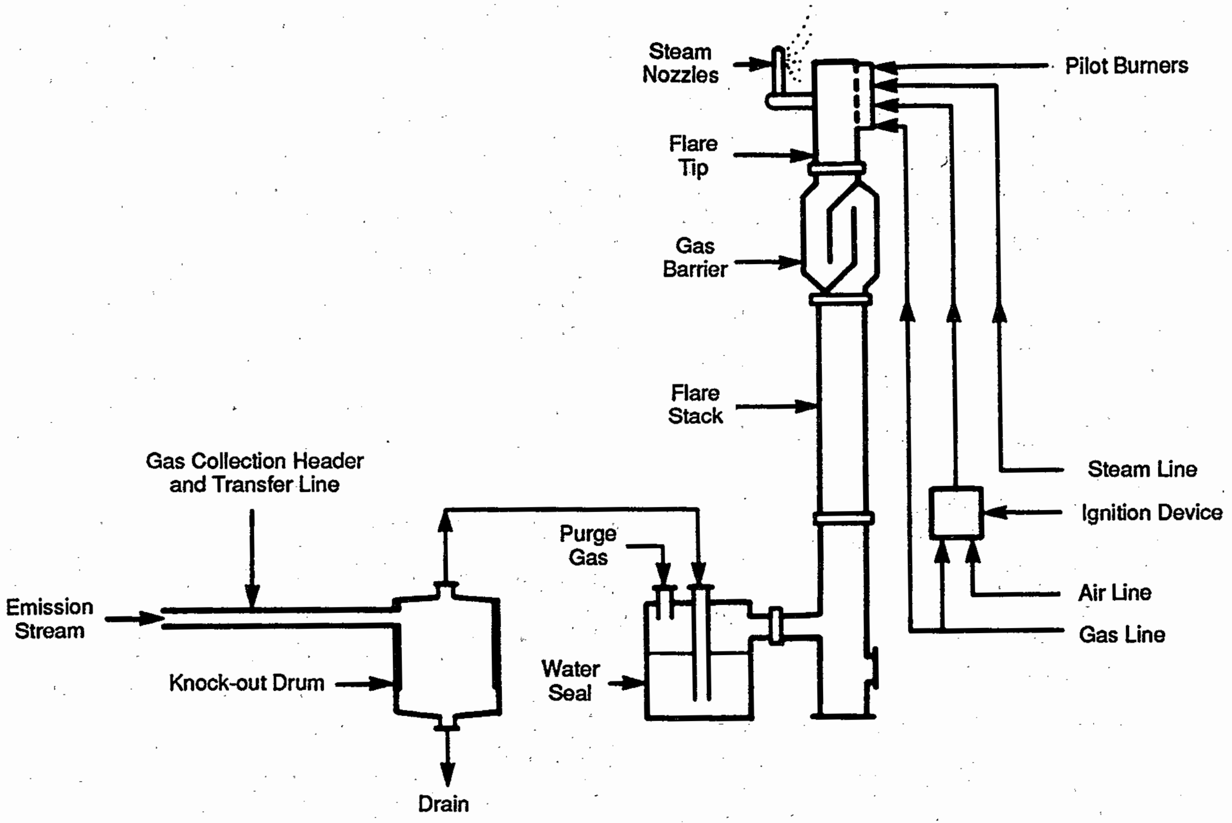
Once the off-gases enter the flare stack, flame flashback can occur if the emission stream flow rate is too low. Flashback may be prevented, however, by passing the gas through a gas barrier, a water seal, or a stack seal. Purge gas is another option. At the flare tip, the emission stream is ignited by pilot burners. If conditions in the flame zone are optimum (oxygen availability, adequate residence time, etc.), the VOC in the emission stream may be completely burned (~100 percent efficiency). In some cases, it may be necessary to add supplementary fuel (natural gas) to the emission stream to achieve destruction efficiencies of 98 percent and greater if the net heating value of the emission stream is less than 300 Btu/scf.[1,2]

Typically, existing flare systems will be used to control HAP emission streams. Therefore, the following sections describe how to evaluate whether an existing flare system is likely to achieve a 98 percent destruction efficiency under expected flow conditions (e.g., continuous, start-up, shut-down, etc.). The discussion will be based on the recent regulatory requirements of 98 percent destruction efficiency for flares.[1] The calculation procedure will be illustrated for Emission Stream 3 described in Chapter 3 using a steam-assisted flare system. Note that flares often serve more than one process unit and the total flow rate to the flare needs to be determined before the following calculation procedure can be applied. A flare sizing algorithm (the Pegasus algorithm) has been developed using a computer to obtain quick algorithm convergence. For more information on this system, consult Reference 8.

4.4.1 Data Required

The data necessary to perform the calculations consist of HAP emission stream characteristics previously compiled on the HAP Emission Stream Data Form, flare dimensions, and the required HAP control as determined by the applicable regulations.

Figure 4.4-1. Typical steam assisted flare.



Example Case

Expected emission stream flow rate,
Q_e = 30,000 scfm
Emission stream temperature, T_e = 100°F
Heat content, h_e = 180 Btu/scf[a]
Mean molecular weight of emission stream,
MW_e = 33.5 lb/lb-mole
Flare tip diameter, D_{tip} = 54 in

Based on the control requirements for the emission stream:

Required destruction efficiency, DE = 98%

In the case of a permit review, the data outlined below should be supplied by the applicant. The calculations in this section will then be used to check the applicant's values. Worksheets are provided in Appendix C.5.

Flare system variables at standard conditions (77°F, 1 atm):

Flare tip diameter, D_{tip}, in
Expected emission stream flow rate, Q_e, scfm
Emission stream heat content, h_e, Btu/scf
Temperature of emission stream, T_e, °F
Mean molecular weight of emission stream, MW_e, lb/lb-mole
Steam flow rate, Q_s, lb/min
Flare gas exit velocity, U_{flg}, ft/sec
Supplementary fuel flow rate, Q_f, scfm
Supplementary fuel heat content, h_f, Btu/scf
Temperature of flare gas, T_{flg}, °F
Flare gas flow rate, Q_{flg}, scfm
Flare gas heat content, h_{flg}, Btu/scf

4.4.2 Determination of Flare Operating Variables

Based on studies conducted by EPA, relief gases having heating values less than 300 Btu/scf are not assured of achieving 98 percent destruction efficiency when they are flared in steam- or air-assisted flares.[1,2] Therefore, the first step in the evaluation procedure is to check the heat content of the emission stream and determine if additional fuel is needed.

In a permit review case, if the heat content of the emission stream is less than 300 Btu/scf and no supplementary fuel has been added, then the application is considered unacceptable. The reviewer may then wish to follow the calculations described below. If the reported value for the emission stream heat content is above 300 Btu/scf, however, then the reviewer should skip to Section 4.4.2.3.

4.4.2.1 Supplementary Fuel Requirements

If the emission stream heat content is less than the 300 Btu/scf required to achieve a destruction level of 98 percent, it is assumed that natural gas will be added to the emission stream to bring its heat content to 300 Btu/scf. Calculate the required natural gas requirements using the following equation:

$$Q_f = [(300 - h_e)Q_e]/582 \qquad (4.4\text{-}1)$$

where:

Q_e = emission stream flow rate, scfm
Q_f = natural gas flow rate, scfm
h_e = emission stream heat content, Btu/scf
582 = 882-300; 882=lower heating value of natural gas, Btu/scf

If the emission steam heat content is greater than or equal to 300 Btu/scf, then $Q_f = 0$.

Example Case

Using Equation 4.4-1:
Since h_e is less than 300 Btu/scf, supplementary fuel is needed.
h_e = 180 Btu/scf
Q_e = 30,000 scfm
Q_f = [(300 - 180)(30,000)]/582
Q_f = 6,200 scfm

4.4.2.2 Flare Gas Flow Rate and Heat Content

The flare gas flow rate is determined from the flow rates of the emission stream and natural gas using the following equation:

$$Q_{flg} = Q_e + Q_f \qquad (4.4\text{-}2)$$

where:

Q_{flg} = flare gas flow rate, scfm

Note that if $Q_f = 0$, then $Q_{flg} = Q_e$

The heat content of the flare gas (h_{flg}) is dependent on whether supplementary fuel is added to the emission stream. When h_e is greater than or equal to 300 Btu/scf, then $h_{flg} = h_e$. If h_e is less than 300 Btu/scf, since supplementary fuel is added to increase h_e to 300 Btu/scf, h_{flg} = 300 Btu/scf.

Example Case

Using Equation 4.4-2:

Q_e = 30,000 scfm
Q_f = 6,200 scfm
Q_{flg} = 36,200 scfm
Since $h_e < 300$ Btu/scf, $h_{flg} = 300$ Btu/scf.

4.4.2.3 Flare Gas Exit Velocity and Destruction Efficiency

Table 4.4-1 presents maximum flare gas exit velocities (U_{max}) necessary to achieve at least 98 percent destruction efficiency in a steam-assisted flare system. These values are based on studies conducted by EPA.[1,2] Flare gas exit velocities are expressed as a function of flare gas heat content. The maximum allowable exit velocity can be determined using the equation presented in Table 4.4-1.

The information available on flare destruction efficiency as a function of exit velocity does not allow for a precise determination of this value. All that can be ascertained is whether the destruction efficiency is greater than or less than 98 percent, depending the exit velocity.

If a flare is controlling an intermittent process stream (or streams), a continuous monitoring system should be employed to ensure that the pilot light has a flame. If a flare is controlling a continuous process stream, continuous monitoring of either the flare flame or the pilot light is acceptable.

Example Case

Since h_{flg} = 300 Btu/scf, use the equation in Table 4.4-1 to calculate U_{max}:

U_{max} = $3.28\,[10^{(0.00118\,hflg + 0.908)}]$
= $3.28\,[10^{(0.00118 \times 300 + 0.908)}]$
U_{max} = 60 ft/sec

From the emission stream data (expected flow rate, temperature) and information on flare diameter, calculate the flare gas exit velocity (U_{flg}); compare this value

Table 4.4-1. Flare Gas Exit Velocities for 98 Percent Destruction Efficiency[1]

Flare Gas Heat Constant[a] h_{flg} (Btu/scf)	Maximum Exit Velocity U_{max} (ft/sec)
$h_{flg} < 300$	--[b]
$300 \le h_{flg} < 1{,}000$	$3.28\,[10^{(0.00118\,h_{flg} + 0.908)}]$
h_{flg} , <1,000	400

[a] If no supplementary fuel is used, $h_{flg} = h_e$.
[b] Based on studies conducted by EPA, waste gases having heating values less than 300 Btu/scf are not assured of achieving 98% destruction efficiency when they are flared in steam-assisted flares.[3]

with U_{max}. Use Equation 4.4-3 to calculate U_{flg}. This equation is taken from Reference 6.

$$U_{flg} = \frac{(5.766 \times 10^{-3})(Q_{flg})(T_{flg} + 460)}{(D_{tip}^2)} \qquad (4.4\text{-}3)$$

where:

U_{flg} = exit velocity of flare gas, ft/sec
Q_{flg} = flare gas flow rate, scfm
D_{tip} = flare tip diameter, in

If U_{flg} is less than U_{max}, then the 98 percent destruction level can be achieved. However, if U_{flg} exceeds U_{max}, this destruction efficiency level may not be achieved. This indicates that the existing flare diameter is too small for the emission stream under consideration, and may lead to reduced efficiency. Note that at very low flare gas exit velocities, flame instability may occur, affecting destruction efficiency. The minimum flare gas exit velocity for a stable flame is assumed as 0.03 ft/sec in this manual[4]. Thus, if U_{flg} is below 0.03 ft/sec, the desired destruction efficiency may not be achieved. In summary, Uflg should fall in the range of 0.03 ft/sec and U_{max} for a 98 percent destruction efficiency level.

In a permit review case, if U_{flg} exceeds U_{max}, then the application is not acceptable. If U_{flg} is below U_{max} and exceeds 0.03 ft/sec, then the proposed design is considered acceptable and the reviewer may proceed with the calculations.

Example Case

Using Equation 4.4-3:

Given:
Q_{flg} = 36,200 scfm
T_{flg} = 95°F
D_{tip} = 54 in

Then:
U_{flg} = $(5.766 \times 10^{-3})(36,200)(95 + 460)/(54^2)$
U_{flg} = 39.7 = 40 ft/sec

Since 0.03 ft/sec < U_{flg} = 40 ft/sec < U_{max} = 60 ft/sec, the required level of 98% destruction efficiency can be achieved under these conditions.

4.4.2.4 Steam Requirements

Steam requirements for steam-assisted flare operation depend on the composition of the flare gas and the flare-tip design. Typical values range from 0.15 to 0.50 lb steam/lb flare gas. In this handbook, the amount of steam required for 98 percent destruction efficiency is assumed as 0.4 lb steam/lb flare gas.[5] Use the following equation to determine steam requirements:

$$Q_s = 1.03 \times 10^{-3} \times Q_{flg} \times MW_{flg} \qquad (4.4\text{-}4)$$

where:

Q_s = steam requirement, lb/min
MW_{flg} = $[(Q_f)(16.7) + (Q_e)(MW_e)]/Q_{flg}$

Example Case

Using Equation 4.4-4:

Q_{flg} = 36,200 scfm
MW_{flg} = $[(6,200)(16.7)+(30,000)(33.5)]/36,200$
= 30.6 lb/lb-mole
Q_s = $1.03 \times 10^{-3} \times 36,200 \times 30.6$
Q_s = 1,140 lb/min

4.4.3 Evaluation of Permit Application

Compare the results from the calculated and reported values using Table 4.4-2. If the calculated values of Q_f, U_{flg}, Q_{flg}, and Q_s are different from the reported values for these variables, the differences may be due to the assumptions (e.g., steam to flare gas ratios, etc.) involved in the calculations. In such a case, the reviewer may wish to discuss the details of the proposed system with the permit applicant.

If the calculated values agree with the reported values, then the operation of the proposed flare system may be considered appropriate based on the assumptions made in this handbook.

4.4.4 Capital and Annual Costs of Flares

In many cases, existing flares are employed by a facility and hence, obtaining flare costs for a new system is not necessary. For cases where cost information is necessary, Section 4.4.4 can be used to obtain capital and annual flare costs.

4.4.4.1 Capital Costs of Flares

The capital cost for a flare is composed of purchased equipment costs and direct and indirect installation costs. The purchased equipment cost is the sum of the equipment costs (flare + auxiliary equipment) and the cost of instrumentation, freight, and taxes. Factors for these costs are presented in Table 4.4-3. The cost of auxiliary equipment for a flare can be obtained from Section 4.12 and includes the cost of ductwork, dampers, and fans.

The equipment cost of a flare is a function of the flare tip diameter (D_{tip}), height (H), and the cost of auxiliary equipment. The procedure used to obtain the flare height, H, is taken from Reference 6, while the flare cost equations were obtained from the Emissions Standards Division of the Office of Air Quality Planning and Standards, US EPA, RTP, NC. The flare cost is dependent upon the type of flare stack used. Typical configurations include the self supporting configuration used between 30 and 100 feet; guy towers, used for up to 300 feet; and derrick towers, used for heights above 200 feet.

Table 4.4-2. Comparison of Calculated Values and Values Supplied by the Permit Applicant for Flares

	Calculated Value (Example Case)[a]	Reported Value
Appropriate continuous monitoring system	Yes	...
Emission stream heating value, h_e	180 Btu/scf	...
Supplementary fuel flow rate, Q_f	6,200 scfm	...
Flare gas exit velocity, U_{flg}	40 ft/sec	...
Flare gas flow rate, Q_{flg}	36,200 scfm	...
Steam flow rate, Q_s	1,140 lb/min	...

[a] Based on Emission Stream 3.

Recall the flare tip diameter, D_{tip}, was provided in Section 4.4.1. This calculated diameter should be rounded up to the next largest commercially available size. The minimum diameter is 1 inch with larger diameters available in 2-inch increments between 2 and 24 inches, and 6-inch increments between 24 and 60 inches.

The flame angle, θ, is calculated below:

$$\theta = \mathrm{TAN}^{-1} (1.47\, V_w/(550\, (\Delta P/55)^{1/2})] \qquad (4.4\text{-}5)$$

where:

θ = Flame angle, degrees

V_w = wind velocity (assumed to equal 60 mph)

ΔP = pressure drop, in. H_2O

= $55\,(U_{flg}/550)^2$ where U_{flg} is obtained from Section 4.4.2.3

Table 4.4-3. Capital Cost Factors for Flares[a]

Cost Item	Factor
Direct Costs	
Purchased equipment costs	
Flare (FC) + auxiliary equipment, EC	As estimated, EC
Instrumentation	0.10 EC
Sales taxes	0.03 EC
Freight	0.05 EC
Purchased Equipment Cost, PEC	PEC = 1.18 EC
Direct installation costs	
Foundations & supports	0.12 PEC
Handling & erection	0.40 PEC
Electrical	0.01 PEC
Piping	0.01 PEC
Insulation for ductwork	0.01 PEC
Painting	0.01 PEC
Direct Installation Cost	0.56 PEC
Site preparation	As required, SP
Buildings	As required, Bldg.
Total Direct Cost (DC)	1.56 PEC + SP + Bldg.
Indirect Costs (installation)	
Engineering	0.10 PEC
Construction and field expenses	0.10 PEC
Contractor fees	0.10 PEC
Start-up	0.01 PEC
Performance test	0.01 PEC
Contingencies	0.03 PEC
Total Indirect Cost (IC)	0.35 PEC
Total Capital Costs = DC + IC	1.91 PEC + SP + Bldg.

[a] Obtained from Emissions Standards Division, OAQPS, EPA, RTP, NC.

Table 4.4-4. Example Case Capital Costs

Cost Item	Factor	Cost($)
Direct Costs		
Purchased equipment costs		
Flare (EC) + auxiliary equipment, EC	As required	$396,000
Instrumentation	0.10 EC	39,600
Sales taxes	0.03 EC	11,900
Freight	0.05 EC	19,800
Purchased Equipment Cost, PEC	PEC = 1.18EC	$467,000
Direct installation costs		
Foundations & supports	0.12 PEC	$ 56,000
Handling & erection	0.40 PEC	187,000
Electrical	0.01 PEC	4,670
Piping	0.01 PEC	4,670
Painting	0.01 PEC	4,670
Insulation	0.01 PEC	4,670
Direct Installation Cost	0.56 PEC	$262,000
Site preparation		As required, SP
Buildings		As required, Bldg.
Total Direct Cost, DC	1.56 PEC + SP + Bldg.	$467,000 + $262,000 + SP + Bldg.
Indirect Costs (installation)		
Engineering	0.10 PEC	$ 46,700
Construction and field expenses	0.10 PEC	46,700
Contractor fees	0.10 PEC	46,700
Start-up	0.01 PEC	4,670
Performance test	0.01 PEC	4,670
Contingencies	0.03 PEC	14,000
Total Indirect Cost, IC	0.35 PEC	$163,000
Total Capital Cost = DC + IC	1.91 PEC + SP + Bldg	$892,000 + SP + Bldg.

This reduces to:

$$\theta = \text{TAN}^{-1}(88.2/U_{flg}) \qquad (4.4\text{-}6)$$

The flare height is calculated using Equation 4.4-7:

$$H = [(0.02185)(Q_{flg} \times h_{flg})^{1/2} - (6.05 \times 10^{-3})(D_{tip})(U_{flg})(\text{Cos}(\theta))] \qquad (4.4\text{-}7)$$

Flare equipment costs in March 1990 dollars are presented in Equations 4.4-8 through 4.4-10 as a function of flare height and diameter. Equation 4.4-8 is used for self supporting flares, Equation 4.4-9 is used for guy support flares, and Equation 4.4-10 is used for derrick support flares.

$$FC = [78 + 9.14(D_{tip}) + 0.749(H)]^2] \qquad (4.4\text{-}8)$$

where: FC = flare cost for self support

$$FC = [103 + 8.68(D_{tip}) + 0.470(H)]^2 \qquad (4.4\text{-}9)$$

where: FC = flare cost for guy support

$$FC = [76.4 + 2.72(D_{tip}) + 1.64(H)]^2 \qquad (4.4\text{-}10)$$

where: FC = flare cost for derrick support

For all three cases, the flare cost includes the flare stack and support, burner tip, pilots, utility piping, 100 feet of vent stream piping, utility metering and control, water and gas seals, and platforms and ladders. The costs are based on carbon steel construction except for the upper four feet and the burner tip which is constructed of 316L stainless steel.

Once FC has been obtained, Table 4.4-3 is used to obtain the flare capital costs. The flare equipment cost (EC) is obtained by adding FC to any auxiliary equipment, while the purchased equipment cost (PEC) is obtained using the factors given in Table 4.4-3.

The total capital cost (TCC) of a flare is the sum of the purchased equipment cost and the direct and indirect installation cost factors. These factors are given in Table 4.4-3 as a percentage of the purchased equipment cost.

Example Case

From Section 4.4.2.3, $U_{flg} = 40$ ft/sec. Using Equation 4.4-6 to obtain the flame angle, θ, we have:

$$\theta = TAN^{-1}[88.2/40] = 65.6^\circ$$

Next, use Equation 4.4-7 to obtain the flare height, H:

$$H = \{(0.02185)(36{,}200 \times 300)^{1/2} - 6.05 \times 10^{-3}(60)(40)(Cos(65.6^\circ))\}$$

$$H = 66 \text{ ft}$$

Since H is between 45 and 200 feet, Equation 4.4-8 is used for the flare cost FC.

$$FC = [78 + 9.14\,(54) + 0.749\,(66)]^2$$

$$FC = \$386{,}000$$

Assume auxiliary equipment costs (i.e., ductwork, dampers, and fans) from Section 4.12 are $10,000. The equipment cost EC is then $386,000 + $10,000 = $396,000.

Next, use Table 4.4-3 to obtain the purchased equipment cost, PEC, as shown below:

Instrumentation	= 0.10 (EC) =	$39,600
Sales taxes	= 0.03 (EC) =	$11,900
Freight	= 0.05 (EC) =	$19,800
		$71,300

The purchased equipment cost, PEC, is therefore equal to $467,000. Table 4.4-3 is then used to obtain the total capital cost, TCC. These costs are given in Table 4.4-4.

4.4.4.2 Flare Annual Costs

The total annual cost (TAC) of a flare is the sum of the direct and indirect annual costs, which are discussed in more detail below. Table 4.4-4 contains the appropriate factors necessary to estimate the TAC.

Direct Annual Cost. The direct annual cost includes the cost of fuel, electricity, pilot gas, steam, operating and supervisory labor, and maintenance labor and materials.

Fuel usage (in scfm) is calculated in Section 4.4.2.1. Once this value (Q_f) is calculated, multiply it by 60 to obtain the fuel usage in scfh, and multiply this by the annual operating hours to obtain the annual fuel usage. Then simply multiply the annual fuel usage by the cost of fuel provided in Table 4.4-5 to obtain annual fuel costs.

The electricity cost is primarily associated with a fan needed to move the gas through the flare. Equation 4.4-10 can be used to estimate the power requirements for a fan. This equation assumes a fan-motor efficiency of 65 percent and a fluid specific gravity of 1.0.

Table 4.4-5. Annual Cost Factors for Flares[a]

Cost Item	Factor
Direct Annual Costs (DAC)[b]	
Utilities	
Fuel (natural gas)[c]	$3.30/10³ ft³
Electricity	$0.059/kwh
Steam	$6.00/10³ lb steam
Operating Labor	
Operator	$12.96/hr
Supervisor	15% of operator labor
Maintenance	
Labor	$14.26/hr
Material	100% of maintenance labor
Indirect Annual Cost (IAC)	
Overhead	0.60 (Operating labor and maintenance costs)
Administrative	2% of TCC
Property taxes	1% of TCC
Insurance	1% of TCC
Capital recovery[d]	0.1315 (TCC)

[a] Reference 6, 7.

[b] 1988 $.

[c] This cost may vary. When possible, obtain a value more appropriate for the situation.

[d] The capital recovery factor is calculated as: $i(1+i)^n/(1+i)^n - 1$

where: i = interest rate, 10 percent
n = equipment life, 15 yrs

$$F_p = 1.81 \times 10-4\,(Q_{flg,a})\,(P)\,(HRS) \qquad (4.4\text{-}11)$$

where:

F_p = power requirement for fan, kWh/hr
$Q_{flg,a}$ = actual flare gas flow rate, scfm
P = system pressure drop, in. H_2O (typically, 16 inches of H_2O)
HRS = annual operating hours, hr/yr

The steam requirement for a flare is calculated in Section 4.4.2.4. This value (Q_s) is then multiplied by 60 to obtain the steam requirement on an hourly basis. This is multiplied by the annual operating hours and by the cost of steam provided in Table 4.4-5, to obtain annual steam costs.

Operating labor requirements are estimated as 0.5 hours per 8-hour shift. The operator labor wage rate is provided in Table 4.4-5. Supervisory costs are estimated as 15 percent of operator labor costs.

Maintenance labor requirements are estimated as 0.5 hours per 8-hour shift with a slightly higher labor rate (see Table 4.4-5) to reflect increased skill levels. Maintenance materials are estimated as 100 percent of maintenance labor.

Indirect Annual Costs. These costs include the capital recovery cost, overhead, property taxes, insurance, and administrative charges. The capital recovery cost is based on an estimated 15-year equipment life, while overhead, property taxes, insurance, and administrative costs are percentages of the total capital cost, Table 4.4-5 contains the appropriate factors for this cost.

Example Case

Assume the flare operates 1,000 hours per year.

Direct Annual Costs

Fuel usage, Q_f = 6,200 scfm
= 6,200 (ft^3/min) x 60 (min/hr) x 1,000 (hrs/yr)
= 3.72×10^8 ft^3/yr

Fuel cost = 3.72×10^8 (ft^3/yr) x 3.3/1,000 ft^3
= $1,230,000/yr

Electricity usage is estimated from Eq. 4.4-11:

F_p = 1.81×10^{-4} (36,200)(16) (1,000)
= 1.05×10^5 kWh/yr

Electricity cost = $0.059 ($1.05 \times 10^5$) = $6,200/yr

Steam usage, Q_s = 1,140 lb/min
= 1,140 (lb/min) x 60 (min/hr) x 1000 (hr/yr)
= 6.84×10^7 lb/yr

Steam cost = 6.84×10^7 (lb/yr) x $6.00/$10^3$ lb
= $410,000/yr

Operating labor costs are estimated as:
[(0.5 hr/shift)/(8 hrs/shift)] 1,000 hr/yr = 62.5 hr/yr
62.5 hr/yr ($12.96/hr) = $810/yr

Supervisory costs are taken as 15 percent of this value, or $121/yr

Maintenance labor costs are estimated as:
[(0.5 hr/shift)/(8 hr/shift)] 1,000 hr/yr = 62.5 hr/yr
62.5 hr/yr ($14.26/hr) = $890/yr

Maintenance materials are taken as 100 percent of this value, or $890/yr

Total Direct Cost = $1,230,000 + $6,200 +
$410,000 + $810 + $121 +
$890 + $890 = $1,650,000

Indirect Annual Costs

These costs are obtained from the factors presented in Table 4.4-5, and the example case presented above.

Example Case (Cont.)

Overhead = 0.60 ($810 + $121 + $890 + $890) = $1,630
Administrative = 0.02 ($892,000) = $17,800
Property taxes = 0.01 ($892,000) = $ 8,920
Insurance = 0.01 ($892,000) = $ 8,920
Capital recovery = 0.1315 ($892,000)
= $117,000

Total Indirect Cost = $1,630 + $17,800 + $8,920 +
$8,902 + $117,000 = $155,000

Total Annual Costs = $1,650,000 + $155,000 =
$1,800,000

4.4.5 References

1. Federal Register. Vol. 50. April 16, 1985. pp. 14941-14945.

2. U.S. EPA. Evaluation of the Efficiency of Industrial Flares: Test Results. EPA 600/2-84-095 (NTIS PB84-199371). May 1984.

3. U.S. EPA. Parametric Evaluation of VOC/HAP Destruction Via Catalytic Incineration. EPA-600/2-85-041 (NTIS PB85-191187). April 1985.

4. U.S. EPA. Organic Chemical Manufacturing. Vol. 4: Combustion Control Devices. EPA-450/3-80-026 (NTIS PB81-220535). December 1980.

5. U.S. EPA. Reactor Processes in Synthetic Organic Chemical Manufacturing Industry - Background Information for Proposed Standards. Draft EIS. Research Triangle Park, NC. October 1984.

6. U.S. EPA. Polymer Manufacturing Industry - Background Information for Proposed Standards. EPA-450/3-83-019a (NTIS PB88-114996). September 1985.

7. U.S. EPA. OAQPS Control Cost Manual. Fourth Edition, EPA-450/3-90-006 (NTIS PB90-169954). January 1990.

8. G.S. Mason and R. Kamar. Algorithm Sizes Flare Piping. Chemical Engineering, Vol. 95, No. 9. June 20, 1988

4.5 Boiler/Process Heaters

Boilers or process heaters may be used as a HAP vapor control technique for selected sites. However, the application of the devices is very site specific. The level of detail required to evaluate a boiler/process heater as a HAP vapor control technique is beyond the scope of this manual and therefore is not presented.

4.6 Carbon Adsorption

Adsorption is a surface phenomenon where volatile organic compounds are selectively adsorbed on the surface of such materials as activated carbon, silica gel or alumina. Activated carbon is the most widely used adsorbent and the focus of the discussion below. Adsorption systems using silica gel or alumina are less likely to be encountered in air pollution control and are not discussed in this manual.

Adsorbed VOCs are removed from the carbon bed by heating to a sufficiently high temperature (usually via steam) or by reducing the pressure to a sufficiently low value (vacuum desorption). During desorption, about 3 to 5 percent of organics desorbed on virgin activated carbon is adsorbed so strongly that it cannot be desorbed during regeneration.

The equilibrium adsorption capacity of carbon is often represented by adsorption isotherms that relate the amount of VOC adsorbed (adsorbate) to the equilibrium pressure (or concentration) at constant temperature. Typically, the absorption capacity of activated carbon increases as the molecular weight of the adsorbate increases. Also, unsaturated compounds and cyclic compounds are generally more completely adsorbed than either saturated compounds or linear compounds. For virtually any adsorbate, the adsorption capacity is enhanced by lower operating temperatures and higher VOC concentrations. VOCs having lower vapor pressures are more easily adsorbed than those with higher vapor pressures. For most volatile organic compounds, the vapor pressure is inversely proportional to the molecular weight of the compounds. Thus, heavier compounds tend to be more easily adsorbed than lighter compounds for a given adsorption system. Very heavy compounds however, are difficult to desorb, and hence carbon adsorption is not recommended for compounds with molecular weights above 130 lb/lb-mole.

A carbon adsorber system may have difficulties when controlling an emission stream containing ketones (e.g. acetone, methyl ethyl ketone). Ketones exothermically polymerize on the carbon bed, clogging the pores on the surface of the carbon which reduces the effective amount of carbon contained in the vessel. This in turn, decreases the system efficiency. If a carbon adsorber system is used to control ketones, the reader should be aware of this potential problem.

4.6.1 Data Required

The data necessary to perform the calculations consist of HAP emission stream characteristics previously compiled on the HAP Emission Stream Data Form and the required HAP control as determined by the applicable regulations.

Example Case

Maximum Flow rate, Q_e = 15,000 scfm
Temperature, T_e = 90°F
Relative humidity, R_{hum} = 40 percent
HAP Pollutant = toluene
Required removal efficiency, RE = 95 percent

If dilution air is added to the emission stream upon exit from the process (e.g. because of high HAP concentrations), the data that will be used in the calculations are the resulting characteristics after dilution.

In a permit review case for a carbon adsorber, the following data should be supplied by the applicant. The calculations in this section will then be used to check the applicant's values.

Fixed bed carbon adsorber system variables at standard conditions (77°F, 1 atm):

Reported removal efficiency, $RE_{reported}$ %
HAP concentration, HAP_e, ppmv
HAP inlet loading rate, M_{HAP}, lb/hr
Emission stream flow rate, Q_e, ft³/min
Carbon bed working capacity, W_C, lbs HAP/lbs carbon
Number of beds, N
Amount of carbon required, C_{req}, lb
Cycle time for adsorption, θ_{ad}, hr
Cycle time for regeneration θ_{reg}, hr
Emission stream velocity thru carbon bed, U_e, ft/min
Vessel diameter, D_v, ft
Vessel length, L_v, ft
Steam used for regeneration, Q_s, lb/min

4.6.2 Adsorption Theory

At equilibrium, the quantity of HAP in a gas stream that is adsorbed on activated carbon is a function of the adsorption temperature and pressure, the specific compound being adsorbed, and the carbon characteristics (e.g., pore size and structure). For a given constant temperature, a relationship exists between the mass of adsorbate (i.e. HAP) per unit weight of adsorbent (i.e., carbon) to the partial pressure of HAP in the gas stream as discussed above. This is called the equilibrium adsorptivity. Adsorption isotherms are typically fitted to a power curve as shown below:

$$W_e = kP_{partial}^{m}$$

where:

W_e = equilibrium adsorptivity (lb adsorbate/lb adsorbent)
$P_{partial}$ = partial pressure of HAP in emission stream
k,m = empirical parameters

The partial pressure is calculated as:

$$P_{partial} = (HAP_e)(14.696 \times 10^{-6}) \text{ psia}$$

This equation type (i.e., the "Freundlich" equation) is only valid for a specified absorbate partial pressure range, and is a curve fit.[1] For data outside the range of the Freundlich equation the reader should refer to reference 1. The equilibrium adsorptivity, We, is the maximum amount of adsorbate the carbon can hold at a given temperature and partial pressure. In practice, the carbon bed is never allowed to reach equilibrium as this would result in excessive emissions and bed breakthrough. At the point where the bed is taken off-line, the bed HAP concentration may be only 50 percent of the equilibrium concentration. Hence, in practice, the actual bed capacity is less than the equilibrium capacity. This actual capacity is called the effective, or working, capacity. The working capacity, W_c, is usually 50 percent or less than the equilibrium capacity. Table 4.6-1 provides adsorption isotherm parameters for selected organic components. If no other information is known, a default value of 50 percent of W_e can be used to obtain W_c. If no information on W_e or W_c can be found, use a default value of 0.100 for W_c.

If the emission stream contains multiple HAPs, the working capacity for the control system may be based on the HAP with the lowest working capacity in the emission stream. This conservative assumption will probably yield a carbon requirement somewhat higher than that calculated by a vendor. Nonetheless, the value obtained from the calculations below can serve as a general guide for the carbon requirement.

Example Case

These parameters are taken from Emission Stream 4, in Chapter 3.

HAP pollutant = Toluene
Stream temperature = 90°F
HAP_e = 1000 ppm

Note that the adsorption temperature given in Table 4.6-1 (77°F) is lower than the stream temperature (90°F). Nonetheless, assume this difference in temperature does not significantly affect the calculation results. The partial pressure P is directly proportional to the concentration in the emission stream and is calculated as:

$$P_{partial} = (HAP_e) \times (14.696 \text{ psia} \times 10^{-6}) \text{ psia}$$
$$P_{partial} = (1{,}000 \text{ ppmv}) \times 14.696 \times 10^{-6}$$
$$P_{partial} = 0.0147 \text{ psia}$$

thus,

$$W_e = kP_{partial}^{m}$$
$$W_e = 0.551\,(0.0147)^{0.110}$$
$$W_e = 0.346 \text{ (lbs HAP/lb carbon)}$$

and

$$W_c = 0.5\,W_e$$
$$W_c = 0.173 \text{ (lb HAP/lb carbon)}$$

Note: Did not need to use default of 0.100 for W_c since information on W_e was available.

Table 4.6-1. Parameters for Selected Adsorption Isotherms[a,b]

Adsorbate	Adsorption Temp. (°F)	Isotherm Parameters k	m	Range of Isotherm[c] (psia)
(1) Benzene	77	0.597	0.176	0.0001-0.05
(2) Chlorobenzene	77	1.05	0.188	0.0001-0.01
(3) Cyclohexane	100	0.508	0.210	0.0001-0.05
(4) Dichloroethane	77	0.976	0.281	0.0001-0.04
(5) Phenol	104	0.855	0.153	0.0001-0.03
(6) Trichloroethane	77	1.06	0.161	0.0001-0.04
(7) Vinyl Chloride	100	0.20	0.477	0.0001-0.05
(8) m-Xylene	77	0.708	0.113	0.0001-0.001
	77	0.527	0.0703	0.001-0.05
(9) Acrylonitrile	100	0.935	0.424	0.0001-0.015
(10) Acetone	100	0.412	0.389	0.0001-0.05
(11) Toluene	77	0.551	0.110	0.0001-0.05

[a] Reference 1.
[b] Each isotherm is of the form: $W_e = kP^m$. (See text for definition of terms) Data are for adsorption on Calgon type "BPL" carbon (4 x 10 mesh).
[c] Equations should ***not*** be extrapolated outside these ranges.

4.6.3 *Design Parameters*

Typically, the size (and purchase cost) of carbon adsorber system depends primarily upon four parameters:

1. The volumetric flow rate of the VOC laden gas stream
2. The mass loading of VOC
3. The adsorption time
4. The working capacity of the carbon bed

The volumetric flow rate and mass loading of VOC are the two most important factors is designing and costing an adsorber system. The flow rate determines the size of the vessels housing the carbon, the capacities of the fan and motor required, and the diameter of the internal ducting. The mass loading determines the carbon requirement. The other two parameters, while less influential than flow rate and mass loading, do need to be accounted for in any design and costing procedure. These parameters are discussed in more detail in the following section.

4.6.4 *Pretreatment of the Emission Stream*

Cooling. Adsorption of VOCs is favored by lower temperatures. If the temperature of the emission stream is significantly higher than 130 °F, a heat exchanger may be needed to cool the emission stream to 130°F or less.

Example Case
The temperature of the emission stream is 90°F which is below 130°F. Therefore, cooling is not necessary.

Dehumidification. Since vapor competes with the VOCs in the emission stream for adsorption sites on the carbon surface, emission stream humidity levels exceeding 50 percent (relative humidity) may limit efficiency for dilute streams. However, if the emission stream HAP concentration exceeds 1,000 ppmv, relative humidities above 50 percent can probably be tolerated.[3] If the HAP concentration is less than 1,000 ppmv, relative humidities should be reduced to 50 percent or less.

Dehumidification may be carried out by cooling and condensing the water vapor in the emission stream. A shell-and-tube type heat exchanger can be employed for this purpose. Refer to Section 4.8 where calculational procedures for sizing condensers are described.

Another alternative for dehumidification is adding dilution air to the emission stream if the dilution air humidity is significantly less than that of the emission stream. However, since this will increase the size of the adsorber system required, it may not be cost effective. Moreover, since a carbon adsorber is a constant outlet device, dilution air will decrease the removal efficiency.

Example Case
Since the relative humidity of the emission stream is less than 50 percent, dehumidification is not necessary.

High VOC Concentrations. If flammable vapors are present in emission streams that are mixtures of VOC and air, the VOC content usually is limited to below 25 percent of the LEL for safety reasons. In some cases, it can be increased to 40 to 50 percent of the LEL if proper monitoring and controls are used. In addition, since high bed temperatures may occur due to heat released during adsorption, high VOC concentrations may need to be reduced. In this handbook, it is assumed that the VOC content will be limited to less than 25 percent of the LEL. See Table 4.2-1 for a listing of LELs for common organic compounds.

Example Case
The HAP concentration of the emission stream is 1,000 ppmv (toluene). This is below 25% of the LEL for toluene, which is 12,000 ppmv (see Table 4.2-1).

4.6.5 Typical Operational Characteristics, Problems and Adsorber Types

In a properly operated carbon adsorber the HAP effluent emissions will tend to remain in the 50-150 ppmv range, although effluent concentrations may be as low as 20-25 ppmv.[2,3]. This concentration usually will translate to 95-99 percent efficiency depending on inlet loading. When the working capacity begins to be approached, the effluent concentration will increase significantly. This increase is called breakthrough and results in much higher emissions. The bed should be taken off-line for desorption before the working capacity is approached.

Several operating problems can result in substantial decreases in the HAP control efficiency. These problems include:

1. An increase in emission stream temperature
2. An increase in emission stream flow rate
3. An increase in HAP concentration
4. Loss of carbon adsorption activity due to heel buildup
5. Deterioration of carbon bed due to aging
6. Incomplete capture of HAP from the source

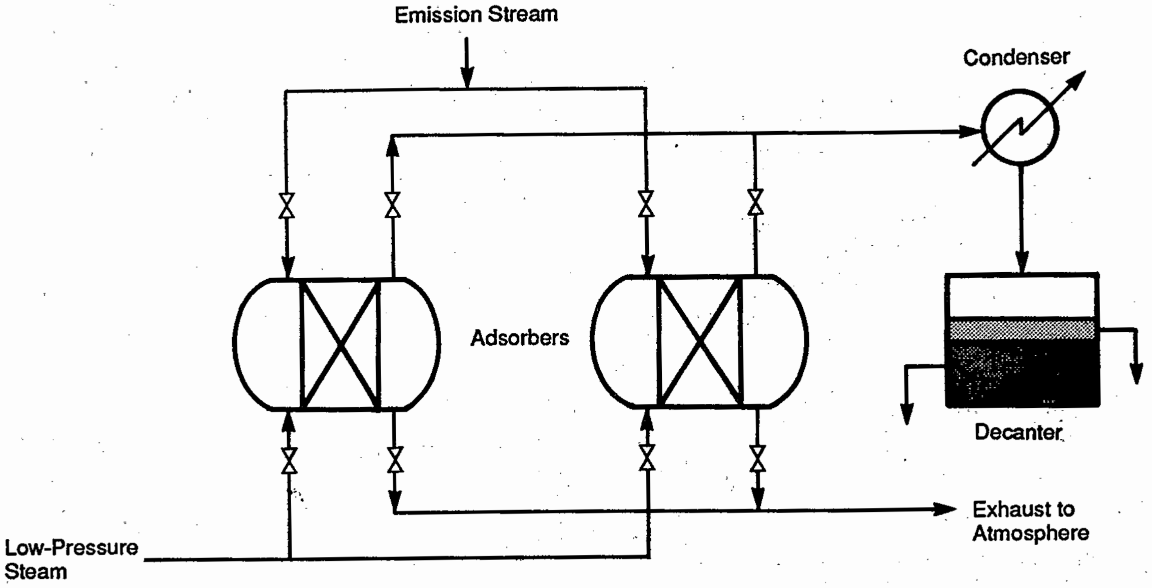
Heel buildup refers to organic compounds left on the carbon that do not desorb. The first five problems listed above will lead to higher than normal HAP effluent emissions. The sixth problem may be more difficult to detect since it generally would not lead to higher effluent emissions. Usually capture efficiency problems are detected by an increase in fugitive HAP emissions or a decrease in inlet HAP concentration.[2]

Carbon adsorption is used for pollution control and/or solvent recovery in a variety of industries. It is usually a batch operation and can involve multiple beds. Five types of adsorption equipment are used in collecting gases: (1) fixed regenerative beds; (2) disposal/rechargeable canisters; (3) traveling bed adsorbers; (4) fluidized adsorbers; (5) chromatographic baghouses. Of these five, the first two are the most common and are discussed in detail below. The other three are mentioned primarily to inform the reader that other types of adsorption systems are employed in industry.

4.6.6 Fixed Bed Regenerative Systems

Fixed bed regenerative units are used to control continuous VOC laden streams with flow rates ranging from about 2,000 acfm to over 200,000 acfm. These units can efficiently operate at concentrations in the low ppmv range or as high as 25 percent of the compound's lower explosive limit (LEL). For most organic compounds, 25 percent of the LEL ranges from about 2,500 ppmv to 10,000 ppmv. See Table 4.2-1 for a listing of LELs for common organic compounds. These adsorbers can be operated in either intermittent or continuous modes. In the intermittent mode, the adsorber removes VOC for a specified time corresponding to the time during which the source emits VOC. After the source has stopped emitting VOC, the adsorber begins the desorption cycle. This cycle consists of three steps: (1) regeneration of the

Figure 4.6-1. Typical two-bed regenerative carbon adsorption system.



carbon; (2) drying of the bed; (3) cooling of the bed to its operating temperature which is usually around ambient temperature. At the end of the desorption cycle (usually 1 to 1-1 1/2 hours), the bed sits idle until the source again begins to emit VOCs.

In continuous operation, multiple fixed bed adsorbers are employed in parallel so that at least one bed is always available to control the emission stream. A typical two bed system is shown in Figure 4.6-1. The operation of this system can be described as follows: The VOC-laden gas is introduced to the available bed where VOCs are adsorbed on the beds surface. As the adsorption capacity is approached, the effluent VOC concentration increases significantly, indicating the breakthrough point has been reached. The emission stream is then directed to a parallel bed containing regenerated adsorbent, which continues to control the emission stream. Concurrently, the first bed is undergoing a desorption cycle so that it can control the emission stream before breakthrough on the second bed is attained. For any regenerative system, an off-line bed(s) must be ready for use (i.,e. desorbed and cooled) before breakthrough on the on-line bed(s) occurs. For control of HAPs, the effluent concentration from each bed (HAP_o) should be monitored continuously.

These units normally are used to control continuous streams over a wide range of flow rates and VOC concentrations and commonly are employed at sites in which the expected cleanup duration is relatively long.[1,6] Typically, the system consists of two or more carbon beds. One bed will be adsorbing while the other(s) will be either in a regenerative phase or idle. The adsorption time of the on-line bed must be greater than or equal to the regeneration time (i.e. regeneration, drying, and cooling) of the off-line bed.

4.6.6.1 Fixed Bed Design

The design of a fixed-bed carbon adsorption system can be performed in a two step process. (The procedure below assumes a horizontal bed system). First, the carbon requirement, C_{req}, is estimated based on expected inlet HAP loading, the adsorption time, the number of beds, and the working capacity of the carbon. The relationship is described in Equation 4.6-1.

$$C_{req} = \frac{M_{HAP}\,\theta_{ad}\,(1 + ND/NA)}{W_c} \qquad (4.6\text{-}1)$$

where:

C_{req} = total amount of carbon required, lbs
M_{HAP} = HAP inlet loading, lb/hr
θ_{ad} = Adsorption time, hrs
ND = Number of beds desorbing
NA = Number of beds adsorbing
W_c = working capacity of carbon, lbs HAP/lb carbon

If the value for M_{HAP} is not given, it may be obtained from Equation 4.6-2 below:

$$M_{HAP} = 6.0 \times 10^{-5}\,(HAP_e)(Q_e)(D_{HAP}) \qquad (4.6\text{-}2)$$

where:

M_{HAP} = HAP inlet loading, lbs HAP/hr
HAP_e = HAP emission stream concentration, ppmv
Q_e = HAP emission stream flow rate, scfm
D_{HAP} = HAP density (gas), lb/ft^3

For purposes of this report, D_{HAP} can be estimated as:

$$D_{HAP} = PM/RT$$

where:

P = System pressure, atm (usually 1.0)
M = HAP molecular weight, lb/lb-mole
R = Gas constant, 0.7302 ft^3-atm/lb-mole °R
T = Temperature, °R

After obtaining the carbon requirement, the next step is to size the vessels containing the carbon. The necessary dimensions (D_v, L_v, and S) can be obtained from Equations 4.6-3, 4.6-4, and 4.6-5. Note that these equations do not provide the carbon bed dimensions, but rather the vessel dimensions. They have been derived assuming the carbon occupies 1/3 of the vessel volume and horizontal erection. For some applications, Equations 4.6-3 and 4.6-4 may yield unrealistic vessel dimensions, in particular small vessel diameters coupled with long vessel lengths. The reader can obtain more realistic dimensions by increasing U_e, although the value of U_e should not exceed approximately 100 ft/s for most cases. If unrealistic dimensions are still obtained after adjusting U_e, the reader should contact a vendor to obtain more specific design information for a given application.

$$D_v = \frac{0.127\ C'_{req}\ U_e}{Q'_{e,a}} \qquad (4.6\text{-}3)$$

where:

D_v = Diameter of vessel, ft
C'_{req} = Carbon required per vessel, lbs
U_e = Emission stream bed velocity, ft/min (default = 85 ft/min)
$Q'_{e,a}$ = Emission stream flow rate *per adsorbing* bed, acfm

$$L_v = \frac{(7.87)\ (Q'_{e,a}/U_e)^2}{C'_{req}} \qquad (4.6\text{-}4)$$

where: Lv = vessel length, ft

$Q_{e,a}$ can be obtained from Q_e and T_e using the following equation:

$$Q_{e,a} = Q_e\ (T_e + 460)/537$$

D_v is generally limited to about 12 feet, while L_v rarely exceeds 50 feet for shipping purposes. Once D_v and L_v are known the vessel surface area, S, is calculated:

$$S = \pi D_v\ (L_v + D_v/2) \qquad (4.6\text{-}5)$$

This calculational procedure is accurate for a range of vessel sizes bounded by a low value of 97 ft^2 to a high value of 2,110 ft^2.

Example Case

The example case is based on a two-bed system and the stream characteristics given earlier. Note that M_{HAP} is not given but the HAP concentration, HAP_e, is. Therefore, the first step is to use Equation 4.6-2 to obtain the HAP inlet loading:

$$M_{HAP} = 6.0 \times 10^{-5}\ (1{,}000\ \text{ppmv})(15{,}000\ \text{scfm})\ (0.23\ \text{lb/ft}^3) = 207\ \text{lbs/hr}$$

where the density, D_{HAP}, has been obtained from:

$$(1)(92)/(0.7302)(550) = 0.23\ \text{lb/ft}^3$$

Use Table 4.6-2 (discussed below) to determine the adsorption time as 2 hours. Since $\theta_{ad} \geq \theta_{req}$, a two bed system may be employed. The carbon requirement, C_{req}, is then estimated by using Equation 4.6-1.

$$C_{req} = M_{HAP}\,\theta_{ad}\,\frac{(1 + ND/NA)}{W_c}$$

$$= \frac{(207\ \text{lb/hr})\ (2\ \text{hr})\ (1 + 1/1)}{0.173}$$

$$= 4{,}790\ \text{lbs carbon}$$

$$C'_{req} = 4{,}790/2 = 2390\ \text{lbs}$$

The vessel size, S, is then calculated from Equations 4.6-3, 4.6-4, and 4.6-5.

$$D_v = \frac{0.127\ (2{,}390)\ (85)}{(15{,}360)} = 1.68\ \text{ft}$$

$$L_v = \frac{(7.87)}{2{,}390}\ (15{,}360/85\ )^2 = 107\ \text{ft}$$

$$S = \pi\,(1.68)(107 + 1.68/2)$$

$$S = 569\ \text{ft}^2$$

Note that the vessel diameter and length are somewhat unrealistic. Increasing U_e to 100 ft/s yields D_v equal to 1.98 ft and L_v equal to 77.7 ft which is still unrealistic. In this instance, it may be beneficial to contact a vendor for further assistance. However, for example purposes, the original adsorber design (D_v = 1.68 ft, L_v = 107 ft) will be continued in the later example case illustrations.

4.6.6.2 Carbon Adsorber Efficiency

Unlike most other add-on VOC control techniques, a properly operated and maintained fixed-bed carbon

Table 4.6-2. Carbon Adsorber System Efficiency Variables[a,b]

Outlet Concentration HAP (ppmv)	Adsorption Cycle Time θ_{ad} (hr)	Regeneration Cycle Time[c] θ_{reg} (hr)	Steam Requirement for Regeneration, St (lb steam/lb carbon)
70	2	2	0.3
10-12	2	2	1.0

[a] Reference 7.

[b] In some instances, cycle times may be considerably longer than the values given above. The values in this table are approximate, not definitive.

[c] Regeneration cycle time is the sum of the steam regeneration time, and the time it takes to dry and cool the bed. Drying and cooling a bed with air may be carried out in as little as 15 minutes.

adsorber system is not an efficiency device. Rather, the system functions as a constant outlet concentration device.[3] The outlet concentration from a carbon adsorber system is, for the most part, a function of the heel buildup within the bed that remains after regeneration. For inlet concentrations that vary significantly, the outlet concentration will remain relatively constant until breakthrough is approached. Therefore, the removal efficiency of a properly sized and operated carbon adsorber is largely dependant on the inlet concentration and the regeneration (i.e., steam requirement) of the bed. The more rigorous the regeneration, the lower the outlet concentration.

A precise estimation of carbon adsorber efficiency from process parameters involves a rigorous and complex calculational methodology, and is often performed on a computer. Hand analysis techniques to determine carbon adsorber efficiency may be somewhat inaccurate since many variables not accounted for in hand analysis contribute to efficiency. However, to provide the reader with a general indication of carbon adsorber efficiency, a rough estimate of outlet HAP concentration based on adsorption time and steam regeneration rate is given in Table 4.6-2. The reader should recognize that the values given in Table 4.6-2 are approximations. A computer model which can account for other variables may yield different estimates. The values contained in this table are taken from previous EPA publications.[6] In revising this manual, these values were updated by utilizing some of the recent computer design work employed to estimate adsorption parameters. However, the focus of this design work is more suited for advanced computer modeling techniques and does not readily translate into simple hand calculations. Therefore, previous efficiency values were retained.

Specific applications of carbon adsorber systems may achieve very high control efficiencies. However, these systems are very site specific and do no lend themselves readily to extrapolation for general application equations. For a more complete discussion, the reader should contact carbon adsorber vendors. [8,9]

For a carbon canister system, no steam regeneration or cycle time occurs, and hence the values given in Table 4.6-2 do not apply. Removal efficiency estimates for canister systems are typically incorporated into the carbon requirement which is discussed in Section 4.6.9.1. For purposes of this report, assume the removal efficiency of a canister system is 90 percent, provided the carbon requirement is sufficient.[6]

Example Case

The stream inlet HAP concentration is 1000 ppmv with a control requirement of 95 percent or 50 ppmv outlet concentration. From Table 4.6-2 an adsorption cycle time of 2 hours, a regeneration cycle time of 2 hours, and 0.3 lb steam/lb carbon regeneration rate will provide an outlet concentration of about 70 ppmv, or slightly less than 95 percent control efficiency assuming the bed does not get close to breakthrough. For purposes of this manual, these values will probably suffice.

4.6.6.3 Steam Requirement for Regeneration

Carbon beds may be regenerated by various means; the most common regenerant used is steam. Regeneration with steam usually is followed by condensation. The quantity of steam required for regeneration depends on the required removal efficiency (or outlet concentration) and on how much material is to be desorbed from the bed. A certain amount of steam is required to raise the bed to its regeneration temperature and provide the heat of desorption. The major portion of the steam flow, about 60 to 70 percent, acts as a carrier gas for the desorbed VOCs. It is not cost-effective to achieve complete desorption; acceptable working capacities of adsorption can be obtained without consuming large quantities of steam. For solvent recovery systems a requirement of 0.25 to 0.35 lb steam/lb carbon has usually been specified. For applications where outlet VOC concentrations need to be fairly low (e.g., odor control), steam usage ratios are higher.

In this handbook, it is assumed that with a steam ratio of 0.3 lb steam/lb carbon, a HAP outlet concentration of 70 ppmv can be achieved after regeneration, and with a ratio of 1 lb steam/lb carbon, a HAP outlet concentration of 10-12 ppmv can be achieved (Table 4.6-2). The regeneration cycle time, θ_{reg}, is dependent on the time required to regenerate, dry, and cool the bed. The flow rate of the steam used for regeneration can be determined using the following expression:

$$Q_s = NA\,[St(C'_{req})/(\theta_{reg} - \theta_{dry\text{-}cool})]\,/60 \qquad (4.6\text{-}6)$$

where:

Q_s = steam flow rate, lb/min

C'_{req} = carbon requirement per adsorbing bed, lb

$\theta_{dry\text{-}cool}$ = cycle time for drying and cooling the bed, hr

Cooling and drying the bed with air may be carried out in as little as 15 minutes or 0.25 hr. In any event, the regeneration time must allow for bed drying and cooling before it is placed on-line.

Steam flow rates based on the cross-sectional area of the bed (Q_s/A_{bed}) generally are limited to less than 4 lb steam/min-ft² to prevent the carbon from being fluidized in the bed. If Q_s/A_{bed} exceeds 4, the regeneration cycle time or the steam ratio may need to be modified. The value of A_{bed} is obtained by dividing ($Q_{e,a}$/NA) by U_e.

Example Case

Using Equation 4.6-6:

RE = 95%

HAP_o = 50 ppmv

St = 0.3 lb steam/lb carbon (Table 4.6-2)

θ_{reg} = 2 hours (Table 4.6-2)

Assuming $\theta_{dry\text{-}cool}$ = 0.25 hours:

Q_s = 1 [0.3 (2,390)/(2 - 0.25)]/60

Q_s = 6.84 lb/min

Q_s/A_{bed} = 6.84/181 = 0.0378 lb steam/min-ft²

Since Q_s/A_{bed} is less than 4 lb steam/min ft², fluidization in the carbon bed is not expected.

4.6.7 Evaluation of Permit Application

Compare the results from the calculated values and reported values using Table 4.6-3. If the calculated values of C_{req}, D_v, L_v, S, and Q_s are different from the reported values, the differences may be due to the assumptions involved in the calculations. In this case, the reviewer may wish to discuss specific design details of the proposed system with the applicant.

If the calculated values agree with the reported values, the design of the proposed fixed-bed system may be considered appropriate based upon the assumptions made in this handbook.

4.6.8 Capital and Annual Costs of Fixed Bed Regenerative Adsorbers

The capital cost of a fixed bed system is primarily a function of the amount of carbon necessary for control and the cost of the vessels used to enclose the carbon. This in turn, depends upon the amount of pollutant introduced to the system. The auxiliary costs of a fixed bed system such as fans, pumps, condensers, decanters, and piping are usually factored from the costs of carbon and vessels. The costing procedures for regenerative systems contained within this chapter apply to horizontal adsorber vessels only. Reference 1 provides sizing procedures for horizontal as well as vertical vessels.

4.6.8.1 Costs of Carbon

This cost (C_c, \$) is the product of the initial carbon requirement (C_{req}, lb) and the cost of activated carbon (\$/lb). The cost of activated carbon is about \$2/lb.[4]

The cost of carbon is then:

$$C_c = \$2.00\,(C_{req}) \qquad (4.6\text{-}7)$$

where:

C_c = carbon costs, 1989 \$

4.6.8.2 Vessel Costs

This cost (C_v) is primarily determined by vessel dimensions, which in turn, depend upon the amount of carbon contained *per vessel*, and the superficial gas velocity through the bed, U_e. The value of U_e is typically established empirically. For the purposes of this report, this value is taken to be 85 ft/min. EPA has developed a correlation between S, calculated from Equation 4.6-5, and vessel cost C_v, based upon vendor data and given in Equation 4.6-8:

$$C_v = \$\,271\,S^{0.778} \qquad (4.6\text{-}8)$$

where:

C_v = vessel cost, fall 1989 \$

and $97 \leq S \leq 2{,}110$ ft²

Table 4.6-3. Comparison of Calculated Values and Values Supplied by Permit Applicant for Carbon Adsorption

Variable	Calculated Value (Example Case)	Reported Value
Continuous Effluent Monitoring	Yes	...
Carbon Requirement, C_{req}	4,790 lbs	...
Vessel Diameter, D_v	1.68 ft	...
Vessel Length, L_v	107 ft.	...
Vessel Surface Area, S	569 ft²	...
Steam regeneration rate, Q_s	6.84 lb/min	...

The vessel costs given above are assumed to be constructed with 304 stainless steel, which is the most common material used when fabricating adsorber vessels. However, other materials may be substituted for 304 stainless steel. This substitution will not affect the design equations presented above, but will change the vessel costs. Table 4.6-4 provides multiplication factors, F_m, to be used with other materials. Multiply C_v by F_m to obtain a vessel cost estimate for the materials given in Table 4.6-4.

Table 4.6-4. Multiplication Cost Factors for Materials

Material	Factor, F_m
304 stainless steel	1.0
316 stainless steel	1.3
Carpenter 20 CB-3	1.9
Manel-400	2.3
Nickel - 200	3.2
Titanium	4.5

[a] Reference 1.

4.6.8.3 Purchased Equipment Cost

The equipment cost of an adsorber system can be estimated as a function of the sum of C_v and C_c and ductwork and damper costs as given in Equation 4.6-9.

$$EC = R_c [C_c + C_v (NA+ND)] + \text{Ductwork and damper costs} \qquad (4.6\text{-}9)$$

where:

EC = equipment cost of adsorber system

$R_c = 5.82\, Q_{e,a}^{-0.133}$

R_c = Factor to account for auxiliary equipment cost. This cost includes fans, pumps, condenser, decanter, stack, instrumentation, and internal piping. Note that this correlation uses flow rate in acfm, not scfm and does not include the cost of ductwork or dampers.

The purchased equipment cost (PEC) is then estimated as the sum of the equipment cost estimated from Eq. 4.6-9 and the cost of sales tax, and freight. Factors used to estimate sales tax and freight costs are given in Table 4.6-5.

Table 4.6-5. Installation Factors for Fixed Bed Carbon Adsorbers[a]

Cost Item	Cost Factor
Direct Costs	
Purchased Equipment Cost	
Adsorber and auxiliary equipment[b]	As estimated, EC
Taxes	0.03 EC
Freight	0.05 EC
Purchased Equipment Cost, PEC	1.08 EC
Installation Direct Costs	
Foundations and supports	0.08 PEC
Erection and handling	0.14 PEC
Electrical	0.04 PEC
Piping, installation, and painting	0.04 PEC
Total Installed Direct Cost	0.30 PEC
Site preparation	As required, SP
Buildings	As required, Bldg.
Total Direct Cost, DC	1.30 PEC + SP + Bldg.
Indirect Costs	
Engineering and supervision	0.10 PEC
Construction, field expenses, and fee	0.15 PEC
Start-up and performance test	0.03 PEC
Contingency	0.03 PEC
Total Indirect Costs, IC	0.31 PEC
Total Capital Cost, TCC = DC + IC = 1.61 PEC + SP + Bldg.	

[a] Reference 1.

[b] The equipment cost (EC) usually includes instrumentation. If not included, estimate instrumentation costs at 10 percent of the EC.

Table 4.6-6. Example Case Capital Costs

Cost Item	Factor	Cost
Direct Costs		
Purchased Equipment Costs		
Adsorber and auxiliary equipment, EC	As estimated, EC	$137,000
Taxes	0.03 EC	$ 4,110
Freight	0.05 EC	$ 6,850
Purchased Equipment Cost, PEC	1.08 EC	$148,000
Installation Direct Costs		
Foundations and supports	0.08 PEC	$ 11,800
Erection and handling	0.14 PEC	$ 20,700
Electrical	0.04 PEC	$ 5,920
Piping, installation, and painting	0.04 PEC	$ 5,920
Total Installed Direct Cost	0.30 PEC	$ 44,300
Site preparation	As required, SP	--
Buildings	As required, Bldg	--
Total Direct Cost	1.30 PEC + SP + Bldg.	$192,000 + SP + Bldg.
Indirect Costs		
Engineering and supervision	0.10PEC	$ 14,800
Construction, field expenses, and fee	0.15PEC	$ 22,200
Start-up and performance test	0.03PEC	$ 4,440
Contingency	0.03PEC	$ 4,440
Total Indirect Cost	0.31PEC	$ 45,900
Total Capital Cost, TCC	1.61 PEC + SP + Bldg.	$238,000 + SP + Bldg.

4.6.8.4 Total Capital Cost

The total capital cost (TCC) is estimated from purchased equipment cost, PEC, through direct and indirect installation cost factors. Table 4.6-5 provides the breakdown of the direct and indirect cost factors for fixed bed carbon adsorbers. These cost factors reflect "average" conditions and may vary appreciably from site to site. Also, the cost of site preparation and buildings will depend upon site specific factors and are not included in this analysis.

Example Case

The carbon cost, C_c, is calculated from Eq. 4.6-7 as:

$$C_c = \$2.00(4{,}790) = \$9{,}580$$

The vessel cost, C_v, is calculated from Eq. 4.6-8 as:

$$C_v = \$271(569)^{0.778} = \$37{,}700$$

Equation 4.8-9 is then used to calculate the equipment cost, EC. For example purposes, assume ductwork and damper costs are equal to zero.

Example Case (Cont.)

$$EC = R_c\,[\$9{,}580 + \$37{,}700\,(1+1)] + \$0$$

where:

$$R_c = 5.82\,(15{,}400)^{-0.133} = 1.61$$

or

$$EC = 1.61\,[9{,}580 + \$37{,}700\,(1+1)] = \$137{,}000$$

From Table 4.6-5, the cost of taxes are:

$$0.03\,(137{,}000) = \$4{,}110$$

Similarly, the cost of freight is:

$$0.05\,(137{,}000) = \$6{,}850$$

Therefore, the purchased equipment cost (PEC) is $137,000 + $4,110 + $6,850 = $148,000

The direct and indirect installation costs for the example case are given in Table 4.6-6.

Table 4.6-7. Unit Cost Factors for Carbon Adsorption Annual Costs[a]

Cost Element	Unit Cost Factor
Direct Annual Cost, DAC	
Utilities:	
Steam (C_s)	\$6.00/10^3 lbs steam
Cooling water	\$0.20/10^3 gal
Electricity	\$0.059/kWh
Operating:	
Operating labor	\$12.96/hr
Supervisory labor	15% of operator labor
Maintenance:	
Labor	\$14.26/hr
Materials	100% of maintenance labor
Replacement:	
Carbon[b]	\$2.00/lb
Labor	100% of replacement carbon
Solid waste disposal (Canister systems only):	
Disposal cost	\$65/canister
Transportation	As appropriate
Indirect Annual Costs, IAC	
Overhead	0.60 (Operating + maintenance)
Property tax	1 percent of TCC
Insurance	1 percent of TCC
Administrative	2 percent of TCC
Capital recovery[c] (fixed-bed)	0.1628 (TCC - 0.05 (C_{req}) - 1.08 (C_c))
Capital recovery[c] (canister)	0.1628 (Auxiliary eq. cost)
Canister expense[d]	(1.2)(1.1)(1.8)(RCN)(EC)
Recovery Credits	As applicable

[a] Reference 1.

[b] Reference 4.

[c] Capital Recovery Factor (CRF) = $\dfrac{i\,(1+i)^n}{(1+i)^n - 1}$

where: i = interest rate (10 percent assumed)
n = system lifetime, yrs

For a 10-year life and 10 percent interest rate, the CRF equals 0.1628. For canister systems, see Section 4.6.10.

[d] For canister systems only.

4.6.8.5 Fixed-Bed Carbon Adsorption Annual Cost Estimates

The annual operating cost of regenerative fixed-bed systems is comprised of three elements: 1) direct costs; 2) indirect costs; 3) recovery credits. Table 4.6-7 presents the factors used to estimate direct and indirect annualized costs. Table 4.6-8 gives the equations used to estimate selected components of annual cost. Since the number of equations to estimate the carbon adsorption annualized cost is large, Table 4.6-8 contains a summary of these equations. However, Table 4.6-8 does not include all annual cost items (e.g., operating and maintenance labor).

Direct Annual Costs. Direct costs are those which are related in some manner to the quantity of gas processed by the control system. This includes costs for utilities (steam, electricity, water, etc.) raw materials, maintenance materials, replacement parts, operating, supervisory, and maintenance labor.

Steam costs are calculated using Equation 4.6-10:

$$C_s = Q_s\,(60)\,(HRS)\,(P_s)/1{,}000 \qquad (4.6\text{-}10)$$

Table 4.6-8. Selected Equations for Carbon Adsorption Annual Cost Estimate

Cost Item	Equation
I. Direct Costs	
1. Steam Costs, C_s	$C_s = Q_s (60) (HRS) (P_s) / 1,000$ where: Q_s = steam requirement, lbs/hr HRS = operating hours per year, hr/yr P_s = Steam price, \$/10^3 lbs
2. Cooling Water Cost, C_{cw}	$C_{cw} = 3.43 (C_s / P_s) P_{cw}$ where: P_{cw} = cooling water price, \$/10^3 gal (assumed to equal \$0.20/10^3 gal)
3. Electricity	
a. Pressure drop, P_b, for Regenerative systems	$P_b = [0.03679 U_e + 1.107 \times 10^{-4} U_e^2] t_b$ where: t_b = bed thickness, ft carbon or $t_b = \dfrac{0.0333 C'_{req}}{L_V D_V}$
b. Pressure drop, P_c, for Canister systems	$P_c = 0.0471 \dot{Q}_{e,a} + 9.29 \times 10^{-4} (\dot{Q}_{e,a})^2$ where: $\dot{Q}_{e,a}$ = emission stream flow rate, per bed ft³/min.
c. System fan horsepower, hp_{sf}	$hp_{sf} = 2.5 \times 10^{-4} [(P_b \text{ or } P_c) + 1] Q_{e,a}$
d. Bed drying/cooling fan, P_{dcf}	$P_{dcf} = 1.86 \times 10^{-4} (FR_{dcf})(P_b + 1)(\theta_{dcf})$ where: P_{dcf} = power requirement for fan, kWh/yr $FR_{dcf} = (100)(C'_{req}) / \theta_{dry-cool}$ $\theta_{dcf} = 0.4(\theta_{reg}) (NA) (HRS) / \theta_{ad}$
e. Cooling water horsepower, hp_{cwp}	$hp_{cwp} = [2.52 \times 10^{-4} q_{cw} H S_g] / n$ where: q_{cw} = cooling water flow rate, gal/min H = required head (usually 100 ft. H_2O) S_g = specific gravity of fluid n = pump and motor efficiency
f. Required electricity usage per year, F_p	$F_p = 0.746 [hp_{sf} + hp_{cwp}] HRS + P_{dcf}$
4. Carbon Replacement Cost, CRC (Note: There is no carbon replacement cost for Canister carbon systems.)	$CRC = CRF_c [1.08 C_c + C_{cl}]$ where: CRF_c = Capital Recovery Factor for Carbon C_c = Carbon Cost \$/lb C_{cl} = Replacement labor cost, \$/lb (typically about \$0.05/lb)
II. Recovery credits, Q_{rec} (lb/yr)	$Q_{rec} = (M_{HAP})(HRS)(RE/100)$

where:

C_s = steam cost ,\$/yr
Q_s = steam requirement obtained in Section 4.6.6.3
HRS = annual operating hours, hr/yr
P_s = steam price, \$/1,000 lb (Table 4.6-7)

Cooling water costs are calculated using Equation 4.6-11:

$$C_{cw} = 3.43\ (C_s/P_s)\ (P_{cw}) \qquad (4.6\text{-}11)$$

where:

C_{cw} = Cooling water cost, \$/yr
P_{cw} = Cooling water price, \$/10^3 gal (Table 4.6-7)

Several steps are necessary to obtain the electricity cost. First, the pressure drop through the bed, P_b, is calculated using Equation 4.6-12.

$$P_b = [0.03679\ U_e + 1.107 \times 10^{-4}\ U_e^2] \times [0.0333\ C'_{req}\ /L_V D_V] \qquad (4.6\text{-}12)$$

where:

P_b = pressure drop through the bed, in. H_2O
U_e = superficial velocity, ft/s (default = 85 ft/sec)
C'_{req} = carbon requirement per bed, lb
L_v = vessel length, ft
D_v = vessel diameter, ft

Next, the system fan horsepower, hp_{sf}, is calculated:

$$hp_{sf} = 2.5 \times 10^{-4}\ [Q_{e,a}]\ [P_b + 1] \qquad (4.6\text{-}13)$$

The horsepower requirement for the bed drying/cooling fan is computed in a similar manner. The bed pressure drop (P_b) is identical to that given above, but the operating time and gas flow rate are different. The operating time per year is given by:

$$\theta_{dcf} = 0.4\ (\theta_{reg})(NA)(HRS)/\theta_{ad} \qquad (4.6\text{-}14)$$

The gas flow rate typically falls between 50 and 150 ft³/lb carbon. Taking the midpoint of this to obtain the flow rate yields:

$$FR_{dcf} = (100\ ft^3/lb)(C'_{req})/\theta_{dry-cool} \qquad (4.6\text{-}15)$$

This value is substituted into the equation below to obtain the power requirement for this fan:

$$P_{dcf} = 1.86 \times 10^{-4}\ (FR_{dcf})(P_b + 1)(\theta_{dcf})\ kWh/yr \qquad (4.6\text{-}16)$$

The horsepower requirement for the cooling water pump, hp_{cwp}, is then calculated using Equation 4.6-17.

$$hp_{cwp} = [2.52 \times 10^{-4}\ q_{cw}\ H\ S_g]/n \qquad (4.6\text{-}17)$$

where:

hp_{cwp} = cooling water pump horsepower, hp
q_{cw} = cooling water flow rate, gal/min (3.43 Q_s)
H = required head (usually 100 ft. of water) at

60°F
S_g = specific gravity of fluid relative to water (usually 1.0)
n = combined pump motor efficiency (usually 0.65)

The electricity usage is calculated using Equation 4.6-18.

$$F_p = 0.746\ [hp_{sf} + hp_{cwp}]\ HRS + P_{dcf} \qquad (4.6\text{-}18)$$

where:

F_p = required electricity usage, kWh/yr
HRS = operating hours per year, hr/yr

Finally, the cost of electricity is calculated as the product of the annual electricity cost and the required electricity usage:

$$AEC = \$0.059\ [F_p] \qquad (4.6\text{-}19)$$

Carbon Replacement Cost. Since the carbon has a different economic life than the rest of the adsorber system, the replacement cost must be calculated as follows:

$$CRC_c = CRF_c\ (1.08C_c + C_{cl})$$

where:

CRC_c = carbon replacement cost, \$/yr
CRF_c = capital recovery factor for carbon
C_c = initial cost of carbon, \$
C_{cl} = replacement cost of carbon, \$

CRF_c equals 0.2638 for a five-year carbon life. If the carbon has a shorter lifetime, a different factor using the formula given in Table 4.6-7 should be substituted. The cost of carbon (C_c) is obtained from Equation 4.6-7, and C_{cl} is estimated as \$0.05 C_{req}.

The cost of operating labor consists of operating labor and supervisory labor. A factor of 0.5 hr/shift is estimated as the operator time. The cost of operator labor is the product of the wage rate and the operator time/yr. The supervisory labor cost is estimated as 15 percent of the operator labor cost.

The cost of maintenance consists of maintenance labor and materials. A factor of 0.5 hr/shift is estimated as the maintenance time. The cost of maintenance labor is estimated as the product of the wage rate (110 percent of the operating wage rate) and the maintenance time per year. The cost of materials is estimated as 100 percent of the maintenance labor cost.

Indirect Annual Costs. These costs are usually considered "fixed" costs, in that they are not usually related to the size and operation of control equipment and would have to be paid even if the system shut down. This includes costs for overhead, property taxes, insurance, and capital recovery. The capital recovery cost must be offset to account for the carbon replacement cost. Tables 4.6-7 and 4.6-8 present the necessary equations to estimate direct and indirect annual costs for regenerative systems.

Recovery Credits. To calculate recovery credits, the quantity of recovered product that can be sold and/or recycled to the process has to be calculated. Use the following equation:

$$Q_{rec} = (M_{HAP})(HRS)(RE/100) \qquad (4.6\text{-}20)$$

where:

Q_{rec} = the quantity of recovered product, lb/yr

Example Case

To obtain the direct annual costs, we must add the costs of steam, cooling water, electricity, carbon replacement, operating and maintenance costs. Using the information provided in earlier example cases, we have:

1. Steam Cost,
   C_s = (6.84)(60)(6,000)(6.00/1,000)
   C_s = \$14,800/yr

2. Cooling water,
   C_{cw} = 3.43 (14,800/\$6.00)(\$0.2)

   C_{cw} = \$1,700/yr

3. Electricity, AEC

   (a) $P_b = [0.03679(85) + 1.107 \times 10^{-4} (85^2)] \times [0.0333(4{,}790)/(1.68)(107)]$
   P_b = 4.8 in. H_2O

   (b) $hp_{sf} = 2.5 \times 10^{-4} [15{,}400][4.8 + 1]$
   hp_{sf} = 22.3

   (c) θ_{dcf} = 0.4(2)(1)(6,000)/2 = 2,400 hr/yr
   FR_{dcf} = 100 (4,790)/15 = 31,900 cfm
   $P_{dcf} = 1.86 \times 10^{-4} (31{,}900)(5.8)(2{,}400)$
   = 82,600 kWh/yr

   (d) $hp_{cwp} = 2.52 \times 10^{-4} (23.5)(100)(1.0)/0.65$
   hp_{cwp} = 0.91

   (e) F_p = 0.746 [22.3 + 0.91] (6000) + 82,600
   F_p = 187,000 kWh/yr

Example Case (Cont.)

   (f) AEC = \$0.059
   AEC = \$11,000/yr

4. Carbon Replacement cost, CRC_c = 0.2638 1.08(9,580) + 240]

   CRC_c = \$2,790

5. Operating and Supervisory labor
   (6000 hr/yr)/(8hr/shift) = 750 shifts/yr
   (750 shifts/yr)(0.5 hr/shift) = 375 hr/yr
   (375 hrs/yr)(\$12.96/hr) = \$4,900/yr

Supervisory costs are taken as 15 percent of this cost, or \$700.

6. Maintenance materials
   (6000 hr/yr)/(8hr/shift) = 750 shifts/yr
   (750 shifts/yr)(0.5 hr/shift) = 375 hr/yr
   (375 hrs/yr)(1.1 x \$12.96/hr) = \$5,300/yr

Maintenance materials are taken as 100 percent of this cost, or \$5,300

Total Direct Costs = \$14,800 + \$1,700 + \$11,000 + \$2,790 + \$4,900 + \$700 + \$5,300 + \$5,300
= \$46,500

Indirect Annual Costs

Overhead = 0.60 (\$4,900 + \$700 + \$5,300 + \$5,300) = \$ 9,720
Property tax = 0.01 (\$238,000) = \$ 2,380
Insurance = 0.01 (\$238,000) = \$ 2,380
Administration = 0.02 (\$238,000) = \$ 4,760
Capital recovery = 0.1628 (\$238,000 - 0.05 (4,790) - 1.08 (\$9,580)) = \$37,000

Total Indirect Annual Costs = \$56,200

Recovery Credits Equation 4.6-20 is used to calculate the amount of recovered toluene:

$$\begin{aligned} Q_{rec} &= (M_{HAP})(HRS)(RE/100) \\ &= (207\ \text{lb/hr})(6{,}000\ \text{hr/yr})(95/100) \\ &= 1{,}179{,}000\ \text{lb/yr} \end{aligned}$$

This quantity is multiplied by the value of recovered toluene to obtain the recovery credits. The value of recovered toluene is taken from Reference 1.

1,179,900 (\$0.0553/lb) = \$65,200/yr

Total Annual Costs = \$46,500 + \$56,200 - \$65,200 = \$37,500

4.6.9 Carbon Canister System Design

Carbon canister systems are normally used for control of intermittent lower volume air streams and are generally employed on sources where the expected volume of VOC recovered is fairly small.[1,6] Carbon canister systems cannot be desorbed at the site, and must be either landfilled, or shipped back to the vendors central facility for desorption. Therefore, there are no recovery credits for canister systems. In addition, the effluent from canisters is usually not monitored continuously (via an FID, for example), meaning that operators do not have an indication of breakthrough.

4.6.9.1 Carbon Requirement

The fundamental variable to be determined in designing a canister system is the carbon requirement. This is because canister systems are fairly self-contained units coming equipped with vessels, piping, flanges, etc. Because canister systems cannot be desorbed of the site, the calculation of the carbon requirement, C_{req}, must necessarily be based on the expected volume of HAP recovered, or the total adsorption time necessary to remove the HAP. Thus, the adsorption time for canister systems has a somewhat different meaning than that for regenerative systems.

The carbon requirement for canisters can be estimated in an identical fashion to the fixed-bed system using equation 4.6-21 below:

$$C_{req} = \frac{M_{HAP}\,\theta_{ad}}{W_c}(1 + ND/NA) \qquad (4.6\text{-}21)$$

where: C_{req} = carbon requirement, lbs
M_{HAP} = VOC inlet loading, lb/hr
θ_{ad} = total adsorption time, hrs
W_c = working capacity, lbs HAP/lbs carbon
ND = number of beds desorbing
NA = number of bed adsorbing

For a canister system the number of beds desorbing (ND) equals zero. Therefore, Equation 4.6-21 becomes:

$$C_{req} = \frac{M_{HAP}\,\theta_{ad}}{W_c} \qquad (4.6\text{-}22)$$

The number of canisters required is determined by simply dividing the value of C_{req} calculated from Equation 4.6-22 by the amount of carbon contained within a canister (typically 150 lbs). The result rounded to the next highest digit yields the required canister number, RCN. For the purposes of this handbook, once the RCN is calculated, the design of a canister system is fairly complete, and costing of the system is then performed.

Example Case

Typically canister systems are utilized for streams with flow rates less than 2,000 scfm. Therefore, the stream parameters given in the example case are taken from Emission Stream 7 given in Chapter 3. In this example, assume that the adsorption time is estimated based on the total volume of recovered solvent.

Maximum Flow rate, Q_e = 2,000 scfm
Temperature, T_e = 90°F
Relative humidity, R_{hum} = 40 percent
HAP Pollutant = acetone
Required removal efficiency, RE = 90 percent
HAP emission stream conc., HAP_e = 700 ppmv
Adsorption time, θ_{ad} = 40 hours

The first step necessary is to calculate the HAP inlet loading, M_{HAP}, using the procedure outlined in the regenerative discussion. The HAP density, D_{HAP}, is calculated as:

$$D_{HAP} = PM/RT$$

where:

P = system pressure, atm
M = HAP molecular weight, lb/lb-mole
R = gas constant, 0.7302 ft^3-atm/lb-mole °R
T = stream temperature, °R

Next, the value of M_{HAP} is calculated from Equation 4.6-2.

The amount of carbon required, C_{req}, is then calculated using Equation 4.6-22. It is therefore assumed (from Section 4.6.6.2) that this amount of carbon will yield a removal efficiency of 90 percent. The required canister number, RCN, is then calculated by dividing C_{req} by the amount of carbon contained in a canister (typically, 150 lbs.).

Example Case

First calculate the HAP density, D_{HAP}

D_{HAP} = PM/RT

D_{HAP} = (1 atm)(58 lb/lb-mole)/0.7302(ft^3 atm/lb-mole°R)(550 °R) = 0.144 lbs/ft^3

From Eq. 4.6-2, the value of M_{HAP} is then:

M_{HAP} = 6.0×10^{-5}(700 ppmv)(2000 scfm) (0.144 lb/ft^3) = 12.10 lbs/hr

Example Case (Cont.)

Use Eq. 4.6-22 to obtain the carbon requirement, C_{req},

$$C_{req} = \frac{(12.1 \text{ lb/hr})(40 \text{ hours})}{0.085 \text{ lb acetone/lb carbon}}$$

$$C_{req} = 5{,}700 \text{ lbs carbon}$$

The working capacity value W_c, has been calculated using Table 4.6-1. The required canister number (RCN) is calculated by dividing C_{req} by the carbon contained in a single canister. For purposes of this example case it is assumed that 150 lbs carbon are contained within a single canister.

RCN = 5,700 lbs/150 lbs/canister
= 38 canisters

4.6.9.2 Evaluation of Permit Application

Compare the results from the calculated values and reported values using Table 4.6-9. If the calculated values of C_{req} and RCN differ from the reported values, the differences may be due to assumptions involved in the calculations. In this case, the reviewer may wish to discuss specific design details of the proposed system with the applicant.

If the calculated values agree with the reported values, the design of the proposed canister system may be considered appropriate based on the assumptions used in this handbook.

4.6.10 Capital and Annual Costs of Canister Systems

4.6.10.1 Capital Costs for Canister Systems

The capital cost of a canister system is typically a function of the required number of canisters, RCN. Equipment costs (EC) for Calgon's Ventsorb canister, common in industry, are provided in Table 4.6-10. This cost includes the carbon, vessel, and necessary connections, but do not include freight, taxes, or installation charges. The canister costs given in Table 4.6-10 are estimated based upon the cost of Calgon's "BPL" carbon (4 x 10 mesh), a commonly used industrial adsorbent. The costs are given in April 1986 $ and should be escalated to current costs using a factor of 1.1. A factor of 1.08 is used to estimate the costs of taxes and freight.

Table 4.6-9. Comparison of Calculated Values and Values Supplied by the Permit Applicant for Carbon Canister Systems

Parameter	Calculated Value (Example Case)	Reported Value
Adsorption time, θ_{ad}	40	...
M_{HAP}, lb/hr	12.1	...
Carbon Requirement, C_{req}	5,700	...
Required Canister Number, RCN	38	...

The canister equipment cost (CEC) includes the equipment cost and the cost of any necessary auxiliary equipment. Refer to section 4.12 for auxiliary equipment costs. The cost of materials and labor is significantly less for canister systems than for fixed bed systems. Twenty percent of the sum of the canister costs can be used to estimate the total capital cost (TCC) of a canister system as shown by Equation 4.6-23. The canister equipment cost is multiplied by a factor of 1.1 to obtain current canister costs.

$$TCC = 1.2\,[CEC] \qquad (4.6\text{-}23)$$

where:

TCC = Total Capital Cost
CEC = Canister Equipment Cost
= (1.1)(1.08)(RCN) [EC] + Aex
Aex = Auxiliary Equipment Cost

Example Case

Canister Capital Costs

Use Eq. 4.6-23 to obtain the TCC for a canister system. For example purposes, let auxiliary costs equal zero.

$$TCC = 1.2[(1.1)(1.08)(38)(\$579)] = \$31{,}400$$

4.6.10.2 Annual Costs for Canister Systems

The annual cost of a canister system is comprised of direct costs and indirect costs. Direct costs are those which relate to system flow rate and include utilities, raw materials, and operating and maintenance costs. Indirect costs are considered fixed and include overhead, property taxes, insurance, and capital recovery.

Table 4.6-10. Equipment Costs for Canister Units[a] (April 1986 $)

Quantity	Equipment Cost EC, each[b]
1-3	$ 687
4-9	$ 659
10-29	$622
≥ 30	$579

[a] Reference 1.

[b] The canister equipment cost, CEC, is obtained by multiplying the appropriate equipment cost, EC, by the required canister number, RCN. Costs are quoted for canisters containing 150 lbs of carbon. These costs do not include taxes and freight charges. Current prices for these canisters are about 10 percent higher than quoted in this table.

For canister systems, utility costs include electricity and solid waste disposal. To estimate the pressure drop through the canister, use the following equation:

$$P_c = 0.0471 \; Q'_{e,a} + 9.29 \times 10^{-4} [Q'_{e,a}]^2 \qquad (4.6\text{-}24)$$

where:

P_c = total canister system pressure drop, in H_2O
$Q'_{e,a}$ = emission stream flow rate per canister, acfm

Once this value is obtained, it can be substituted into Equation 4.6-25:

$$hp_{sf} = 2.5 \times 10^{-4} [P_c + 1] [Q_{e,a}] \qquad (4.6\text{-}25)$$

where:

$Q_{e,a}$ = total emission stream flowrate, acfm
P_c+1 = total pressure drop of canisters and ductwork

To obtain the required electricity usage, use Equation 4.2-26:

$$F_p = 0.746 [hp_{sf}] \, HRS \qquad (4.6\text{-}26)$$

The value of F_p is then multiplied by the electricity cost given in Table 4.6-7 to obtain annual electricity costs.

The cost of solid waste disposal can vary significantly. For purposes of this report, a cost of \$65/canister is appropriate (Reference 1).

Carbon canister systems typically do not require any operating labor, supervisory labor, maintenance labor or maintenance materials.[1] Therefore, these costs are not considered in the example case illustration. There are also no overhead costs for a canister system since overhead costs are based on operating and maintenance costs.

Indirect costs consist of overhead, property tax, insurance, administrative and capital recovery costs. Table 4.6-7 presents the necessary factors and equations to estimate direct and indirect annualized cost for canister systems. The major difference in these factors for canister systems vs. fixed-bed systems is the capital recovery factor.

The capital recovery factor is a function of the interest rate and the expected equipment lifespan, in most cases. This factor reflects the fact that most companies incur an opportunity cost when financing the installation of control equipment. Typically, the opportunity cost duration equals the expected equipment lifespan, and the annual interest rate is usually estimated to be 10 percent. For example, fixed-bed carbon adsorbers have typical lifespans of ten years, and are usually installed in plants for control of a continuous process. The process is typically expected to operate at least as long as the control device. For canister systems, however, the usual cleanup time is far less than ten years, meaning the VOC control device lifespan will be significantly less than the fixed-bed expected lifespan. For this reason, the carbon canister unit costs should be expensed, not capitalized. That is, the initial cost of the canister unit minus the auxiliary equipment cost should be included as an annual cost. The cost of auxiliary equipment should be capitalized using the CRF given in Table 4.6-7.

Example Case

Canister Annual Costs

Direct Costs. Use Eq. 4.6-24 to obtain the pressure drop. First, obtain $Q_{e,a}$ (Eq. 4.6-4):

$$Q_{e,a} = 2{,}000((90 + 460)/537) = 2{,}050 \text{ acfm}$$
$$Q'_{e,a} = 2{,}050/38 = 54 \text{ acfm}$$
$$P_c = 0.0471(54) + 9.29 \times 10^{-4}(54)^2$$
$$= 5.25 \text{ in. } H_2O$$

The power requirement is estimated from Eq. 4.6-25 as:

$$hp_{sf} = 2.5 \times 10^{-4} [5.25 + 1] \, 2{,}050 = 3.20$$

The required electricity usage (Eq. 4.6-26) is then:

$$F_p = 0.746 [3.20] \, 40 = 95 \text{ kWh/yr}$$

The cost of electricity (rounded to the nearest \$10) is:

(\$0.059)95 = \$10

Solid waste costs are estimated as:

(\$65/canister)(38 canisters) = \$2,470

The cost of operating labor, supervisory labor, maintenance labor, and maintenance materials are assumed to equal zero for a carbon canister system. The cost of overhead is also assumed to equal zero since overhead is based on operating and maintenance costs.

Total Direct Cost = \$10 + \$2,470 = \$2,480

Indirect Costs

Overhead = 0.6 (\$0) = \$0
Property tax = 0.02 (\$31,400) = \$628
Insurance = 0.01 (\$31,400 = \$314
Administrative = 0.01 (\$31,400) = \$314
Canister expense = 1.0 (\$31,400) = \$31,400
Capital recovery cost = 0.1628 (\$0) = \$0

Example Case (Cont.)

Note: For this example, auxiliary equipment costs are considered equal to zero. Therefore, there is no capital recovery cost of auxiliary equipment.

Total Indirect Costs = \$32,700
Total Annual Costs = \$2,480 + \$32,700 = \$35,200

4.6.11. References

1. U.S. EPA. OAQPS Control Cost Manual. Fourth Edition, EPA 450/3-90-006 (NTIS PB90-169954). January 1990.
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5. PES, Inc. Company data for the evaluation of continuous compliance monitors.
6. U.S. EPA. Soil Vapor Extraction VOC Control Technology Assessment. EPA-450/4-89-017 (NTIS PB 90-216995). September 1989.
7. U.S. EPA. Handbook: Control Technologies for Hazardous Air Pollutants. EPA 625/6-86-014. (NTIS PB91-228809) Cincinnati, OH. September 1986.
8. Telecon. Michael Sink, Pacific Environmental Services, Inc. to U. Sen Gupta, Calgon. July 2, 1991.
9. U.S. EPA. Carbon Adsorption for Control of VOC Emissions: Theory and Full Scale System Performance. EPA-450/3-88-012. Research Triangle Park, NC. June 1988.

4.7 Absorption

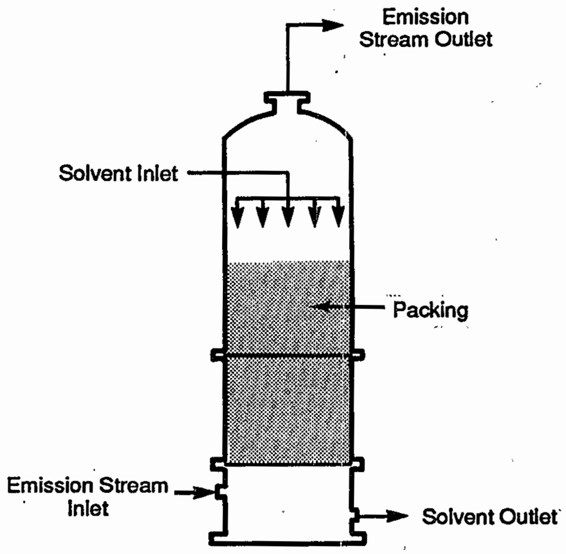
Absorption is an operation in which one or more components of a gas mixture are selectively transferred into a relatively nonvolatile liquid. Absorption of a gaseous component by a liquid occurs when the liquid contains less than the equilibrium concentration of the gaseous component. The difference between the actual concentration and the equilibrium concentration provides the driving force for absorption. The absorption rate depends on the physical properties of the gaseous/liquid system (e.g., diffusivity, viscosity, density) and the absorber operating conditions (e.g., temperature, flow rates of the gaseous and liquid streams). It is enhanced by lower temperatures, greater contacting surface, higher liquid-gas ratios, and higher concentrations in the gas stream.[1,2,9,10]

Absorption can be physical or chemical. Physical absorption occurs when the absorbed compound simply dissolves in the solvent. When a reaction occurs between the absorbed compound and the solvent, it is termed chemical absorption. Liquids commonly used as solvents for organic and inorganic compounds include water, mineral oils, nonvolatile hydrocarbon oils, and aqueous solutions (e.g., sodium hydroxide).

The design of an absorption system generally is considered somewhat more complex than the design of other vapor control techniques. This complexity is due largely to the two phase (gas and liquid) flow that characterizes these systems. The design parameters for an absorber system are dependent on such factors as equilibrium concentrations, packing constants, and absorption factors. These factors in turn are dependent upon specific HAP compounds and emission stream parameters which will vary from application to application. Therefore, to include all the necessary data within this section is not possible. Instead, most of the necessary data are included in Appendix C.7. Additional information on packing constants can be found in References 1, 2, 6, and 14.

The types of equipment commonly used for gas/liquid contact operations include packed towers, plate or tray towers, spray chambers, and venturi scrubbers. These devices are designed to provide maximum contact between the gas and liquid streams in order to increase the mass transfer rate between the two phases. A packed tower is filled with packing material that is designed to expose a large wetted surface area to the gas steam and is the focus of the discussion below. Plate towers use plates or trays that are arranged so that the gas stream is dispersed through a layer of liquid on each plate. Bubble-cap plates have been widely used; other types of plates include perforated trays and valve trays. Plate towers may be encountered in some permit applications. These are typically designed using a theoretical stage concept. Refer to References 1, 2, and 10 for further discussion. In a spray tower, the gas mixture is contacted with a liquid spray. In a venturi scrubber, the gas and liquid streams come into contact at the throat of the venturi nozzle; venturi scrubbers are typically used for removal of particulate matter (see Section 4.11).

Figure 4.7-1. Typical countercurrent packed column absorber.



Several new packing types are used in absorber systems. These packings tend to increase liquid/gas contact relative to older packings and result in smaller packing volumes and towers. Information on cost and packing constants of these new types was requested, but most vendors currently view this information as proprietary. Such information is therefore not included in this section. The reader should contact appropriate packing vendors directly to obtain specific information for a given application.

Several different configurations of absorber systems are used for controlling vapor emissions. The simplest configuration is one in which the solvent (usually water) is used on a once-through basis, and is then either discharged to a wastewater treatment system or introduced as a process water stream (see Figure 4.7-1). The possibility of using solvents other than water on a once-through basis may exist when fresh solvent is available in large quantities as a process raw material or fuel. Another configuration involves using the solvent (usually water) on a once-through basis and stripping it (reverse of absorption) before discharging. In yet another configuration, an organic liquid is used as a solvent and recycled to the absorber after being stripped.

The efficiency of absorption for removing pollutants from a gaseous stream depends on several factors, including (a) solubility of the pollutant in a given solvent, (b) concentration, (c) temperature, (d) flow rates of gaseous and liquid streams (liquid to gas ratio), (e) contact surface area, and (f) efficiency of stripping (if solvent is recycled to the absorber).

Determination of the absorber system variables (absorber column diameter, height, etc.) is dependent on the individual vapor/liquid equilibrium relationship for the specific HAP/solvent system and the type of absorber to be used (packed or plate tower, etc.). Note that equilibrium data may not be readily available for uncommon HAPs.

Detailed design procedures for all types of absorbers are not appropriate for this handbook; therefore, important design considerations for one type of absorber will be discussed briefly. Since packed towers commonly are used in air pollution control, the discussion will be based on packed tower absorbers. For illustration purposes, a simple configuration is chosen for the absorber system: a packed tower absorber using 2 inch ceramic Raschig rings as the packing material with water used as the absorbent on a once-through basis. The effluent from the absorber is assumed to be discharged to a wastewater treatment facility. The treatment in the following subsections is equally applicable to both organic and inorganic vapor emissions control. (For more information on gas absorption, see References 1, 2, 3, and 14.)

As indicated in Chapter 3, absorption is the most widely used control method for inorganic vapor emissions; therefore, Emission Stream 5 containing inorganic vapors will be used in the example case to illustrate the calculation procedures. Worksheets and necessary data for calculations are provided in Appendix C.7

4.7.1 Data Required

The Data necessary to perform the calculations consist of HAP emission stream characteristics previously compiled on the HAP Emission Stream Data Form and the required HAP control as determined by the applicable regulations.

Example Case

Maximum flow rate, Q_e = 3,000 scfm
Temperature, T_e = 85°F
HAP = ammonia
HAP concentration, HAP_e = 20,000 ppmv
Pressure, P_e = 760 mm Hg

Based on the control requirements for the emission stream: Required removal efficiency, RE = 98%

In the case of a permit review for an absorber, the following data outlined below should be supplied by the applicant. The calculations in this section will then be used to check the applicant's values.

Absorption system variables at standard conditions (77°F, 1 atm):

Reported removal efficiency, $RE_{reported}$, percent
Emission stream flow rate, Q_e, scfm
Temperature of emission stream, T_e, °F
Molecular weight of emission stream, MW_e (lb/lb-mole)
Specific HAP
HAP concentration, HAP_e, ppmv
Solvent used
Slope of the equilibrium curve, m
Solvent flow rate, L_{gal}, gal/min
Density of the emission stream, D_e, lb/ft^3
Schmidt No. for the HAP/emission stream and HAP/solvent systems, Sc_G, Sc_L (To calculate Sc_G or Sc_L, see References 1 or 3 for viscosity, density, and diffusivity data.)

Properties of the solvent:
  Density, D_L, lb/ft^3
  Viscosity, μ_L, centipoise
Type of packing used
Packing constants a, b, c, d, e, Y, s, g, r
Column diameter, D_{column}, ft
Tower height (packed), Ht_{column}, ft
Pressure drop, P_{total}, in. H_2O

4.7.2 Absorption System Design Variables

In absorption, the removal efficiencies (or outlet concentrations) are limited by the driving force available from gas to the liquid phase. The driving force for a given set of operating conditions is determined by the difference between the actual HAP concentrations in the gas stream and solvent and the corresponding equilibrium concentrations.

When the slope (m) of the equilibrium curve is small for a given HAP/solvent system, indicating that the HAP is readily soluble in the solvent, the driving force for absorption is large and absorption occurs readily. On the other hand, if m is large (e.g., >50), the HAP is not readily soluble in the solvent and the driving force for absorption is small; therefore, long contact times, tall absorption towers, and/or high liquid-gas ratios are required for adequate performance (high removal efficiency and/or low outlet concentrations). Hence, as a conservative guideline, assume that if m is greater than about 50 for a given HAP/solvent system at atmospheric pressure, then high removal efficiencies (~99 percent) are not possible.

4.7.3 Determination of Absorber System Design and Operating Variables

In most applications involving the absorption of a gaseous pollutant from an effluent gas stream, the inlet conditions (flow rate, composition, and temperature) are usually known. The composition of the outlet gas is specified by the control requirements. The conditions of the inlet liquid are also known. The main objectives, then, in the design of an absorption column will be the determination of the solvent flow rate and the calculation of the principal dimensions of the equipment (column diameter and height to accomplish the absorption operation) for a selected solvent.

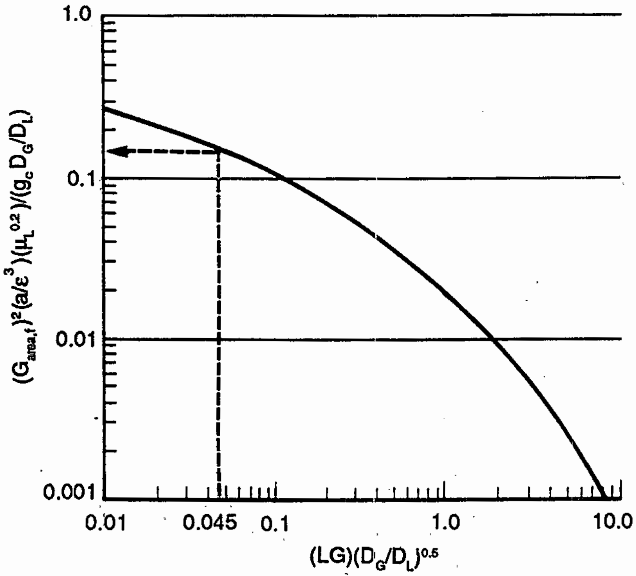
To keep the discussion simple, the following assumptions are made: (1) there are no heat effects associated with the absorption operation, and (2) both the gas and liquid streams are dilute solutions (i.e., flow rates are constant throughout the absorption column and the equilibrium curve can be approximated as a straight line). All of the data (e.g., packing factors, Schmidt numbers, etc.) required in the calculation of the design variables can be found in References 1, 3, 4, 5, 11, and 14. All data required for the example case illustration can be found in Appendix C.7.

4.7.3.1 Solvent Flow Rate

The quantity of solvent to be used is typically estimated from the minimum liquid-gas ratio as determined from material balances and equilibrium considerations. As a rule of thumb for purposes of rapid estimates, it has frequently been found that the most economical value for the absorption factor will be in the range from 1.25 to 2.0.[9,10] The absorption factor quantifies the relationship between liquid and gas molar flow rates. For purposes of this report the value will be assumed to equal 1.6.

$$L_{mol} = (AF)(m)\,(G_{mol}) \qquad (4.7\text{-}1)$$

Figure 4.7-2. Flooding correlation in randomly packed towers.



where:

AF = absorption factor (usually between 1.25 and 2.0)
L_{mol} = liquid (solvent) flow rate, lb-moles/hr
G_{mol} = gas stream flow rate, lb-moles/hr
m = slope of the equilibrium curve

The value of m is determined from the equilibrium data at a specific temperature level for the HAP/solvent system under consideration. (See References 1, 4 and 5 for equilibrium data for specific systems. For information on other systems, see References 1, 3, 6, and 14.) Assuming a value of 1.6 for AF, use Equation 4.7-1 to calculate the solvent flow rate:

$$L_{mol} = 1.6\ m\ G_{mol} \qquad (4.7\text{-}2)$$

The variable G_{mol} can be expressed in terms of Q_e as follows:

$$G_{mol} = 0.155\ Q_e \qquad (4.7\text{-}3)$$

Note that L_{mol} can be converted to gal/hr basis as follows:

$$L_{gal} = [L_{mol} \times MW_{solvent} \times (1/D_L) \times 7.48]\,/60 \qquad (4.7\text{-}4)$$

where:

L_{gal} = solvent flow rate, gal/min
$MW_{solvent}$ = molecular weight of solvent, lb/lb-mole
D_L = density of solvent (liquid), lb/ft³

The factor 7.48 is used to convert from ft³ to gal. basis. For water as the solvent, D_L = 62.43 lb/ft³ and $MW_{solvent}$ = 18 lb/lb-mole[1]; then:

$$L_{gal} = 0.036\ L_{mol} \qquad (4.7\text{-}5)$$

Example Case

Using Equations 4.7-2, -3, -4, and -5:

$m = 1.3$

(for the operating conditions in the system, consult Reference 11)

Q_e = 3,000 scfm

G_{mol} = (0.155)(3,000)
G_{mol} = 465 lb-moles/hr

L_{mol} = 1.6 x 1.3 x 465
L_{mol} = 967 lb-moles/hr

L_{gal} = (970)(18)(1/62.43)(7.48)/60
L_{gal} = 0.036 L_{mol}
L_{gal} = 35 gal/min

4.7.3.2 Column Diameter

Once the gas and liquid streams entering and leaving the absorber column and their concentrations are identified, flow rates calculated, and operating conditions (type of packing) determined, the physical dimensions of the column can be calculated. The column must be sufficient diameter to accommodate the gas and liquid streams.

The calculation of the column diameter is based on flooding considerations, the usual operating range being taken as 60 to 75 percent of the flooding rate. Flooding is defined as the point where the gas flow through the column is of such high velocity that it impedes the water flow in the column. One of the commonly used correlations in determining the column diameter is shown in Figure 4.7-2.[4] The procedure to calculate the column diameter is as follows: First, calculate the abscissa (ABS):

$$ABS = (L/G)(D_G/D_L)^{0.5} \qquad (4.7\text{-}6)$$

where:

L = solvent flow rate, lb/hr [$L = (MW_{solvent})(L_{mol})$]
G = gas stream flow rate, lb/hr [$G = (MW_e)(G_{mol})$]
D_L = density of liquid solvent, lb/ft³
D_G = density of emission stream, lb/ft³

The density of a gas, D_G, can be approximated using the formula:

$$D_G = PM/RT$$

where:

D_G = density of gas, lb/ft³
P = pressure, atm (usually 1.0)
M = molecular weight of gas, lb/lb-mole
R = gas constant, 0.7302 ft³ atm/lb-mole °R
T = temperature, °R

The values for the variables L and G can be calculated by multiplying L_{mol} and G_{mol} with their respective molecular weights. Then proceed to the flooding line in Figure 4.7-2 and read the ordinate (ORD), and solve the ordinate expression for $G_{area,f}$ at flooding:

$$ORD = [(G_{area,f})^2\ (a/e^3)\ (\mu_L^{0.2})]\ /\ D_G D_L g_c \qquad (4.7\text{-}7)$$

Thus,

$$G_{area,f} = [ORD\ D_G D_L g_c\ /\ (a/e^3)\ (\mu_L^{0.2})]^{0.5} \qquad (4.7\text{-}8)$$

where:

$G_{area,f}$ = gas stream flow rate based on column cross sectional area (at flooding conditions), lb/ft²-sec
a,e = packing factors (see Appendix C.7 or Reference 11)
μ_L = viscosity of solvent, centipoises
g_c = gravitational constant, 32.2 ft/sec²

Assuming f as the fraction of flooding velocity appropriate for the proposed operation, the gas stream flow rate (based on cross-sectional area) can be expressed as:

$$G_{area} = f\ G_{area,f} \qquad (4.7\text{-}9)$$

The usual column operating range for f is taken as 0.60 to 0.75. Calculate the column cross-sectional area by the following expression:

$$A_{column} = G/(3{,}600\ G_{area}) \qquad (4.7\text{-}10)$$

The column diameter is then determined by:

$$D_{column} = [(4/\pi)(A_{column})]^{0.5} = 1.13(A_{column})^{0.5} \qquad (4.7\text{-}11)$$

where:

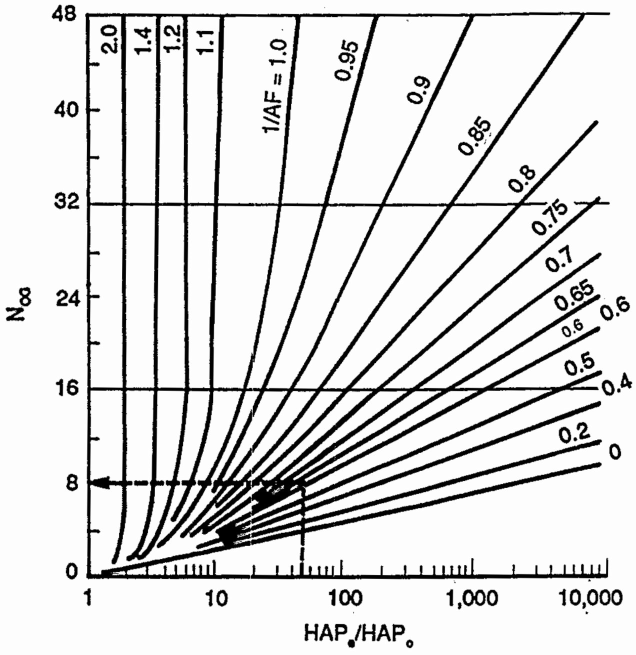
D_{column} = column diameter, ft

Example Case

Using Equations 4.7-6, -7, -8, -9, -10, and -11:

L = $MW_{solvent}$ x L_{mol} = 18 x 967 = 17,410 lb/hr
G = MW_e x G_{mol} = 28.4 x 465 = 13,200 lb/hr
D_G = (1.0)(28.4)/(0.7302)(460 + 85)
= 0.071 lb/ft³
D_L = 62.18 lb/ft³ (Reference 1; at 85°F)
ABS = $(17{,}410/13{,}200)(0.071/62.18)^{0.5}$ = 0.045

Figure 4.7-3. Relationship between N_{og}, AF, and Efficiency.



Example Case (Cont.)

From Figure 4.7-2, at ABS = 0.045, the value of ORD at flooding conditions is about 0.15. For 2-inch ceramic Raschig rings, from Reference 11 or Appendix C.7:

a = 28
e = 0.74

Also,

g_c = 32.2 ft/sec²
μ_L = 0.85 cp (Reference 1, at 85°F)

Thus,

$$G_{area,f} = \left[\frac{(0.15 \times 0.071 \times 62.18 \times 32.2)}{[28/(0.74)^3]\,(0.85)^{0.2}}\right]^{0.5}$$

$G_{area,f}$ = 0.56 lb/sec-ft² (at flooding)

Assuming f = 0.60

G_{area} = 0.60 x 0.56 = 0.34 lb/sec-ft²

Thus,

A_{column} = 13,200/(3,600 x 0.34)

A_{column} = 10.8 ft²

D_{column} = 1.13 (10.8)$^{0.5}$ = 3.7 ~4 ft

4.7.3.3 Column Height and Removal Efficiency

The column must be of sufficient height to ensure that the required removal efficiency is achieved. The height of a packed column is calculated by determining the required number of theoretical transfer units and multiplying by the height of a transfer unit. A transfer unit is a measure of the difficulty of the mass transfer operation and is a function of the solubility and concentrations of the solute in the gas and liquid streams. It is expressed as N_{og} or N_{ol} depending on whether the gas film or liquid film resistance controls the absorption rate. In emission control applications, gas film resistance will typically be controlling, therefore N_{og} will be used in the following calculations.

The expression for the column height (packed) is:

$$Ht_{column} = N_{og}\,H_{og} \qquad (4.7\text{-}12)$$

where:

Ht_{column} = packed column height, ft
N_{og} = number of gas transfer units (based on overall gas film coefficients)
H_{og} = height of an overall gas transfer unit (based on overall gas film coefficients), ft

Although the determination of N_{og} is usually complicated, when dilute solutions are involved, N_{og} can be calculated using the following equation:

$$N_{og} = \ln\left[\frac{(HAP_e / HAP_o)\,(1 - \frac{1}{AF}) + \frac{1}{AF}}{1 - \frac{1}{AF}}\right] \qquad (4.7\text{-}13)$$

This expression is simplified based on the assumption that no HAP is present in the solvent as it enters the column (see Reference 8 for details). Alternatively, use Figure 4.7-3 directly to determine N_{og}.[9] Equation 4.7-13 is the basic design equation for absorber system efficiency. It relates the inlet and desired outlet concentration to the number of transfer units (N_{og}) through the absorption factor, AF, discussed earlier in Section 4.7.3.1. The user must calculate the desired outlet concentration HAP_o, from the inlet concentration HAP_e, and the required removal efficiency, RE, using the expression:

$$HAP_o = HAP_e\,(1\text{-}RE/100) \qquad (4.7\text{-}14)$$

The outlet concentration (HAP_o) is then input into equation 4.7-13 and the corresponding column height is obtained. In general, a larger value for N_{og} will yield a greater removal efficiency, until the driving force of the two streams are roughly equal, and HAP transfer from the gas stream to the liquid (or vice versa) ceases. At this point, for all practical purposes no further transfer occurs.

Once the number of transfer units (N_{og}) is known, the height of each transfer unit (H_{og}) must be calculated. The variable H_{og} can be calculated from the following equation:

$$H_{og} = H_G + (1/AF)\,H_L \qquad (4.7\text{-}15)$$

where:

H_G = height of a gas transfer unit, ft
H_L = height of a liquid transfer unit, ft

Generalized correlations are available to calculate H_G and H_L; these are based on the type of packing and the gas and solvent flow rates. The correlations for H_G and H_L are as follows:[4]

$$H_G = [b\,(3{,}600\,G_{area})^c/(L'')^d](Sc_G)^{0.5} \qquad (4.7\text{-}16)$$

$$H_L = Y(L''/\mu_L'')^s(Sc_L)^{0.5} \qquad (4.7\text{-}17)$$

where:

b, c, d, Y, and s = empirical packing constants (see Tables C.7-1, C.7-2 or Reference 1)
L'' = liquid flow rate, lb/hr-ft^2
$\mu L''$ = liquid viscosity, lb/ft-hr
Sc_G = Schmidt number for the gas stream (Table C.7-3)
Sc_L = Schmidt number for the liquid stream (Table C.7-4)

Other values of Sc_G and Sc_L for several compounds are listed in References 3 and 4. In the calculations, it is assumed that the effect of temperature on Sc is negligible. The value for the variable L" in this equation is calculated as follows:

$$L'' = L/A_{column} \qquad (4.7\text{-}18)$$

Use the following expression to calculate the total column height (Ht_{total}) once the variable Ht_{column} has been obtained through use of Equation 4.7-12:[5]

$$Ht_{total} = Ht_{column} + 2 + 0.25\,D_{column} \qquad (4.7\text{-}19)$$

Example Case

1. Calculation of N_{og} with AF = 1.6
   Using Equation 4.7-13:

   HAP_e = 20,000 ppmv
   RE = 98 percent
   HAP_o = 20,000 (1 - 0.98) = 400 ppmv
   N_{og} = (ln[(20,000/400)(1-1/AF) +1/AF])/(1-1/AF)
   N_{og} = 7.97

Example Case (Cont.)

   Using Figure 4.7-3:

   HAP_e/HAP_o = 20,000/400 = 50
   At AF = 1.6, 1/AF = 0.63, and N_{og} = 8

2. Calculation of H_{og}:
   Using Equations 4.7-15, -16, -17, and -18:

   L'' = 17,410/10.8 = 1,612 lb/hr-ft^2
   3,600 G_{area} = 1,224 lb/hr-ft^2

   From Appendix C.7, the packing factors are:

   b = 3.82
   c = 0.41
   d = 0.45
   Y = 0.0125
   s = 0.22

Although 1,224 lb/hr-ft^2 is outside the range shown in the table, assume that the packing factors are applicable and the error introduced into the calculations will be negligible. From Appendix C.7:

   Sc_G = 0.66
   Sc_L = 570

Also,

   μ_L'' = 0.85 x 2.42 = 2.06 lb/ft-hr (The factor 2.42 is used to convert from centipoise to lb/ft-hr.)

Hence,

   H_G = $[3.82(1{,}224)^{0.41}/(1{,}612)^{0.45}](0.66)^{0.5}$
   = 2.06
   H_L = $0.0125\,(1{,}612/2.06)^{0.22}(570)^{0.5} = 1.29$
   Using AF = 1.6,
   H_{og} = 2.06 + (1/1.6) 1.29 = 2.87 ~2.9

3. Calculation of Ht_{column}:
   Using Equation 4.7-12:

   Ht_{column} = 7.97 x 2.9 = 23.1 ~23 ft

4. Calculation of Ht_{total}:
   Using Equation 4.7-19:

   Ht_{total} = 23 + 2 + (0.25 x 4) = 26 ft

To determine packing costs, the volume occupied by the packing material ($V_{packing}$) has to be calculated.

Use the following expressions:

$$V_{packing} = (\pi/4)(D_{column})^2 \times Ht_{column} \qquad (4.7\text{-}20)$$

$$V_{packing} = 0.785\,(D_{column})^2 \times Ht_{column}$$

Table 4.7-1. Comparison of Calculated Values and Values Supplied by the Permit Applicant for Absorption

Parameter	Calculated Value (Example Case)[a]	Reported Value
Solvent flow rate, L_{gal}	35 gal/min	...
Column diameter, D_{column}	4 ft	...
Column height, Ht_{column}	23 ft	...
Total column height, Ht_{total}	26 ft	...
Packing volume, $V_{packing}$	290 ft³	...
Pressure drop, P_{total}	12 in. H_2O	...

[a] Based on Emission Stream 5.

Table 4.7-2. Cost of Packing Materials[a]

Packing Type and Material	Cost per ft³			
Packing Diameter, in.	1	1.5	2	3
<u>Flexisaddles</u>				
Porcelain	19.50	17.75	16.75	16.00
Polypropylene	20.00	18.00	--	--
Stoneware	19.50	17.75	16.75	16.00
<u>Raschig Rings</u>				
Porcelain	16.00	14.50	12.75	13.25
<u>Pall Rings</u>				
Carbon Steel	35.00	30.00	--	--
304L Stainless Steel	73.50	69.80	66.00	
316L Stainless Steel	103.00	101.00	97.00	--

[a] Reference 8.

Example Case

Using Equation 4.7-20:

Ht_{column} = 23 ft
$V_{packing}$ = $0.785 \times (4)^2 \times 23$
$V_{packing}$ = 290 ft³

4.7.3.4 Pressure Drop through the Column

The pressure drop through a packed column or any combination of liquid and gas flows in the operable range is an important economic consideration in the design of such columns. For a particular packing, the most accurate data will be those available from the manufacturer. For purposes of estimation, use the following correlation:[4]

$$P_a = (g \times 10^{-8}) \left[10^{(rL''/D_L)}\right] (3{,}600\ G_{area})^2/D_G \qquad (4.7\text{-}21)$$

where:

P_a = pressure drop, lb/ft²-ft
g, r = packing constants (see Appendix C.7 or Reference 4)

The total pressure drop through the column is then expressed as:

$$P_{total} = P_a \times Ht_{column} \qquad (4.7\text{-}22)$$

Figure 4.7-4. Costs of absorber towers.

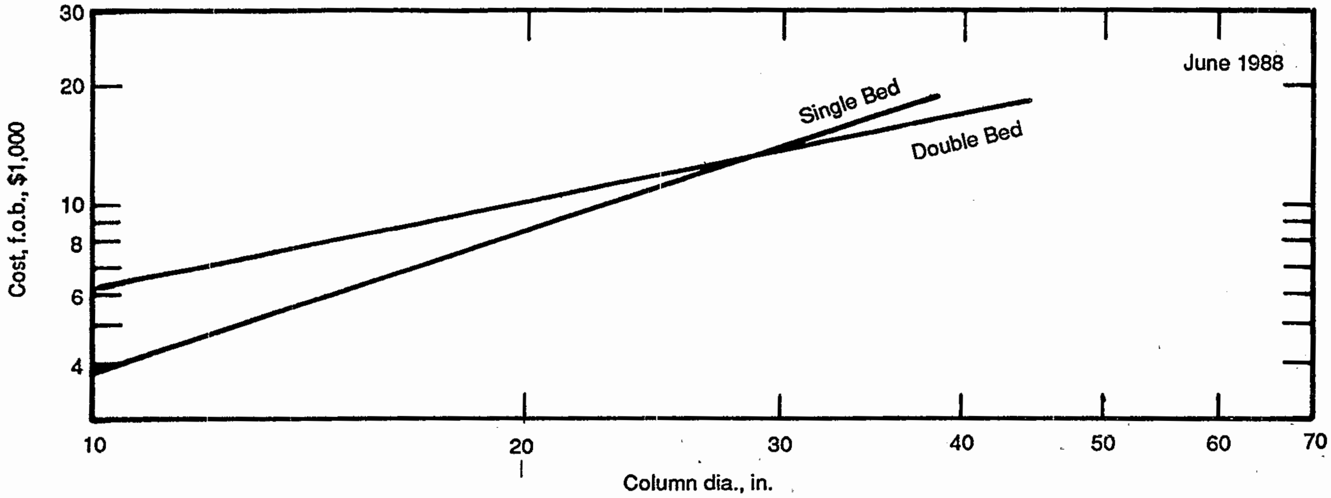


Table 4.7-3. Capital Cost Factors for Absorbers[a]

Cost Item	Factor
Direct Costs, DC	
Purchased equipment cost	
Absorber (tower & packing) + auxiliary equipment	As estimated, EC
Instrumentation	0.10 EC
Sales tax	0.03 EC
Freight	0.05 EC
Purchased Equipment Cost, PEC	1.18 EC
Direct Installation Costs	
Foundation and supports	0.12 PEC
Erection and handling	0.40 PEC
Electrical	0.01 PEC
Piping	0.30 PEC
Insulation	0.01 PEC
Painting	0.01 PEC
Direct Installation Cost	0.85 PEC
Site preparation	As required, SP
Building	As required, Bldg.
Total Direct Costs, DC	1.85 PEC + SP + Bldg.
Indirect Costs, IC	
Engineering	0.10 PEC
Construction	0.10 PEC
Contractor fee	0.10 PEC
Start-up	0.01 PEC
Performance test	0.01 PEC
Contingencies	0.03 PEC
Total Indirect Cost	0.35 PEC
Total Capital Costs	2.20 PEC + SP + Bldg.

[a] Reference 9.

Example Case

Using Equation 4.7-21:

From Appendix C.7:

$g = 11.13$

$r = 0.00295$

Also,

$L'' = 1,612 \text{ lb/hr-ft}^2$

$3,600\ G_{area} = 3,600 \times 0.34 = 1,224 \text{ lb/hr-ft}^2$

$D_G = 0.071 \text{ lb/ft}^3$

$D_L = 62.18 \text{ lb/ft}^3$

Thus,

$$P_a = \frac{[11.13 \times 10^{-8} \times 10^{(0.00295 \times 1,612/62.18)} (1,224)^2]}{(0.071)}$$

Example Case (Cont.)

$P_a = 2.8 \text{ lb/ft}^2\text{-ft}$

Using Equation 4.7-22:

$Ht_{column} = 23 \text{ ft}$

$P_{total} = 2.8 \times 23 = 64.4 \text{ lb/ft}^2$

$P_{total} = 64.4/5.2 = 12 \text{ in. } H_2O$

(The factor 5.2 is used to convert from lb/ft² to in. H_2O.)

4.7.4 Evaluation of Permit Application

Compare the results from the calculations and the values supplied by the permit applicant using Table 4.7-1. The calculated values in the table are based on the example case. If the calculated values of L_{gal}, D_{column}, Ht_{column}, Ht_{total}, P_{total}, and $V_{packing}$ are different from the reported values for these variables, the differences may be due to the assumptions involved in the calculations. Therefore, the reviewer may wish to discuss the details of the proposed design with the permit applicant.

Table 4.7-4. Example Case Capital Costs

Cost Item	Factor	Cost
Direct Costs, DC		
Purchased equipment cost		
Absorber (tower & packing)		
+ auxiliary equipment	As estimated, EC	$38,700
Instrumentation	0.10 EC	3,870
Sales tax	0.03 EC	1,160
Freight	0.05 EC	1,940
Purchased Equipment Cost, PEC	1.18 EC	$45,670
Direct Installation Costs		
Foundation and supports	0.12 PEC	$ 5,480
Erection and handling	0.40 PEC	18,300
Electrical	0.01 PEC	457
Piping	0.30 PEC	13,700
Insulation	0.01 PEC	457
Painting	0.01 PEC	457
Direct Installation Cost	0.85 PEC	$38,900
Site preparation	As required, SP	
Building	As required, Bldg.	
Total Direct Costs, DC	1.85 PEC + SP + Bldg.	$84,500 + SP + Bldg.
Indirect Costs, IC		
Engineering	0.10 PEC	$ 4,570
Construction	0.10 PEC	4,570
Contractor fee	0.10 PEC	4,570
Start-up	0.01 PEC	457
Performance test	0.01 PEC	457
Contingencies	0.03 PEC	1,370
Total Indirect Cost	0.35 PEC	$16,000
Total Capital Costs	2.20 PEC + SP + Bldg.	.$100,000 + SP + Bldg.

If the calculated values agree with the reported values, then the design and operation of the proposed scrubber system may be considered appropriate based on the assumptions made in this handbook.

4.7.5 Capital and Annual Costs of Absorbers

The capital cost of an absorber system consists of the purchased equipment cost an direct and indirect installation costs. The annual cost consists of direct and indirect annual costs.

4.7.5.1 Capital Costs for Absorbers

The capital cost of an absorber system is composed of purchased equipment costs and direct and indirect installation costs. The purchased equipment cost consists of the equipment cost, which includes the cost of a tower, packings, auxiliary equipment, instrumentation, freight, and taxes.

Figure 4.7-4 provides the cost in June 1988 dollars of absorber towers as a function of column diameter. These costs were obtained from Reference 7. The cost of various packing materials is given in Table 4.7-2 and was obtained from Reference 8. The cost of auxiliary equipment (e.g., ductwork and fan) may be obtained from Section 4.12. The auxiliary equipment cost, plus the cost of the adsorber tower and packing is the equipment cost, EC. Table 4.7-3 provides the cost factors necessary to estimate the purchased equipment cost as well as the direct and indirect installation cost factors.

Example Case

Column diameter = 4 ft

Extrapolating from Figure 4.7-4, the cost of a single-bed column is about $25,000. The volume of packing is 290 ft^3. Use 2 inch porcelain raschig rings. From Table 4.7-2, the cost of these rings is $12.75/$ft^3$. Therefore the packing cost equals $3,700. Assume auxiliary equipment costs are $10,000. The equipment cost (EC) is the sum of these three cost items, or $38,700.

Example Case (Cont.)

Table 4.7-3 is then used to obtain the purchased equipment cost (PEC) as follows:

Instrumentation = 0.10 ($38,700) = $3,870
Sales tax = 0.03 ($38,700) = $1,160
Freight = 0.05 ($38,700) = $1,940
$6,970

The PEC thus equals $38,700 + $6,970 = $45,670. The direct and indirect installation cost factors given in Table 4.7-3 are used to obtain the total capital cost (TCC) of an absorber system. These costs are detailed in Table 4.7-4.

4.7.5.2 Annual Costs for Absorbers

The annual cost for an absorber system consist of direct and indirect annual costs. For purposes of this manual recovery credits for absorber systems are assumed to equal zero. While an absorber does "recover" HAPs by transferring them to a liquid stream, further separation equipment is usually necessary to obtain the pure HAP. Therefore, recovery credits are assumed zero.

Table 4.7-5 provides the appropriate cost factors to estimate annual costs.

Direct Annual Costs. Direct annual costs consist of utilities (electricity, solvent) and operating labor and maintenance costs.

The electricity usage is a function of the fan power requirement. Equation 4.7-23 is used to estimate this value. The annual usage is then multiplied by the electricity cost (Table 4.7-5) to obtain the electricity cost.

$$F_p = 1.81 \times 10^{-4} (Q_{e,a})(P_{total})(HRS) \qquad (4.7\text{-}23)$$

where:

F_p = fan power requirement, kWh/yr
$Q_{e,a}$ = actual emission stream flow rate, acfm
P_{total} = system pressure drop, in. H_2O
HRS = system operating hours per year, hr/yr

To obtain $Q_{e,a}$ from Q_e, use the following formula:

$$Q_{e,a} = Q_e (T_e + 460)/537$$

The annual electricity cost (AEC) is then:

Annual Electricity Cost = $ 0.059 (F_p)

To obtain the cost of solvent (usually water) use Equation 4.7-24 to estimate the annual consumption of solvent:

$$ASR = 60 (L_{gal}) HRS \qquad (4.7\text{-}24)$$

where:

ASR = annual solvent requirement, gal/yr

This value is then multiplied by the solvent cost provided in Table 4.7-5 to obtain annual costs.

Annual Solvent Costs: $0.20/1,000 gal x (ASR)

The amount of operator labor is estimated as 0.5 hours per 8 hour shift. The operator labor wage rate is provided in Table 4.7-5. Supervisory costs are assumed to be 15 percent of labor costs.

The amount of maintenance labor is estimated as 0.5 hours per 8 hour shift. The maintenance wage rate is provided in Table 4.7-5. Maintenance material costs are assumed to equal 100 percent of maintenance labor costs.

Indirect Annual Costs. These costs consist of overhead, property tax, insurance, administrative, and capital recovery costs. Appropriate cost factors to estimate the indirect annual costs are given in Table 4.7-5.

Example Case

Direct Annual Costs

Electricity costs:

Use Equation 4.7-23 to obtain the fan power requirement, F_p.

$$F_p = 1.81 \times 10^{-4} (3{,}045)(12)(6{,}000)$$
$$= 3.97 \times 10^{4} \text{ kWh/yr}$$

where: $Q_{e,a} = 3{,}000 (85 + 460)/537 = 3{,}045$ acfm

Electricity cost = $0.059 (3.97 x 10^4) = $2,340

The annual solvent requirement (ASR) is obtained using Equation 4.7-24.

ASR = 60 (35)(6,000) = 1.26 x 10^7 gal/yr

The cost of solvent is obtained by multiplying the consumption by the cost factor given in Table 4.7-5.

Solvent Cost = $0.20/1,000 gal (1.26 x 10^7) = $2,520

Operating labor costs are estimated as:

[(0.5 hr/shift)/(8 hr/shift)] 6,000 hr/yr = 375 hr/yr

375 hr/yr x $12.96/hr = $4,860/yr

Supervisory costs are taken as 15 percent of this cost, or $729.

Example Case (Cont.)

Maintenance labor costs are estimated as:
[(0.5 hr/shift)/(8 hr/shift)] 6,000 hr/yr = 375 hr/yr
375 hr/yr x$14.26/hr = $5,350/yr

Maintenance materials are taken as 100 percent of the value, or $5,350/yr.

Total Direct Costs = $2,340 + $2,520 + $4,860 + $729 + $5,350 + $5,350 = $21,100

Indirect Annual Costs

These costs are obtained from the factors given in Table 4.7-5 and the example case presented above.

Overhead = 0.60 ($4,860 + $729 + $5,350 + $5,350) = $9,770
Administrative = 0.02 ($100,000) = $2,000
Insurance = 0.01 ($100,000) = $1,000
Property taxes = 0.01 ($100,000) = $1,000
Capital recovery = 0.1628 ($100,000) = $16,300

Total Indirect Costs = $9,770 + $2,000 + $1,000 + $1,000 + $16,300 = $30,100

Total Annual Costs = $21,100 + $30,100 = $51,200

Table 4.7-5 Annual Cost Factors for Absorber Systems[a]

Cost Item	Factor
Direct Cost, DAC	
Utilities	
Electricity	$0.059/kWh
Solvent (water)	$0.20/$10^3$ gal
Operating Labor	
Operator labor	$12.96/hr
Supervisor	15% of operator labor
Maintenance	
Maintenance labor	$14.96/hr
Materials	100% of maintenance labor
Indirect Costs, IAC	
Overhead	0.60 (Operating labor & maintenance)
Administrative	2% of TCC
Property taxes	1% of TCC
Insurance	1% of TCC
Capital recovery[b]	0.1628 (TCC)

[a] Reference: 9, 12.

[b] Capital recovery factor is estimated as: $i(1+i)^n/(1+i)^n-1$
where: 1 = interest rate, 10 percent
n = equipment life, 10 years

4.7.6 References

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4.8 Condensers

Condensation is a separation technique in which one or more volatile components of a vapor mixture are separated from the remaining vapors through saturation followed by a phase change (see Figure 4.8-1). The phase change from gas to liquid can be accomplished in two ways: (a) the system pressure may be increased at a given temperature, or (b) the system temperature may be reduced at constant pressure.

The design and operation of a condenser are affected significantly by the number and nature of the components present in the emission stream. For example, condenser efficiency is very sensitive to the HAP inlet concentration. In a two-component vapor system where one of the components is noncondensible (e.g., air), condensation occurs at dew point (saturation) when the partial pressure of the condensible compound (e.g., benzene) is equal to its vapor pressure. In most HAP control applications, the emission stream will contain large quantities of noncondensible and small quantities of condensible compounds. To separate the condensible component from the gas stream at a fixed pressure, the temperature of the gas stream must be reduced. The more volatile a compound (i.e., the lower the normal boiling point), the larger the amount that can remain as vapor at a given temperature; hence the lower the temperature required for saturation (condensation).

When condensers are used to control emissions, they are usually operated at the pressure of the emission source, which is typically close to atmospheric. Depending on the temperatures required for condensation, a refrigeration unit may be necessary to supply the coolant (see Section 4.8.3.1). The two most common types of condensers used are surface and contact condensers. Surface condensers are usually shell-and-tube heat exchangers. The coolant typically flows through the tubes and the vapors condense on the shell outside the tubes. The condensed vapors forms a film on the cool tubes and are drained to a collection tank for storage or disposal. In contrast to surface condensers where the coolant does not contact either the vapors or the condensate, *in contact condensers, the vapor mixture is* cooled by spraying a cool liquid directly into the gas stream.

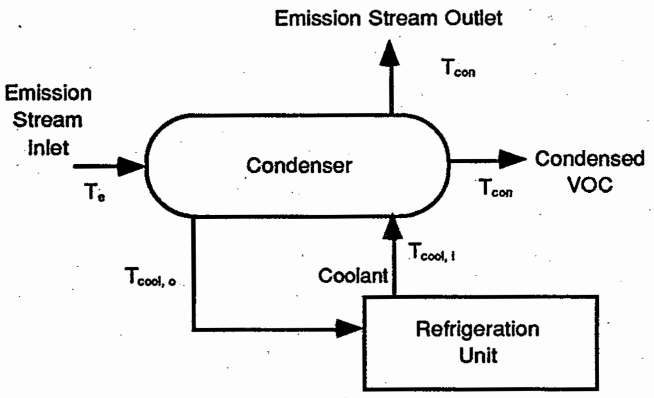

Figure 4.8-1 **Flow diagram for typical refrigerated condenser system.**

Proper maintenance of a condenser system is an important aspect to maintain performance. Over time, scale buildup will tend to foul condenser systems. Symptoms of this include a significant increase in fluid pressure drop, or a decrease in heat transfer resulting in an increase in fluid outlet temperature and a decrease in efficiency. For adequate control of HAPs, the emission stream outlet temperature must be continuously monitored. It is important to perform this cleaning without delay, because scale buildup becomes much harder to remove over time.[1,11]

Design calculations for condenser systems vary in complexity depending on the nature and number of components present in the emission stream. For detailed information on condenser design, consult References 1, 2, and 3. In the following discussion, Emission Stream 6, consisting of a single condensible component and a single noncondensible component, will be used to illustrate the calculation procedure for surface condensers. The moisture content of the emission stream is assumed to be negligible (i.e., no ice is expected to form on the tubes in the condenser). The design procedure will involve determining the condensation temperature required, selection of coolant, and calculation of condenser size and coolant requirements.

4.8.1 Data Required

The data necessary to perform the calculations consist of HAP emission stream characteristics previously compiled on the HAP Emission Stream Data Form and the required HAP control as determined by the applicable regulations.

Example Case

The stream characteristics given below are taken from Emission Stream 6 in Chapter 3.

Maximum flow rate, Q_e = 2,000 scfm
Temperature, T_e = 90°F
HAP = styrene
HAP concentration, HAP_e = 13,000 ppmv
(corresponding to saturation conditions)
Moisture content, M_e = negligible
Pressure, P_e = 760 mm Hg

Based on the control requirements for the emission stream:
Required removal efficiency, RE = 90%

In the case of a permit review for a condenser, the following data should be supplied by the applicant. The calculations in this section will then be used to check the applicant's values. Worksheets for calculations are provided in Appendix C.8.

Condenser system variables at standard conditions (77°F, 1 atm):

Reported removal efficiency, $RE_{reported}$,%
Emission stream flow rate, Q_e, scfm
Temperature of emission stream, T_e, °F
Specific HAP
HAP concentration, HAP_e, ppmv
Moisture content, M_e,%
Temperature of condensation, T_{con}, °F
Coolant used
Inlet temperature of coolant, $T_{cool,i}$, °F
Coolant flow rate, $Q_{coolant}$, lb/hr
Refrigeration capacity, Ref, tons
Condenser surface area, A_{con}, ft^2
Specific heat of HAP, Cp_{HAP}, Btu/lb-mol °F
Heat of vaporization of HAP, ΔH, Btu/lb-mol

(**Note:** Heat capacities for over 700 compounds are provided in Reference 10.)

4.8.2 Pretreatment of the Emission Stream

If water vapor is present in the emission stream, ice may form on the condenser tubes when coolants such as chilled water or brine solutions are used, decreasing the heat transfer efficiency and thus lowering the condenser's removal efficiency. In such cases, dehumidifying the emission stream is necessary. This can be carried out in a heat exchanger prior to the condenser, which cools the vapor down to about 35°F. However, even with pretreatment (e.g. heat exchanger), water vapor can remain a problem for sub-zero systems, and adequate provisions should be integrated into the system. Such provisions can include a dual condenser system where a heated air stream is passed through the condenser that is down.[12]

4.8.3 Condenser System Design Variables

The key design variable in condenser system design is the required condensation temperature for a given removal efficiency or outlet concentration. A condenser's removal efficiency greatly depends on the concentration and nature of emission stream components. For example, compounds with high boiling points (i.e., low volatility) condense more readily compared to those with low boiling points. Assume, as a conservative starting point, that condensation will be considered as a HAP emission control technique for VOCs with boiling points above 100°F.

The temperature necessary to achieve a given removal efficiency (or outlet concentration) depends on the vapor pressure of the HAP in question at the vapor/liquid equilibrium. Once the removal efficiency for a given HAP is specified, the required temperature for condensation can be determined from data on its vapor pressure-temperature relationship. Vapor pressure-temperature data can be represented graphically (Cox charts) as shown in Figure 4.8-2 for typical VOCs. The coolant selection is then based on the condensation temperature required. See Table 4.8-1 for a summary of practical limits for coolant selection.

In a permit evaluation, use Table 4.8-1 to determine if the values reported for the condensation temperature (T_{con}) and the type of coolant selected are consistent. Also, check if the coolant inlet temperature is based on a reasonable approach temperature (a conservative value of 15°F is used in the table). If the reported values are appropriate, proceed with the calculations. The permit reviewer may then follow the calculation procedure outlined below. Otherwise, the applicant's design is considered unacceptable unless supporting documentation indicates the design is feasible.

The condenser system evaluated in this handbook consists of a shell-and-tube heat exchanger with the hot fluid (emission stream) in the shell side and the cold fluid (coolant) in the tube side. Depending on the application, the tube side and shell side fluids may be reversed. The emission stream is assumed to consist of a two-component mixture: one condensible component (HAP) and one noncondensible component (air). Typically, condensation for such a system occurs nonisothermally. To simplify the calculations, it is assumed that condensation occurs isothermally. This assumption usually does not introduce large errors into the calculations.

Table 4.8-1. Coolant Selection[a]

Required Condensation Temperature T_{con} (°F)[b]	Coolant Temperature Coolant	$T_{cool,i}$ (°F)[c]
T_{con}:[d] 60-80	Water	T_{con}-15
$60 > T_{con} > 45$	Chilled water	T_{con}-15
$45 > T_{con} \geq -30$	Brine solutions (e.g., calcium chloride, ethylene glycol)	T_{con}-15
$-30\ T_{con} \geq -90$	Chlorofluorocarbons (e.g., Freon-12)	T_{con}-15

[a] Reference 4.
[b] Also emission steam outlet temperature.
[c] Assume the approach as 15°F.
[d] Summer limit.

4.8.3.1 Estimating Condensation Temperature

In the following calculations, it is assumed that the emission stream entering the condenser consists of air saturated with the HAP in question. Calculations for cases involving mixtures of HAPs and supersaturated streams are quite complex and will not be treated here since they are beyond the scope of this handbook. References 5 and 6 may be consulted for information on these streams.

For a given removal efficiency, the first step in the calculation procedure is to determine the concentration at the outlet of the condenser. Use the following expression:

$$P_{partial} = 760\ \{(1 - 0.01\ RE)/[(1 - (RE \times 10^{-8} \times HAP_e)]\}\ HAP_e \times 10^{-6} \qquad (4.8\text{-}1)$$

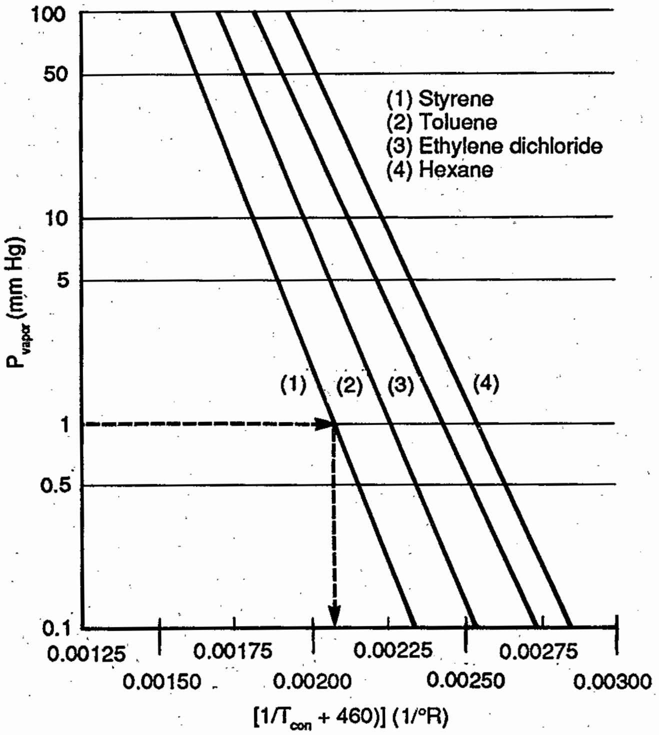

Figure 4.8-2 **Vapor pressure-temperature relationship.**

$P_{partial}$ is the partial pressure (mm Hg) of the HAP in the exit stream assuming the pressure in the condenser is constant and at atmospheric. At equilibrium between the gas and liquid phases, the partial pressure of the HAP is equal to its vapor pressure at that temperature. Therefore, by determining the temperature at which this condition occurs, the condensation temperature (T_{con}) can be specified. To carry out this calculation, vapor pressure-temperature data for the specific HAP are required (see Figure 4.8-2). Such data can be obtained from References 3 and 7.

The partial pressure can be calculated as a function of the desired removal efficiency using Equation 4.8-1. This equation is valid for the range of removal efficiencies likely to be encountered. However, note that the partial pressure necessary to obtain a high removal efficiency may result in a condensation temperature (T_{con}) that is not realistically obtainable. In this case, a lower removal efficiency must be accepted, or a different control technique is warranted. Information on coolants necessary for a given condensation temperature and whether T_{con} is obtainable realistically are provided in Table 4.8-1.

Example Case

Using Equation 4.8-1 and Figure 4.8-2:

HAP_e = 13,000 ppmv (styrene)
RE = 90%

$P_{partial}$ = 760 {[1-(0.01 x 90)]/[(1-(90 x 10^{-8} x 13,000)]} 13,000 x 10^{-6}

$P_{partial}$ = 1.0 mm Hg

For styrene, the value of [1/(T_{con} + 460)] corresponding to 1.0 mm Hg in Figure 4.8-2 is about 0.00208.

Solving for T_{con}:
T_{con} = 20°F

4.8.3.2 Selecting the Coolant

The next step is to select the coolant based on the condensation temperature required. Use Table 4.8-1 to specify the type of coolant. For additional information on coolants and their properties, see References 3 and 7.

Example Case

Based on T_{con} = 20°F, the appropriate coolant is a brine solution. Assume the brine solution is a 29% (wt) calcium chloride solution which can be cooled down to -45°F (see Reference 3).

4.8.3.3 Condenser Heat Load

Condenser heat load is defined as the quantity of heat that must be extracted from the emission stream to achieve a certain level of removal. It is determined from an energy balance, taking into account the heat of condensation of the HAP, sensible heat change of the HAP, and the sensible heat change in the emission stream. This calculation neglects enthalpy changes associated with non-condensible vapors (i.e., air), which is typically a very small value. The calculation steps are outlined below:

1a. Calculate moles of HAP in the inlet emission stream (Basis: 1 min):

$$HAP_{e,m} = (Q_e/392)\ HAP_e \times 10^{-6} \qquad (4.8\text{-}2)$$

The factor 392 is the volume (ft^3) occupied by 1 lb-mole of ideal gas at standard conditions (77°F and 1 atm).

1b. Calculate moles of HAP remaining in the outlet emission stream (Basis: 1 min):

$$HAP_{o,m} = (Q_e/392)[1 - (HAP_e \times 10^{-6})]\ [P_{vapor}/(P_e - P_{vapor})] \qquad (4.8\text{-}3)$$

where P_{vapor} is equal to $P_{partial}$ given in Equation 4.8.1.

1c. Calculate moles of HAP condensed (Basis: 1 min):

$$HAP_{con} = HAP_{e,m} - HAP_{o,m} \qquad (4.8\text{-}4)$$

2a. Determine the HAP's heat of vaporization (ΔH): Typically the heat of vaporization will vary with temperature. Using vapor pressure-temperature data as shown in Figure 4.8-2, ΔH can be estimated by linear regression for the vapor pressure and temperature range of interest (see Reference 3 for details). Compare this value with that of the permit application, taking care to ensure both are in the same units. If these values differ significantly, contact the permit applicant to determine the reason for the difference.

2b. Calculate the enthalpy change associated with the condensed HAP (Basis: 1 min):

$$H_{con} = HAP_{con} [\Delta H + Cp_{HAP} (T_e - T_{con})] \qquad (4.8\text{-}5)$$

Where Cp_{HAP} is the average specific heat of the HAP for the temperature interval $T_{con} - T_e$ (Btu/lb-mole-°F) (See Table C.8-1).

2c. Calculate the enthalpy change associated with the noncondensible vapors (i.e., air) (Basis: 1 min):

$$H_{noncon} = [(Q_e/392) - HAP_{e,m}]\, Cp_{air} (T_e - T_{con}) \qquad (4.8\text{-}6)$$

where Cp_{air} is the average specific heat of air for the temperature interval $T_{con} - T_e$ (Btu/lb-mole-°F) (See Table C.8-1).

3a. Calculate the condenser heat load (Btu/hr) by combining Equations 4.8-5, and 4.8-6:

$$H_{load} = 1.1 \times 60 \, (H_{con} + H_{noncon}) \qquad (4.8\text{-}7)$$

The factor 1.1 is included as a safety factor.

Example Case

Using Equations 4.8-2 to -7:

1a. Q_e = 2,000 scfm
$HAP_{e,m}$ = $(2{,}000/392)\ 13{,}000 \times 10^{-6}$
$HAP_{e,m}$ = 0.06633 lb-moles/min

1b. P_{vapor} = 1.0 mm Hg
P_e = 760 mm Hg
$HAP_{o,m}$ = $(2{,}000/392)(1-13{,}000 \times 10^{-6})$ $[1.0/760-1.0]$

$HAP_{o,m}$ = 0.00663 lb-moles/min

1c. HAP_{con} = 0.0663 - 0.00663
= 0.0597 lb-moles/min

2a. ΔH = 17,445 Btu/lb-mole (see Reference 3)

Example Case (Cont'd)

2b. MW_{HAP} = 104.2 lb/lb-mole
Cp_{HAP} = 24 Btu/lb-mole-°F
(extrapolated from data in Reference 7)
H_{con} = 0.0597 [17,445 + 24(90-20)]
H_{con} = 1,140 Btu/min

2c. Cp_{air} = 7.05 Btu/lb-mole-°F
(see Reference 3 or Table C.8-1 for details)

H_{noncon} = [(2,000/392) - 0.0663] 7.05 x (90-20)
H_{noncon} = 2,480 Btu/min

3a. H_{load} = 1.1 x 60 (1,140 + 2,480)
H_{load} = 239,000 Btu/hr

4.8.3.4 Condenser Size

Condenser systems are typically sized based on the total heat load and the overall heat transfer coefficient estimated from individual heat transfer coefficients of the gas stream and the coolant. An accurate estimate of individual coefficients can be made using physical/chemical property data for the gas stream, the coolant, and the specific shell-and-tube system to be used. Since calculation of individual heat transfer coefficients is beyond the scope of this manual, the value used in this manual for the overall heat transfer coefficient is a conservative estimate. This approach will tend to yield a conservatively large surface area estimate. For additional information on how to calculate individual heat transfer coefficients, consult References 1,2, and 3. This calculation procedure assumes counter current flow, which is commonly found in industrial applications. However, some applications may employ co-current flow, or use fixed heat exchangers. The procedure below is still valid for co-current flow, but an adjustment must be made to the logarithmic mean temperature difference as discussed below.[2]

To size condensers, use the following equation to determine the required heat transfer area:

$$A_{con} = H_{load} / U \, \Delta T_{LM} \qquad (4.8\text{-}9)$$

where:

A_{con} = condenser (heat exchanger) surface area, ft^2
U = overall heat transfer coefficient, Btu/hr-ft^2-°F
ΔT_{LM} = logarithmic mean temperature difference, °F

and:

$$\Delta T_{LM} = \frac{(T_e - T_{cool,o}) - (T_{con} - T_{cool,i})}{\ln [(T_e - T_{cool,o})/(T_{con} - T_{cool,i})]}$$

where:

T_e = emission stream temperature, °F

$T_{cool,o}$ = coolant outlet temperature, °F
T_{con} = condensation temperature, °F
$T_{cool,i}$ = coolant inlet temperature, °F

Note: For co-current flow, this equation becomes:

$$\Delta T_{LM} = \frac{(T_e - T_{cool,i}) - (T_{con} - T_{cool,o})}{\ln[(T_e - T_{cool,i})/(T_{con} - T_{cool,o})]}$$

Assume that the approach temperature at the condenser exit is 15°F. In other words, $T_{cool,i} = (T_{con} - 15)$. Also, the temperature rise of the coolant fluid is specified as 25°F, i.e., $T_{cool,o} = (T_{cool,o} + 25)$ where $T_{cool,o}$ is the coolant exit temperature. In estimating A_{con}, the overall heat transfer coefficient can be conservatively assumed as 20 Btu/hr-ft²-°F; the actual value will depend on the specific system under consideration. This calculation is based on References 2 and 6 in which guidelines on typical overall heat transfer coefficients for condensing vapor-liquid media are reported.

Example Case

Using Equation 4.8-9 with counter-current flow:

T_e = 90°F
T_{con} = 20°F
$T_{cool,i}$ = 20 - 15 = 5°F
$T_{cool,o}$ = $T_{cool,i}$ + 25 = 30°F

$$\Delta T_{LM} = \frac{(90 - 30) - (20 - 5)}{\ln(90 - 30)/(20 - 5)}$$

ΔT_{LM} = 32°F
H_{load} = 239,000 Btu/hr
U = 20 Btu/hr-ft²-°F (assumed value)
A_{con} = 239,000/(20 x 32)
A_{con} = 370 ft²

4.8.3.5 Coolant Flow Rate

The quantity of heat extracted from the emission stream is transferred to the coolant. By a simple energy balance, the flow rate of the coolant can be calculated as follows:

$$Q_{coolant} = H_{load}/[Cp_{coolant}\,(T_{cool,o} - T_{cool,i})] \qquad (4.8\text{-}10)$$

where:

$Q_{coolant}$ = coolant flow rate, lb/hr
$Cp_{coolant}$ = average specific heat of the coolant over the temperature interval $T_{cool,i}$ to $T_{cool,o}$, Btu/lb-°F

Specific heat data for coolants are available in References 3 and 7.

Example Case

Using Equation 4.8-10:
H_{load} = 239,000 Btu/hr
$T_{cool,i}$ = 5°F
$T_{cool,o}$ = 30°F
$Cp_{coolant}$ = 0.65 Btu/lb-°F (Reference 3)
$Q_{coolant}$ = 239,000/[0.65 (30-5)]
$Q_{coolant}$ = 14,700 lb/hr

4.8.3.6 Refrigeration Capacity

A refrigeration unit is assumed to supply the coolant at the required temperature to the condenser. For costing purposes, the required refrigeration capacity is expressed in terms of refrigeration tons as follows:

$$Ref = H_{load}/12,000 \qquad (4.8\text{-}11)$$

where Ref is the refrigeration capacity, tons.

Example Case

Using Equation 4.8-11:
H_{load} = 239,000 Btu/hr
Ref = 239,000/12,000
Ref = 20 tons

4.8.3.7 Recovered Product

To calculate costs, the quantity of recovered product that can be sold and/or recycled to the process must be determined. Use the following equation:

$$Q_{rec} = 60 \times HAP_{con} \times MW_{HAP} \qquad (4.8\text{-}12)$$

where Q_{rec} is the quantity of product recovered, lb/hr.

Example Case

Using Equation 4.8-12:
HAP_{con} = 0.0597 lb-moles/min (from Equation 4.8-4)
MW_{HAP} = 104.2 lb/lb-mole
Q_{rec} = 60 x 0.0597 x 104.2
Q_{rec} = 373 lb/hr

4.8.4 Evaluation of Permit Application

Compare the results from the calculations and the values supplied by the permit applicant using Table 4.8-2. The calculated values in the table are based on the Example Case. If the calculated values of T_{con}, coolant type, A_{con}, $Q_{coolant}$, Ref, and Q_{rec} are different from the reported values for these variables, the differences may be due to the assumptions involved in the calculations. Therefore, the reviewer may wish to discuss the details of the proposed design with the permit applicant. If the calculated values agree with the reported values, then the design and operation of the proposed condenser system may be considered appropriate based on the assumptions made in this handbook.

4.8.5 Capital and Annual Costs of Condensers

The capital costs of a condenser system consists of purchased equipment costs and direct and indirect installation costs. Annual costs consist of direct and indirect annual costs.

4.8.5.1 Capital Costs for Condensers

The capital cost of a condenser system is composed of purchased equipment costs (equipment costs and auxiliary equipment), and direct and indirect installation costs. Factors for these costs are presented in Table 4.8-3. Equipment costs for cold-water condenser systems were obtained from References 4 and 8. Equipment costs for fixed tubesheet and floating head heat exchangers are given in Figures 4.8-3 and 4.8-4 for heat transfer surface areas (A_{con}) from 300-1,500 ft^2. The equipment costs are in July 1988 dollars. The cost of auxiliary equipment can be obtained from Section 4.12 and includes ductwork, dampers, fan and stack costs.

Table 4.8-2. Comparison of Calculated Values and Values Supplied by the Permit Applicant for Condensation

	Calculated Value (Example Case)[a]	Reported Value
Continuous monitoring of exit stream temperature	yes	...
Condensation temperature, T_{con}	20°F	...
Coolant type	Brine Solution	...
Coolant flow rate, $Q_{coolant}$	14,700 lb/hr	...
Condenser surface area, A_{con}	370 ft^2	...
Refrigeration capacity, Ref	20 tons	...
Recovered product, Q_{rec}	373 lb/hr	...

[a] Based on Emission Stream 6.

For condenser systems requiring a coolant based on Table 4.8-1, Table 4.8-4 can be used to estimate the total capital cost (TCC) of a refrigerant system, as a function of refrigeration capacity (Ref) and condensation temperature (T_{con}). This cost must be added to the condenser capital cost (TCC) obtained from Figures 4.8-3 or 4.8-4 and Table 4.8-3. Although refrigerated units are often sold as packaged systems, splitting the cost of the basic condenser system and refrigerant system in this manner allows for more flexibility in estimating the cost of a given system. A refrigerant system may not be necessary for required condensation temperatures above 40°F, depending on the cooling water available.

The costs given in Table 4.8-4 are in spring 1990 dollars and were obtained from Reference 13. Table 4.8-5 provides the Example Case capital costs for the condenser systems.

Table 4.8-3. Capital Cost Factors for Condensers[a]

Cost Item	Factor
Direct Costs	
Purchased Equipment Costs	
Condenser & auxiliary equipment	As estimated, EC
Instrumentation[b]	0.10 EC
Sales tax	0.03 EC
Freight	0.05 EC
Purchased Equipment Cost, PEC	1.08 EC
Direct Installation Costs	
Foundation and supports	0.08 PEC
Erection and handling	0.14 PEC
Electrical	0.08 PEC
Piping	0.02 PEC
Insulation	0.10 PEC
Painting	0.01 PEC
Direct Installation Cost	0.43 PEC
Site preparation	As required, SP
Buildings	As required, Bldg.
Total Direct Costs, DC	1.43 PEC + SP +Bldg.
Indirect Installation Costs	
Engineering	0.10 PEC
Construction	0.05 PEC
Contractor fee	0.10 PEC
Start-up	0.02 PEC
Performance test	0.01 PEC
Contingencies	0.03 PEC
Total Indirect Cost, IC	1.31 PEC
Total Capital Costs[c]	1.74 PEC + SP + Bldg.

[a] References 4,9.

[b] Typically included with the condenser cost.

[c] Does not include cost of refrigeration system.

Example Case

Assume that an 8-foot tube length, 14 BWG fixed tubesheet condenser is used.

From Figure 4.8-3, with a heat transfer surface area, A_{con}, of 370 ft^2, the condenser cost is about $8,500. Assume auxiliary equipment costs from Section 4.12 are $10,000. The equipment cost (EC) is then $18,500. The factors given in Table 4.8-3 are used to obtain the purchased equipment cost (PEC). Instrumentation is included in the cost obtained from Figure 4.8-3.

Sales tax = 0.03 ($18,500) = $555
Freight = 0.05 ($18,500) = $925

The PEC is then $20,000.

The capital cost of this condenser is obtained using the factors given in Table 4.8-3. These costs are detailed in Table 4.8-5.

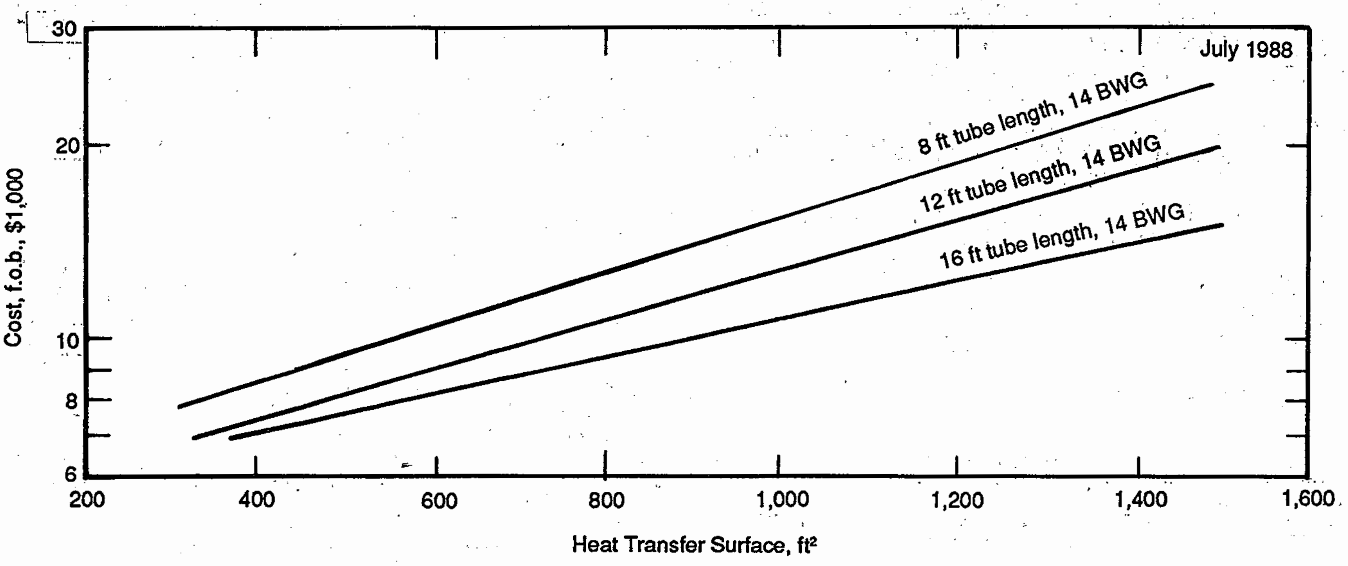

Figure 4.8-3. **Costs for fixed tubesheet condensers.**[8]

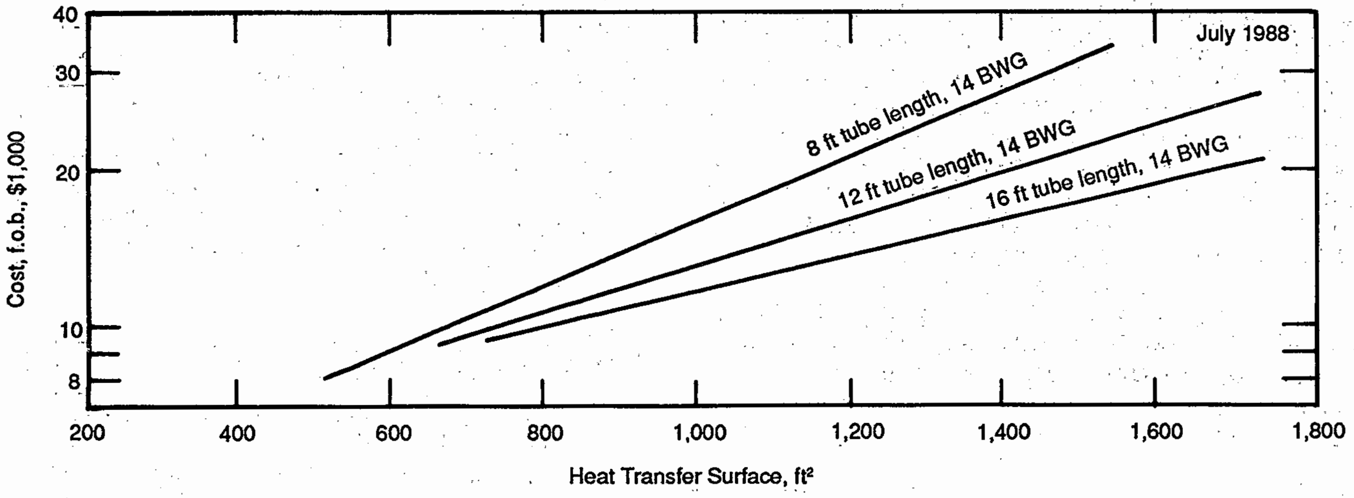

Figure 4.8-4. **Costs for floating head condensers.**[8]

Example Case (Cont'd)

Once the total capital cost (TCC) of a condenser is obtained, the capital cost of the refrigeration system must be added to the TCC, if applicable. For this example case, use Table 4.8-4 to obtain this additional capital cost. The cost obtained from this table equals $107,000 for a T_{con} of 20°F and a refrigeration capacity of 20 tons. The total capital cost of the condenser and refrigerant system is then $34,800 + $107,000 = $142,000, as shown in Table 4.8-5.

Table 4.8-4. Capital Costs for Refrigerant Systems[a,b]

Required Condensation Temperature, °F	Refrigerant System Capital Cost, RTCC $
≥ 40°F[c]	RTCC = 1,989.5 (Ref) + 10,671
≥20°F	RTCC = 4,977 (Ref) + 7,615
≥0°F	RTCC = 7,876.8 (Ref) + 9,959
≥-20°F	RTCC = 6,145.4 (Ref) + 26,722
≥-45°F	RTCC = 10,652 (Ref) + 13,485
≥-85°F	RTCC = 12,489 (Ref) + 28,993

[a] Reference 13

[b] See Equation 4.8-11 for a definition of Ref.

[c] A refrigerant system may be required for condensation temperatures between 40-60°F, although this will be dependent on the cooling water available. If cooling water of a sufficiently low temperature is available, a refrigerant system is not required.

4.8.5.2 Annual Costs for Condensers

The annual costs for a condenser system consists of direct and indirect annual costs minus recovery credits. Table 4.8-6 provides appropriate factors for estimating annual costs.

Direct Annual Costs. Direct annual costs consist of utilities (electricity, refrigerant) and operating labor and maintenance costs.

The electricity cost is a function of the fan power requirement. Equation 4.8-13 can be used to obtain this requirement, assuming a fan-motor efficiency of 65 percent and a fluid specific gravity of 1.0.

$$F_p = 1.81 \times 10^{-4} (Q_{e,a})(P)(HRS) \qquad (4.8\text{-}13)$$

where:

F_p = fan power requirement, kWh/yr

$Q_{e,a}$ = emission stream flow rate, acfm

P = system pressure drop, in. H_2O (default = 5 in. H_2O)

HRS = system operating hours per year, hr/yr

To obtain $Q_{e,a}$ from Q_e, use the following formula

$$Q_{e,a} = Q_e (T_e + 460)/537$$

The cost of refrigerant replacement will vary with each condenser system, but typically is very low. Therefore, assume refrigerant replacement costs are zero unless specific information is available.

The amount of operator labor is estimated as 0.5 hours per 8 hour shift. The operator labor wage rate is given in Table 4.8-6. Supervisory costs are assumed to be 15 percent of operator labor cost. The amount of maintenance labor is estimated as 0.5 hours per 8 hour shift. The maintenance wage rate is provided in Table 4.8-6. Maintenance costs are estimated as 100 percent of maintenance labor costs.

Indirect Annual Costs. These costs consist of overhead, property tax, insurance, administrative, and capital recovery costs. Table 4.8-6 provides the appropriate cost factors.

Recovery Credits. Recovery credits for a condenser system may be significant. The amount of HAP recovered can be estimated using Equation 4.8-12, given in Section 4.8.3.7. The recovery credits are then obtained by multiplying the value of the recovered product by the amount of recovered product.

Example Case

Direct Annual Costs

Electricity consumption is estimated using Equation 4.8-13.

Assume the system pressure drop is 5 inches of water

$$\begin{aligned} F_p &= 1.81 \times 10^{-4} (2{,}050)(5)(6{,}000) \\ &= 11{,}100 \text{ kWh/hr} \end{aligned}$$

Annual Electricity Cost = $0.059 ($F_p$)
Annual Electricity Cost = $655

The cost of refrigerant is assumed to be zero.

Operating labor costs are estimated as:

[(0.5 hr/shift/(8 hr/shift)] x 6,000 hr/yr = 375 hr/yr
375 hr/yr ($12.96/hr) = $4,900/yr

Supervisory costs are taken as 15 percent of this cost, or $700.

Maintenance labor costs are estimated as:

[(0.5 hr/shift)/(8 hr/shift)] x 6,000 hr/yr = 375 hr/yr
375 hr/yr ($14.26/hr) = $5,300/yr

Maintenance materials are taken as 100 percent of this cost or $5,300/yr.

Total Direct Annual Costs:

$655 + $0 + $4,900 + $700 + $5,300 + $5,300
= $16,900

Example Case (Cont'd)

Indirect Annual Costs

Overhead = 0.60 ($4,900 + $700 + $5,300 + $5,300)
= $9,720

Administrative = 0.02 ($142,000) = $2,840

Property taxes = 0.01 ($142,000) = $1,420

Insurance = 0.01($142,000) = $1,420

Capital recovery = 0.1628($142,000)
= $23,100

Example Case (Cont'd)

Total Indirect Costs:

$9,720 + $2,840 + $1,420 + $1,420 + $23,100 = $38,500.

Recovery Credits

The quantity recovered, Q_{rec}, is calculated in Section 4.8.3.7. This quantity is 373 lb/hr, or 2,240,000 lbs/yr. For example purposes, assume the value of the recovered product is $0.03/lb. The recovery credits are then estimated as $67,100/yr.

Total Annual Costs = $16,900 + $38,500 - $67,100 = ($11,700), or a **savings** of $11,700/yr.

Table 4.8-5. Example Case Capital Costs

Cost Item	Factor	Cost($)
Direct Costs		
Purchased Equipment Costs		
Condenser & auxiliary equipment	As estimated, EC	$ 18,500
Instrumentation	0.10 EC	Included
Sales tax	0.03 EC	555
Freight	0.05 EC	925
Purchased Equipment Cost, PEC	1.08 EC	20,000
Direct Installation Costs		
Foundation and supports	0.08 PEC	$ 1,600
Erection and handling	0.14 PEC	2,800
Electrical	0.08 PEC	1,600
Piping	0.02 PEC	400
Insulation	0.10 PEC	2,000
Painting	0.01 PEC	200
	0.43 PEC	$ 8,600
Site preparation	As required, SP	
Buildings	As required, Bldg.	
Total Direct Cost, DC	1.43 PEC + SP + Bldg.	$ 28,600 + SP + Bldg.
Indirect Installation Cost		
Engineering	0.10 PEC	$ 2,000
Construction	0.05 PEC	1,000
Contractor Fee	0.10 PEC	2,000
Start-up	0.02 PEC	400
Performance test	0.01 PEC	200
Contingencies	0.03 PEC	600
Total Indirect Cost, IC	0.31 PEC	$ 6,200
Total Capital Cost	1.74 PEC + SP + Bldg.	$ 34,800
RTCC (fromTable 4.8-4)		107,000
TCC of total system (including refrigeration)		$ 142,000

Table 4.8-6. Annual Cost Factors for Condenser Systems[a]

Cost Item	Factor
Direct Cost, DAC	
Utilities	
Electricity	$0.059/kWh
Refrigerant	0
Operating Labor	
Operator labor	$12.96/hr
Supervisor	15% of operator labor
Maintenance	
Maintenance labor	$14.26/hr
Materials	100% of maintenance labor
Indirect Costs, IAC	
Overhead	0.60 (Operating labor & maintenance)
Administrative	2% of TCC
Property tax	1% of TCC
Insurance	1% of TCC
Capital recovery[b]	0.1628 (TCC)
Recovery Credits	As applicable

[a] References 4 and 9

[b] Capital recovery factor is estimated as: $i(1+i)^n/(1+i)^n-1$

where: i = interest rate, 10 percent.

n = equipment life, 10 yrs.

4.8.6 References

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4.9 Fabric Filters

Fabric filter collectors (also known as baghouses) are one of the most efficient means of separating particulate matter from a gas stream. Fabric filters are capable of maintaining mass collection efficiencies of greater than 99 percent down to a particle size approaching 0.3 um in most applications.[1,2,3,12,13] This efficiency is largely insensitive to the physical characteristics of the gas and dust, and, depending on fabric cleaning method, to the inlet dust loading.[1,4] A large portion of the energy needed to operate the system appears as pressure drop across the bags, system hardware, and ducting. Typical system pressure drop values range from 5 to 20 inches of water. Limitations on the applicability of fabric filters are imposed by emission stream characteristics (e.g., temperature, corrosivity, and moisture content) and particle characteristics (primarily "stickiness"). However, recent advances in fabrics have resulted in greater applicability. For example, temperatures of 500°F with surges to 550°F are now routinely accommodated.[11,14]

Important process variables considered in baghouse design include fabric type, cleaning method, air-to-cloth ratio, and equipment configuration (i.e., forced draft or induced draft). The filter fabric, cleaning method, and air-to-cloth ratio all should be selected concurrently; choice of these parameters is mutually dependent.[1] Equipment configuration is of secondary importance unless site-specific space limitations exist that require configuration to be of primary importance in the fabric filter design. The operating parameter usually monitored is the pressure drop across the system. Typically, baghouses are operated within a certain pressure drop range, which is determined based on site experience.

Currently, work is being done on electrostatically enhanced fabric filters. This technique, employed at pilot plant baghouses, has shown significantly lower pressure drops than conventional designs. Preliminary cost analysis studies have indicated that electrostatically enhanced baghouses may have lower lifetime costs than conventional bag-houses. However, this technique is still in the design stage and therefore is not discussed below. Reference 11 contains more information on this technique.

Fabric filter systems typically are designed on the basis of empirical information obtained through testing and long-term actual operating experience for similar combinations of cleaning method, fabric type, and dust rather than by analytical methods.[1] Although theoretical equations exist to predict the performance of filtering systems under various conditions, these equations are beyond the scope of this manual. A more rigorous discussion on fabric filter theory and design can be found in the OAQPS Control Cost Manual (Reference 11). Discussion of baghouse design in this section provides qualitative guidance rather than predictive equations. Generally, fabric filter design for HAPs is no different than fabric filter design for control of any other type of particulate matter. However, due to the hazards associated with HAPs, greater care must be taken to ensure that control is consistently of high efficiency and that the control device is leak-proof, thus preventing accidental release of the gas stream and captured pollutants. For these reasons, design of a fabric filter system for HAPs should specify an induced draft fan (i.e., a negative pressure or suction baghouse) rather than a forced draft fan (i.e., a positive pressure baghouse). Information presented in this section can be used to provide guidance for or to evaluate the appropriateness of baghouse design for certain HAP applications.

Appendix C.9 provides a worksheet to record the information obtained during the performance of the fabric filter design procedures.

4.9.1 Data Required

The data necessary to perform the design steps consist of the HAP emission stream characteristic previously compiled on the "HAP Emission Stream Data Form" and the required HAP control as determined by the applicable regulations.

Example Case

Fabric filtration was one of the selected control techniques for the municipal incinerator. The pertinent data for these procedures are found on the "HAP Emission Stream Data Form" (see Figure 3-8).

1. Flow rate, $Q_{e,a}$ = 110,000 acfm
2. Moisture content, M_e = 5% vol.
3. Temperature, T_e = 400°F
4. Particle mean dia., D_p = 1.0 µm
5. SO_3 content = 200 ppm (vol)
6. Particulate content = 3.2 grains/scf - flyash
7. HAP content = 10% (mass) cadmium

In the case of a permit review for a fabric filter, the following data should be supplied by the applicant. The design criteria and considerations discussed in this section will be used to evaluate the reasonableness of the applicant's proposed design.

1. Filter fabric material ______________________
2. Cleaning method ______________________
3. Air-to-cloth ratio ft/min ______________ (ft³/min)/ft²
4. Baghouse configuration ______________________
5. System pressure drop range ______________ in. H_2O

4.9.2 Pretreatment of the Emission Stream

As discussed in Section 3.3.1, the temperature of the emission stream should be within 50 to 100°F above the stream dew point. If a emission stream is too close to its dewpoint, moisture can condense and cause corrosion as well as ruptures in bags. This problem is excerbated if acid gas (e.g., SO_3) is present. Procedures for determining the dew point of an emission stream are provided in Appendix B.1. If the emission stream temperature does not fall within the stated range, pretreatment (i.e., emission stream preheating or cooling) is necessary. Methods of pretreatment are briefly discussed in Appendix B.3. If pretreatment is performed, the emission stream characteristics will be altered. The primary characteristics affecting baghouse design are emission stream temperature and flow rate. Therefore, after selecting a temperature for the emission stream, the new stream flow rate must be calculated. The calculation method depends upon the type of pretreatment performed; use appropriate standard industrial equations. The use of pretreatment mechanical dust collectors may also be appropriate. If the emission stream contains an appreciable amount of large particles (20 to 30 um), pretreatment with mechanical dust collectors is typically performed. Appendix B.3 further describes the use of mechanical dust collectors.

4.9.3 Fabric Filter System Design Variables

Successful design of a fabric filter depends on the proper selection of fabric and cleaning method and on an adequate air-to-cloth ratio. All fabric filter systems share the same basic features and operate using the principle of aerodynamic capture of particles by fibers. Systems vary, however, in certain key details of construction and in the operating parameters. The design variables of particular interest are filter bag material, fabric cleaning method, air-to-cloth ratio, baghouse configuration (i.e., forced or induced draft), and materials of construction.

As stated earlier, the first three variables should be considered concurrently. The configuration and construction materials are important, but secondary, considerations. The following subsections discuss step-by-step procedures for selecting each of these design variables as they may apply to a specific particulate HAP control situation. Because HAP control is similar to particulate control in general, a good verification of these procedures can be accomplished by consulting the section about the particular industry in a document entitled "Control Techniques for Particulate Emissions from Stationary Sources - Volume II," or in the McIlvaine Fabric Filter Manual.[4,5] **[Note:** Because these design variables are considered concurrently, the "Example Case" is presented at the end of Section 4.9.3.]

4.9.3.1 Fabric Type

Several types of natural and synthetic fabric are used in baghouse systems. Gas stream characteristics, such as temperature, acidity, alkalinity, and particulate matter properties (e.g., abrasiveness and hygroscopicity), determine the fabric type to be used.[1,6] In many instances, several fabric types will be appropriate, and a final selection will be chosen only when the cleaning method and the desired air-to-cloth ratio are considered.

Most of the principal synthetic fibers have been adapted for use as filtering fabrics while the only natural fibers in common use are cotton and wool. Some of the more common synthetic fibers in commercial use are nylon (aromatic and polyamide), acrylic, polyester, polypropylene, fiberglass, and fluorocarbon. Natural fibers can be used for gas temperatures up to 200°F but have only moderate resistance to acids and alkalis contained in the gas stream.[1,4,6] Synthetics have successfully operated at temperatures up to 550°F and generally have greater chemical resistance.[1,4,6] Recent additional advances in synthetic ceramics (Nextel 312™) have resulted in increasing operating temperatures to 900°F. The ability to operate at these temperatures can significantly reduce any temperature pretreatment requirements necessary for successful operation. However, little cost information of this new fabric type is available, except that it is considerably more expensive than Teflon™.[12] Therefore, while the initial cost of the synthetic filter fabric is greater than the cost for natural fibers, the increased service life and improved operating characteristics of the synthetics make them a preferred choice in a wide range of industrial situations. Almost all of the filter fabrics can be constructed in either a woven or a felted manner (cotton and fiberglass can be constructed in a woven manner only). Woven fabrics are made up of yarn in one of a variety of patterns that allow spaces between the fibers, whereas felted fabrics are composed of a thick mat of randomly oriented fibers. When woven fabrics are new, particles penetrate the pores of the fabric fairly easily. As filtering continues, however, more particles are retained on the filter threads and on the particles already collected. If a woven fabric is equipped with a backing (e.g., Gore-Tex™), it performs more similarly to felted fabrics.

As this dust layer or "cake" builds up, particle penetration drops to a very low level. Cleaning of woven fabrics must be performed so that a layer of this dust cake remains on the fabric, enabling particle penetration to remain low.[1,5] Felted fabrics are thick enough that a dust cake does not need to remain on the fabric in order to maintain a good collection efficiency.[1,4] This difference between woven and felted fabrics has important implications for selection of fabric cleaning method, as described in Section 4.9.3.2, unless a suitable backing enables woven fabrics to perform similarly to felted.

Information on the maximum continuous operating temperature and resistance characteristics of commonly used filter fabrics is presented in Table 4.9-1. Knowing the emission stream characteristics, Table 4.9-1 can be used to select an appropriate fabric filter type (or types). Although the information presented is qualitative, Table 4.9-1 provides a good basis either for selecting a fabric or for evaluating the appropriateness of a fabric in a permit application.

When a number of fabrics are suitable for an application, the relative cost of the fabrics may be the key decision criterion. In general, ceramic, fluorocarbon, and nylon aromatic bags are the most expensive, followed by wool and fiberglass. The remaining commonly used synthetics are generally less expensive than fiberglass (polypropylene, polyester, acrylic, nylon polyamide, and modacrylic), while cotton is generally the least expensive fabric.[2,3,4,7]

4.9.3.2 Cleaning Method

As dust accumulates on the filtering elements, the pressure drop across the bag compartment increases until cleaning of the bags occurs. Usually a timer is used to control the cleaning cycle, or the pressure drop is monitored so that cleaning occurs when some maximum desirable value is reached. At this point the bags in the compartment are cleaned to remove the collected dust and the cycle is then repeated. The two basic mechanisms used to accomplish bag cleaning are flexing of the fabric to break up and dislodge the dust cake, and reversed air flow through the fabric to remove the dust.[1] These may be used separately or in conjunction with one another. The three principal methods used to accomplish fabric cleaning are mechanical shaking (manual or automatic), reverse air flow, and pulse-jet cleaning. The first method uses only the fabric flexing mechanism; the latter two methods use a combination of the reverse air flow and fabric flexing mechanisms.

Selection of a cleaning method is based on the type of fabric used, the pollutant collected, and the manufacturer's, vendor's, and industry's experiences. A poor combination of filter fabric and cleaning method can cause premature failure of the fabric, incomplete cleaning, or blinding of the fabric.[1] Blinding of a filter fabric occurs when the fabric pores are blocked and effective cleaning can not occur. Blinding can result because moisture blocks the pores or increases the adhesion of the dust, or because a high velocity gas stream imbeds the particles too deeply in the fabric.[1] The selection of a cleaning method may be based on cost, especially where more than one method is applicable. Table 4.9-2 contains a comparison of cleaning methods. Cleaning methods are discussed individually below.

With *mechanical shaking*, bags are hung on an oscillating framework that periodically shakes the bags at timed intervals or at a predefined pressure drop level.[1,3,6] The shaker mechanisms produce a violent action on the fabric filter bags and, in general, produce more fabric wear than the other types of cleaning mechanisms.[3] For

Table 4.9-1. Characteristics of Several Fibers Used in Fabric Filtration[a]

		Resistance[c]				
Fiber Type[b]	Max. Operating Temp., °F	Abrasion	Mineral Acids	Organic Acids	Alkalis	Solvent
Cotton[d]	180	VG	P	G	P	E
Wool[e]	200	F/G	VG	VG	P/F	G
Modacrylic[e] (Dynel™)	160	F/G	E	E	E	E
Polypropylene[e]	200	E	E	E	E	G
Nylon Polyamide[e] (Nylon 6 & 66)	200	E[f]	F	F	E	E
Acrylic[e] (Orlon™)	260	G	VG	G	F/G	E
Polyester[e]:						
Dacron[i]	275	VG	G	G	G	E
Creslan™	250	VG	G	G	G	E
Nylon Aromatic[e] (Nomex™)	375	E	F	G	E	E
Fluorocarbon[e] (Teflon™, TFE)	450	F/G	E[g]	E[g]	E[g]	E[g]
Fiberglass[d]	500	F/G[h]	G	G	G	E
Ceramics[j] (Nextel 312™)	900+	—	—	—	—	—

[a] References 4, 11, 12.
[b] Fabric limited.
[c] P = poor resistance, F = fair resistance, G = good resistance, VG = very good resistance, and E = excellent resistance.
[d] Woven fabrics only.
[e] Woven or felted fabrics.
[f] Considered to surpass all other fibers in abrasion resistance.
[g] The most chemically resistant of all these fibers.
[h] After treatment with a lubricant coating.
[i] Dacron™ dissolves partially in concentrated H_2SO_4.
[j] The ceramic fiber market is a very recent development. As a result, little information on long term resistance, and acid and alkali performance has been documented.

this reason, mechanical shaking is used in conjunction with heavier and more durable fabric materials, such as most woven fibers.[3,10] Bags with poor or fair abrasion ratings in Table 4.9-1 (e.g., fiberglass) should not be chosen for fabric filters cleaned by mechanical shaking unless they are treated with a special coating (i.e., a backing) before use. Although shaking is abrasive to the fabric, it does allow a dust cake to remain on the fabric, thus maintaining a high collection efficiency.

Bags are usually taken off-line for cleaning by mechanical shaking so that no gas flows through the bags being cleaned. Thus, reentrainment of particles is minimized. Because dust dislodgement is not severe (i.e., a light dust cake remains on the fabric), and because cleaning occurs off-line, outlet concentrations are almost constant with varying inlet dust loading and through entire cleaning cycles when using mechanical shaking.[1] Further, control efficiency is very high.[4] For these reasons, mechanical shaking is a good method to clean fabric filters controlling emissions containing HAPs.[4]

Table 4.9-2. Comparison of Fabric Filter Bag Cleaning Methods[a]

	Cleaning Method			
Parameter	Mechanical Shake	Reverse Airflow	Pulse-jet Individual Bags	Pulse-jet Compartmented Bags
Cleaning on- or off-line	Off-line	Off-line	On-line	Off-line
Cleaning time	High	High	Low	Low
Cleaning uniformity	Average	Good	Average	Good
Bag attrition	Average	Low	Average	Low
Equipment ruggedness	Average	Good	Good	Good
Fabric type[b]	Woven	Woven	Felt/ Woven[b]	Felt/ Woven[b]
Filter velocity	Average	Average	High	High
Power cost	Low	Low to Medium	High to Medium	Medium
Dust loading	Average	Average	Very high	High
Maximum temperature[c]	High	High	Medium	Medium
Collection efficiency	Good	Good	Good[d]	Good[d]

[a] Reference 4, 11, 12.
[b] With suitable backing, woven fabrics can perform similarly to felted.
[c] Fabric limited.
[d] For a properly operated system with moderate to low pressures, the collection efficiency may rival other methods.

Reverse air flow cleaning is used to flex or collapse the filter bags by allowing a large volume of low pressure air to pass countercurrent to the direction of normal gas stream flow during filtration.[3,6] Reverse air is provided either by a separate fan or by a vent in the fan damper, which allows a backwash of air to clean the fabric filters.[3,6] Reverse air flow cleaning usually occurs off-line. Reverse air cleaning allows the use of fragile bags, such as fiberglass, or lightweight bags, and usually results in longer life for the bags.[3] As with mechanical shaking, woven fabrics are used, and because cleaning is less violent than with pulse-jet cleaning and occurs off-line, outlet concentrations are almost constant with varying inlet dust loading and throughout the cleaning cycle. Reverse air flow cleaning is, therefore, a good choice for fabric cleaning in HAP control situations.

In *pulse-jet cleaning,* a high pressure air pulse is introduced into the bag from the top through a compressed air jet.[3,6] This rapidly expands the bag, dislodging the particles. Thus, the fabric is cleaned thoroughly through a vibration effect. The pulse of air cleans so effectively that no dust cake remains on the fabric to contribute to particulate collection. Because such a cake is essential for effective collection on woven fabrics, felted fabrics are generally used in pulse-jet cleaned fabric filters.[1] Alternatively, woven fabrics with a suitable backing may be used. All of the fabric materials may be used with pulse-jet cleaning except cotton or fiberglass. Previously, mechanical shaking was considered superior to pulse-jet in terms of collection efficiency. Recent advances in pulse-jet cleaning have resulted in efficiencies that may rival mechanical shaking.

Because the cleaning air pulse may be of such high pressure (up to 100 psi) and short duration (≤0.1 sec), cleaning may be accomplished on-line but off-line cleaning is also employed. Extra bags may not be necessary, therefore, to compensate for bags off-line during cleaning. Cleaning occurs more frequently tnan with mechanical shaking or reverse air flow cleaning, which permits higher air velocities (higher A/C ratios) than the other cleaning methods. Further, because the bags move less during cleaning, they may be packed more closely together. In combination, these features allow pulse-jet cleaned fabric filters to be installed in a smaller space, and thus, at a lower cost, than fabric filters cleaned by the other methods.[1,6] This cost savings may be somewhat counterbalanced by the greater expense and more frequent replacement required of bags, the higher power use that may occur, and the installation of the fabric filter framework that pulse-jet cleaning requires.[1,6]

In the past, pulse-jet systems have not been recommended for HAP applications. Reasons for this recommendation included particle reentrainment from the cleaning cycle, reduced filtering efficiency due to relatively little cake buildup, and the fact that pulse-jet system efficiency is strongly dependant on particle loading.

However, recent developments in pulse-jet cleaning have resulted in the use of lower pressure equipment. Several vendors now offer medium and low pressure equipment (10-50 psi) that reduce the particle reentrainment and hence increase the system efficiency. Moreover, pulse-jet systems can operate with efficiencies exceeding 99.9 percent. Little side by side comparison of performance with reverse air or mechanical shaking has been done. Therefore specific conclusions on relative performance between cleaning types cannot be made with a high degree of certainty. Based on the above, it is believed that pulse-jet cleaning can be used for HAP applications provided the system is properly designed and maintained.

4.9.3.3 Air-to-Cloth Ratio

The air-to-cloth (A/C) ratio, or filtration velocity, is a traditional fabric filter design parameter defined as the actual volumetric flow rate (acfm) divided by the total active, or net, fabric area (ft^2). The A/C ratio is an important indicator of the amount of air that can be filtered in a given time when considering the dust to be collected, cleaning method and fabric to be used, and the characteristics of the gas stream to be filtered for an individual situation. Selection of an appropriate range of A/C ratios is not based on any theoretical or empirical relationship, but, rather, is based on industry and fabric filter vendor experience from actual fabric filter installations. A ratio is usually recommended for a specific dust and a specific cleaning method. For typical design calculations, the A/C ratio must be obtained from the literature or the manufacturer.

The A/C ratio is difficult to estimate accurately from basic design equations. At best, a general indication of this ratio is obtained from hand calculations, and in fact tabulated values are frequently used to provide an approximation. More rigorous design procedures exist in available computer model programs. However, the purpose of this section is to provide the reader with some qualitative insight concerning the design and operation of fabric filters. Therefore, these programs are not discussed.

A summary of the ranges of recommended A/C ratios by typical bag cleaning method for many dusts and fumes is found in Table 4.9-3. These ranges are meant to serve as a guide; A/C ratios may vary from those reported. Fabric filter size and cost will vary with A/C ratio; lower A/C ratios, for example, will require that a larger and thus more expensive fabric filter be installed.

Table 4.9-3. Air-to-Cloth Ratios[a,b]

Dust	Shaker/Woven Reverse-Air/Woven	Pulse Jet/Felt
Alumina	2.5	8
Asbestos	3.0	10
Bauxite	2.5	8
Carbon black	1.5	5
Coal	2.5	8
Cocoa, chocolate	2.5	12
Clay	2.5	9
Cement	2.0	8
Cosmetics	1.5	10
Enamel frit	2.5	9
Feeds, grain	3.5	14
Feldspar	2.2	9
Fertilizer	3.0	8
Flour	3.0	12
Fly ash	2.5	5
Graphite	2.0	5
Gypsum	2.0	10
Iron ore	3.0	11
Iron oxide	2.5	7
Iron sulfate	2.0	6
Lead oxide	2.0	6
Leather dust	3.5	12
Lime	2.5	10
Limestone	2.7	8
Mica	2.7	9
Paint pigments	2.5	7
Paper	3.5	10
Plastics	2.5	7
Quartz	2.8	9
Rock dust	3.0	9
Sand	2.5	10
Sawdust (wood)	3.5	12
Silica	2.5	7
Slate	3.5	12
Soap detergents	2.0	5
Spices	2.7	10
Starch	3.0	8
Sugar	2.0	7
Talc	2.5	10
Tobacco	3.5	13
Zinc oxide	2.0	5

[a] Generally safe design values — application requires consideration of particle size and grain loading. A/C ratio units are $(\mathrm{ft^3/min})/(\mathrm{ft^2}$ of cloth area)

[b] Reference 11.

In addition to evaluating a particular fabric filter application, the A/C ratio and the emission stream flow rate ($Q_{e,a}$) are used to calculate net cloth area (A_{nc}).

$$\frac{Q_{e,a}}{\text{A/C ratio}} = A_{nc} \tag{4.9-1}$$

where:

$Q_{e,a}$ = emission stream flow rate at actual conditions, acfm

A/C ratio = air-to-cloth ratio, acfm/ft^2 or ft/min (from Table 4.9-3)

A_{nc} = net cloth area, ft^2

Net cloth area is the cloth area in active use at any point in time. Gross (or total) cloth area (A_{tc}), by comparison, is the total cloth area contained in a fabric filter, including that which is out of service at any point in time for cleaning or maintenance. In this manual, costing of the fabric filter structure and fabric filter bags uses gross cloth area. Table 4.9-4 presents factors to obtain gross cloth area from net cloth area:

$$A_{nc} \times \text{Factor} = A_{tc}$$

where:

Factor = value from Table 4.9-4, dimensionless

A_{tc} = gross cloth area, ft^2

Fabric filters with a higher A/C ratio require fewer bags to accomplish cleaning, and, therefore, require less space and may be less expensive. Other costs, such as more expensive (felted) bags, bag framework structure, use of increased pressure drop and corresponding increased power requirements, etc., may counterbalance to some degree the savings of high A/C ratio systems.

Table 4.9-4. Factors to Obtain Gross Cloth Area from Net Cloth Area[a]

Net Cloth Area, A_{nc} (ft^2)	Factor to Obtain Gross Cloth Area, A_{tc} (ft^2)
1 - 4,000	Multiply by 2
4,001 - 12,000	Multiply by 1.5
12,001 - 24,000	Multiply by 1.25
24,001 - 36,000	Multiply by 1.17
36,001 - 48,000	Multiply by 1.125
48,001 - 60,000	Multiply by 1.11
60,001 - 72,000	Multiply by 1.10
72,001 - 84,000	Multiply by 1.09
84,001 - 96,000	Multiply by 1.08
96,001 - 108,000	Multiply by 1.07
108,001 - 132,000	Multiply by 1.06
132,001 - 180,000	Multiply by 1.05

[a] Reference 11.

4.9.3.4 Baghouse Configuration

The basic configuration of a baghouse varies according to whether the gases are pushed through the system by a fan located on the upstream side (forced draft fan), or pulled through by locating the fan on the downstream side (induced draft fan). A baghouse using forced draft fans is called a positive-pressure baghouse; one using induced draft fans is called a negative-pressure or suction baghouse. Positive-pressure baghouses may be either open to the atmosphere or closed (sealed and pressure-isolated from the atmosphere). Negative pressure baghouses can only be of the closed type. Only the closed suction design should be selected for a HAP application to prevent accidental release of captured pollutants.[6] The lower the gas stream dew point, the greater the precaution that must be taken to prevent condensation, which can moisten the filter cake, plug the cloth, and promote corrosion of the housing and hoppers. In a suction-type fabric filter, infiltration of ambient air can occur, which can lower the temperature below design levels.

Therefore, the structure walls and hoppers of this type of baghouse should be insulated to minimize the possibility of condensation.

4.9.3.5 Materials of Construction

The most common material used in fabric filter construction is carbon steel. In cases where the gas stream contains high concentrations of SO_3 or where liquid-gas contact areas are involved, stainless steel may be required. Stainless steel will increase the cost of the fabric filter significantly when compared to carbon steel.[3] However, by keeping the emission stream temperature above the dew point and by insulating the baghouse, the use of stainless steel should not be necessary.

Example Case

Recall that the emission stream temperature is 400°F, the SO_3 content is 200 ppmv, and the particulate type is flyash. Table 4.9-1 indicates that filter fabrics capable of withstanding a 400°F emission stream temperature are ceramics (Nextel 312™), nylon aromatic (Nomex™), fluorocarbon (Teflon™), and fiberglass. Because there is a high potential for acid damage (i.e., a high SO_3 content), however, Nomex bags should not be considered. To obtain an indication of the A/C ratio, use Table 4.9-3. This table shows that an A/C ratio of around 2.5 is expected for mechanical shaking or reverse air cleaning, and an A/C ratio of about 5.0 is expected for pulse jet cleaning.

A fiberglass bag would provide the most protection during temperature surges (unless ceramics are used), and because fiberglass bags may be less expensive, it may be the fabric of choice for an installation with these emissions characteristics. Fiberglass bags would require that reverse air cleaning be used, unless a suitable backing allows pulse-jet cleaning. Teflon™ bags with mechanical shaking could also be a possibility (References 4,5). Little information on the long-term effectiveness of ceramics has been documented. It is expected that ceramic fibers will have performance characteristics similar to the best synthetic fibers, but will likely cost significantly more.

4.9.4 Determination of Baghouse Operating Parameters

Many times, optimization of a fabric filter's collection efficiency occurs in the field after construction. The following discussion does not pertain to the preliminary design of a fabric filtration control system; however, the information presented should be helpful in achieving and maintaining the desired collection efficiency for the installed control system.

4.9.4.1 Collection Efficiency

To discuss fabric filter "collection efficiency" is somewhat of a misnomer because a properly operated system yields fairly constant outlet concentrations over a broad range of inlet loadings. As such, the system really does not operate as an efficiency device and outlet concentrations are not a strong function of inlet loading. Typical outlet concentrations range between 0.001 to 0.01 gr/dscf, averaging around 0.003 - 0.005 gr/dscf.[15] However, the term "collection efficiency" can be applied to a fabric filter system when describing performance for a given application. For example, the outlet concentrations given above will usually correspond to very high collection efficiencies.

A well designed fabric filter can achieve collection efficiencies in excess of 99 percent, although optimal performance of a fabric filter system may not occur for a number of cleaning cycles as the new filter material achieves a cake buildup. The fabric filter collection efficiency is related to the pressure drop across the system, component life, filter fabric, cleaning method and frequency, and A/C ratio. These operating parameters should be modified as discussed below if fabric filter performance is less than desired or required. Modifications to improve performance include changing the A/C ratio, using a different fabric material, replacing worn or leaking filter bags, and/or modifying the inlet plenum to ensure the gas stream is evenly distributed within the baghouse. Collection efficiency also can be improved by decreasing the frequency of cleaning or allowing the system to operate over a greater pressure drop before cleaning is initiated.

4.9.4.2 System Pressure Drop

The pressure drop across the operating fabric filter system is a function of the difficulty with which the gas stream passes through the filter bags and accumulating dust cake, how heavy the dust deposit is prior to bag cleaning, how efficient cleaning is, and if the filter bags are plugged or blinded. Normally, the value of this parameter is set between 5 to 20 inches of water. In actual operation, variations in pressure drop outside of the design range may be indicative of problems within the fabric filter system. Higher than expected pressure differentials may indicate: (1) an increase in gas stream volume; (2) blinding of the filter fabric; (3) hoppers full of dust, thus blocking the bags; and/or (4) inoperative cleaning mechanism. Lower than expected pressure differentials may indicate: (1) fan or motor problems, (2) broken or unclamped bags, (3) plugged inlet ducting or closed damper, and/or (4) leakage between sections of the baghouse. For these reasons it is recommended that the system pressure drop be monitored continuously.

As the dust cake builds up during filtration, both the collection efficiency and system pressure drop increase. As the pressure drop increases toward a maximum, the filter bags (or at least a group of the bags contained in one isolated compartment) must be cleaned to reduce the dust cake resistance. This cleaning must be timed and performed so as to accomplish the following: (1) to keep the pressure drop and thus operating costs, within reasonable limits; (2) to clean bags as gently and/or infrequently as possible to minimize bag wear and to maximize efficiency; and (3) to leave a sufficient dust layer on the bags to maintain filter efficiency and to keep the instantaneous A/C ratio immediately after cleaning from reaching excessive levels, if woven fabric with no backing is used.

In practice, these various considerations are balanced using engineering judgment and field trial experience to optimize the total system operation. Changes in process or in fabric condition through fabric aging will cause a shift in the cleaning requirements of the system. This shift may require more frequent manual adjustments to the automatic control to achieve the minimum cleaning requirements.

4.9.5 Evaluation of Permit Application

Using Table 4.9-5, compare the results from this section and the data supplied by the permit applicant. The calculated values are based on the example case. As pointed out in the discussion on fabric filter design considerations, the basic design parameters are generally selected without the involved, analytical approach that characterizes many other control systems. Therefore, in evaluating the reasonableness of any system specifications on a permit application, the reviewer's main task will be to examine each parameter in terms of its compatibility with the gas stream and particulate conditions and with the other selected parameters. The following questions should be asked:

1. Is the temperature of the emission stream entering the baghouse within 50 to 100°F above the stream dew point?
2. Is the selected fabric material compatible with the conditions of the emission stream; that is, temperature and composition (see Table 4.9-1)?
3. Is the baghouse cleaning method compatible with the selected fabric material and its construction; that is, material type and woven or felted construction (see Section 4.9.3.2 and Table 4.9-2)?
4. Will the selected cleaning mechanism provide the desired control?
5. Is the A/C ratio appropriate for the application; that is, type of dust and cleaning method used (see Table 4.9-3)?
6. Are the values provided for the gas flow rate, A/C ratio, and net cloth area consistent? The values can be checked with the following equation:

$$A/C\ ratio = \frac{Q_{e,a}}{A_{n,c}}$$

where: A/C ratio = air-to-cloth ratio, ft/min

$Q_{e,a}$ = emission stream flow rate at actual conditions, acfm

A_{nc} = net cloth area, ft^2

7. Is the baghouse configuration appropriate; that is, is it a negative-pressure baghouse?

A particular manufacturer/customer combination may employ somewhat different criteria in their selection of design parameters (such as lower annualized costs of operation at the expense of higher initial costs), and so a departure from the "rules-of-thumb" discussed here may still be compatible with achieving the needed high collection efficiencies. Further discussions with the permit applicant are recommended to evaluate the design assumptions and to reconcile any apparent discrepancies with usual practice.

4.9.6 Capital and Annual Costs of Fabric Filters

Once the equipment has been sized, a study type cost estimate can be obtained using the procedures below. The procedure involves estima-ting the capital cost of a system using a factored approach and obtaining the annualized costs by summing the direct and indirect annual costs.

Table 4.9-5. Comparison of Calculated Values and Values Supplied by the Permit Applicant for Fabric Filters

Process Variables	Calculated Value (Example Case)[a]	Reported Value
Continuous monitoring of system pressure drop and stack opacity	yes	. . .
Emission stream temp. range[b]	365 - 415°F	. . .
Selected fabric material	fiberglas or Teflon™	. . .
Baghouse cleaning method	mechanical shaking, reverse air flow, pulse-jet	. . .
A/C ratio	2.5 ft/min for mechanical shaking or reverse air; 5 ft/min for pulse-jet	. . .
Baghouse configuration	negative pressure	. . .

[a] Based on the municipal incinerator emission stream.
[b] See Section 3.3.1.

4.9.6.1 Total Capital Costs

Total capital costs includes costs for the baghouse structure, the initial complement of bags, auxiliary equipment, and the usual direct and indirect costs associated with installing or erecting new structures. These costs are described below, and may be escalated if desired. The example case assumes that escalation is not necessary.

Structure Cost

A guide to estimate the costs of six types of bare fabric filter systems, which were taken from Reference 11, is provided in Table 4.9-6.

Each figure gives costs for the filter without bags and additional costs for stainless steel construction and for insulation. Extrapolation of these lines is not recommended. All units include unit and exhaust manifolds, supports, platforms, handrails, and hopper discharge devices. The indicated prices are flange to flange. Note that the scales on axes differ.

Table 4.9-6. Guide to Estimate Costs of Bare Fabric Filter Systems

Operation	Cleaning Mechanism	Figure
Preassembled Units		
Intermittent	Shaker	4.9-1
Continuous	Shaker	4.9-2
Continuous	Pulse-jet (common housing)	4.9-3
Continuous	Pulse-jet (modular)	4.9-4
Continuous	Reverse-air	4.9-5
Field-assembled units		
Continuous	Any method	4.9-6

The 304 stainless steel add-on cost is used when stainless steel is necessary to prevent the exhaust stream from corroding the interior of the baghouse as mentioned previously. Stainless steel is substituted for all metal surfaces that are in contact with the exhaust gas stream.

Insulation costs are for 3 inches of shop-installed glass fiber encased in a metal skin. One exception is the custom baghouse, which has field-installed insulation. Costs for insulation include only the flange-to-flange baghouse structure on the outside of all areas in contact with the exhaust gas stream. Insulation for ductwork, fan casings, and stacks must be calculated separately as discussed later.

The costs for intermittent service, mechanical shaker baghouses (including the shaker mechanism) as a function of gross cloth area required are presented in Figure 4.9-1. Because intermittent service baghouses do not require an extra compartment for cleaning, gross and net fabric areas are the same.

The same costs for a continuously operated baghouse cleaned by mechanical shaker as a function of the gross cloth area are presented in Figure 4.9-2. As in Figure 4.9-1, the units are modular in construction. Costs for these units, on a square foot basis, are higher because of increased complexity and generally heavier construction.

Costs of common-housing pulse-jets units and modular pulse-jet units are presented in Figures 4.9-3 and 4.9-4. Modular units are constructed of separate modules that may be arranged for off-line cleaning, while common-Housing units have all bags within one housing. The cleaning system compressor is not included. Because the common housing is relatively inexpensive, the stainless steel add-on is proportionately higher than for modular units. Added material costs and set-up and labor charges associated with the less workable stainless steel account for most of the added expense.

The costs for the reverse-air baghouses are shown in Figure 4.9-5.[15] The construction is modular and the reverse-air fan is included. Costs for custom baghouses which must be field assembled because of their large size are given in Figure 4.9-6. These units often are used on power plants, steel mills, or other applications too large for the factory-assembled baghouses.

Bag Costs, C_B

The price per square foot (in 3rd quarter 1986 dollars) of bags by type of fabric and by type of cleaning system used is given in Table 4.9-7. The prices represent about a 10 percent range. In calculating the cost, the gross area as determined from Table 4.9-4 should be used. These costs should be escalated using the index provided in Table 4.12-1. Gore-Tex™ fabric costs are a combination of the base fabric cost and a premium for the PTFE laminate and its application. As fiber market conditions change, the costs of fabrics relative to each other also change. The bag prices are based on typical fabric weights, in ounces/square yard, for the fabric being priced. Sewn-in snap rings are included in the price, but other mounting hardware, such as clamps or cages, is an added cost. Reference 11 can be used to obtain the cost cages, flow control venturis, and other bag hardware.

Purchased Equipment Cost (PEC) and Total Capital Costs (TCC)

The purchased equipment cost (PEC) of the fabric filter system is the sum of the costs of the baghouse, bags, auxiliary equipment, instruments and controls, and taxes and freight costs. The factors necessary to estimate these costs are presented in Table 4.9-8. Section 4.12 can be used to estimate the cost of auxiliary equipment. The factors necessary to estimate the remaining direct and indirect capital costs to obtain total capital costs are provided in Table 4.9-8.

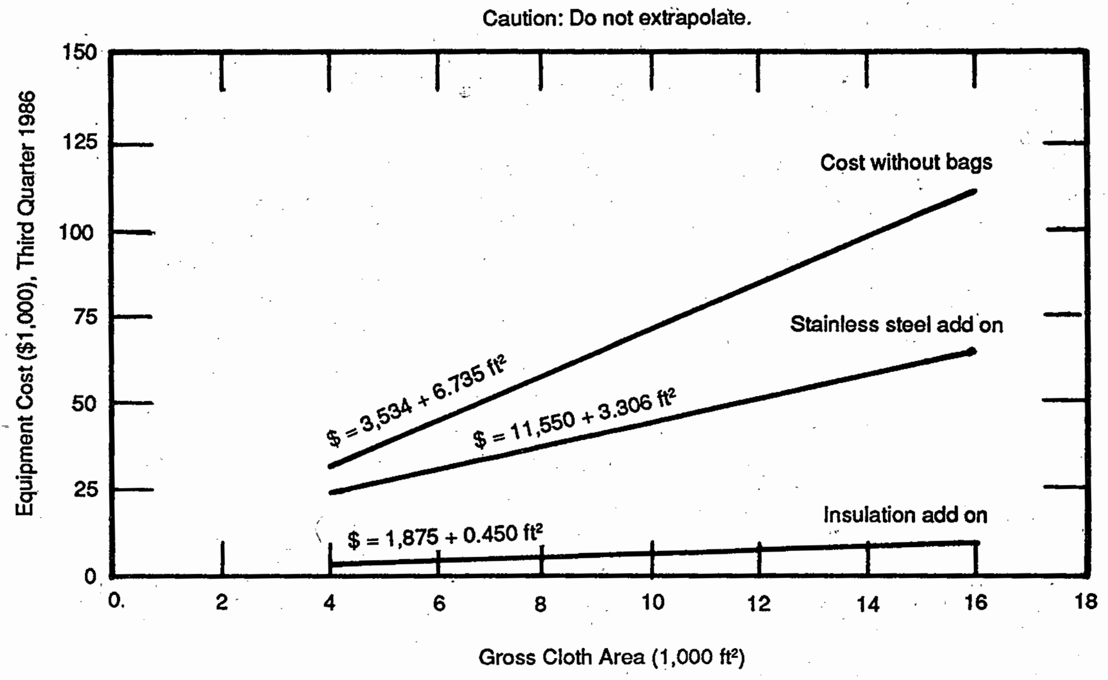

Figure 4.9-1. **Structure costs for intermittent shaker filters.**

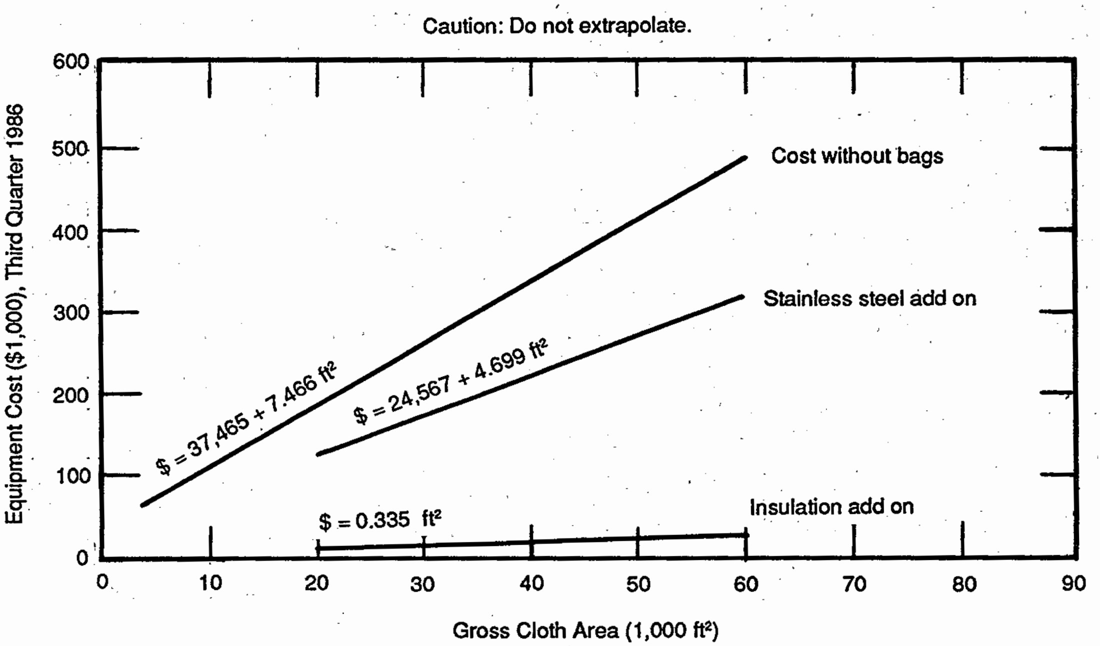

Figure 4.9-2. **Structure costs for continuous shaker filters.**

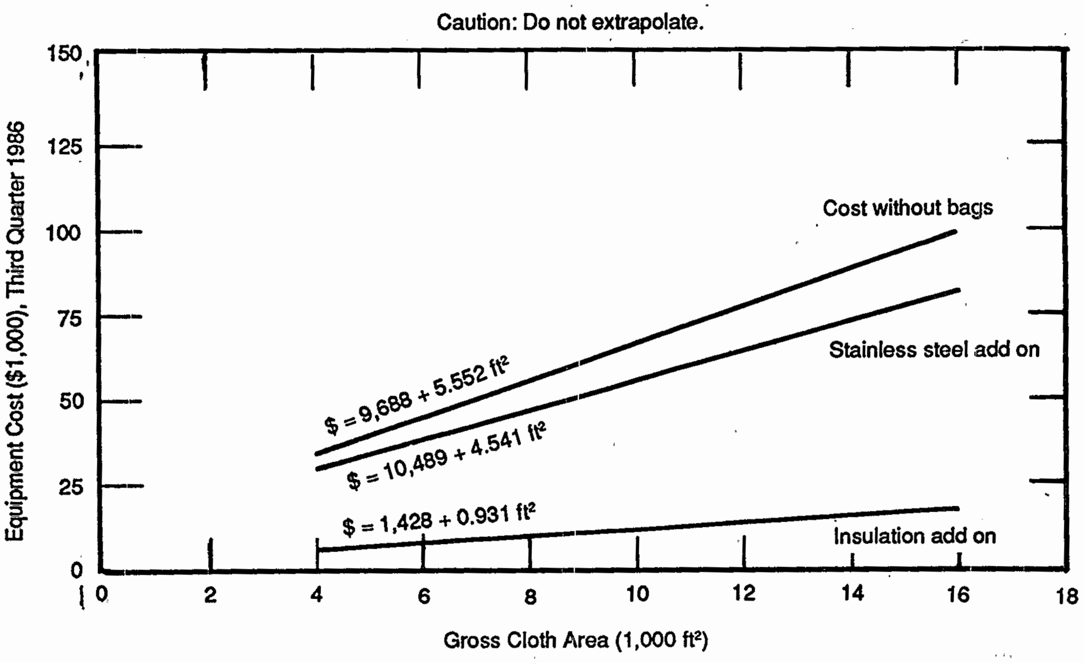

Figure 4.9-3. Structure costs for pulse-jet filters (common housing).

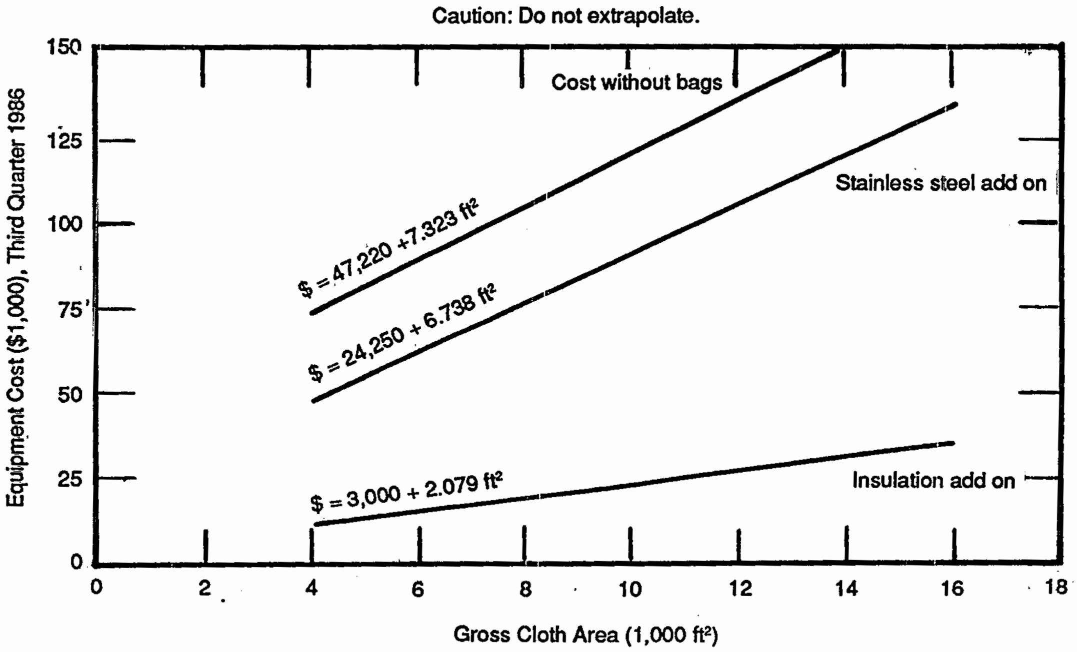

Figure 4.9-4. Structure costs for pulse-jet filters (modular).

Caution: Do not extrapolate.

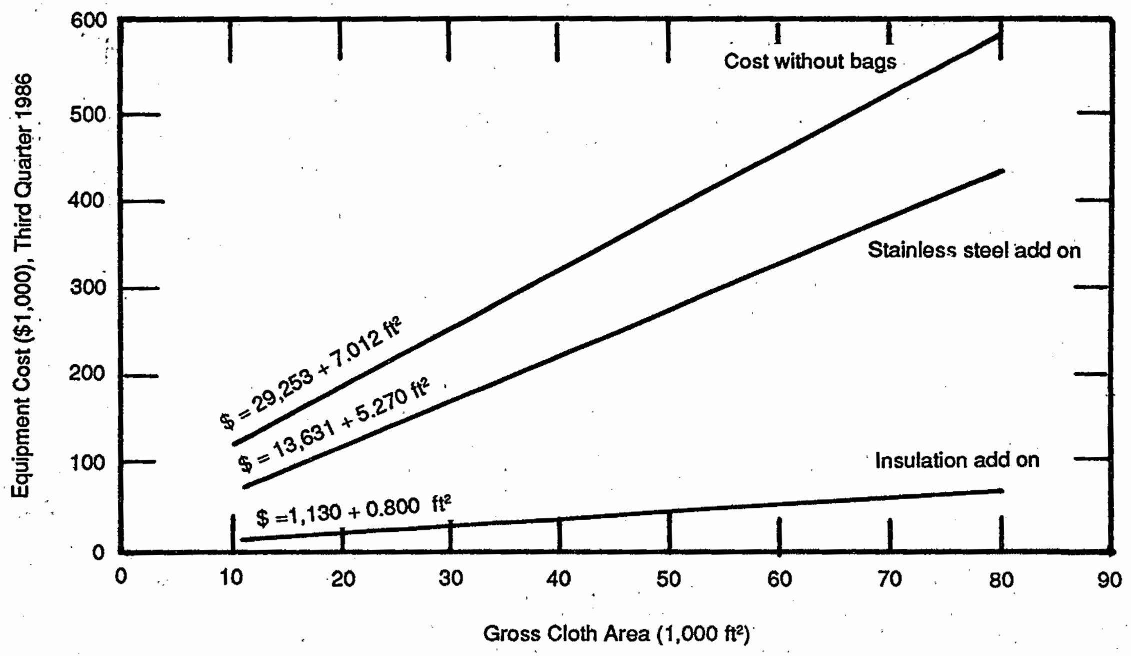

Figure 4.9-5. **Structure costs for reverse-air filters.**

Caution: Do not extrapolate.

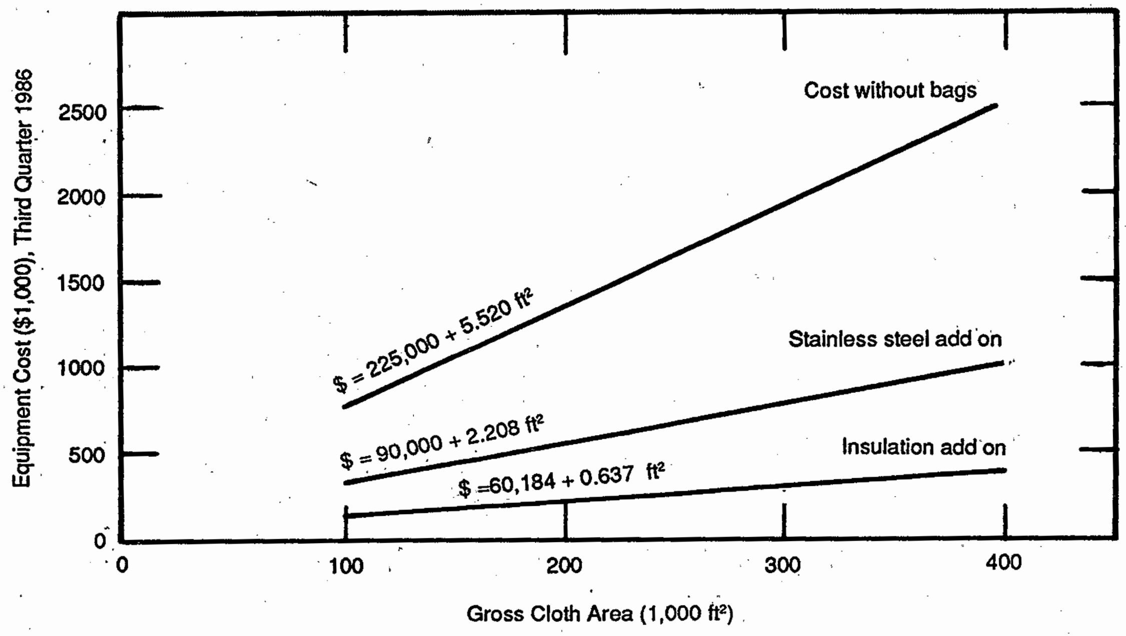

Figure 4.9-6. **Structure costs for custom-built filters.**

Table 4.9-7. Bag Prices[a] (3rd quarter 1986 $/ft^2)

Type of Cleaning	Bag Diameter (inches)	Type of Material[b] PE	PP	NO	HA	FG	CO	TF
Pulse jet, TR[c]	4-1/2 to 5-1/8	0.59	0.61	1.88	0.92	1.29	NA	9.05
	6 to 8	0.43	0.44	1.56	0.71	1.08	NA	6.80
Pulse jet, BBR	4-1/2 to 5-1/8	0.37	0.40	1.37	0.66	1.24	NA	8.78
	6 to 8	0.32	0.33	1.18	0.58	0.95	NA	6.71
Shaker								
Strap top	5	0.45	0.48	1.28	0.75	NA	0.44	NA
Loop top	5	0.43	0.45	1.17	0.66	NA	0.39	NA
Reverse air with rings	8	0.46	NA	1.72	NA	0.99	NA	NA
Reverse air w/o rings[d]	8	0.32	NA	1.20	NA	0.69	NA	NA
	11-1/2	0.32	NA	1.16	NA	0.53	NA	NA

NA = Not applicable.

[a] Reference 11.

[b] Materials:

PE = 16-oz polyester
PP = 16-oz polypropylene
NO = 14-oz nomex
HA = 16-oz homopolymer acrylic
FG = 16-oz fiberglass with 10% Teflon™
CO = 9-oz cotton
TF = 22-oz Teflon™ felt

[c] Bag removal methods:

TR = Top bag removal (snap in)
BBR = Bottom bag removal

[d] Identified as reverse-air bags, but used in low pressure pulse applications.

Note: For pulse-jet baghouses, all bags are felts except for the fiberglass, which is woven. For bottom access pulse-jets, the cage price for one cage can be calculated from the single-bag fabric area using:

In 50 cage lots	$ = 4.941 + 0.163 ft^2	$ = 23.335 + 0.280 ft^2
In 100 cage lots	$ = 4.441 + 0.163 ft^2	$ = 21.791 + 0.263 ft^2
In 500 cage lots	$ = 3.941 + 0.163 ft^2	$ = 20.564 + 0.248 ft^2

These costs apply to 4-1/2-in. or 5-5/8-in. diameter, 8-ft and 10-ft cages made of 11 gauge mild steel and having 10 vertical wires and "Roll Band" tops. For flanged tops, and $1 per cage. If flow control venturis are used (as they are in about half of the pulse-jet manufacturers' designs), add $5 per cage.

For shakers and reverse air baghouses, all bags are woven. All prices are for finished bags, and prices can vary from one supplier to another. For Gore-Tex™ bag prices, multiply base fabric price by factors of 3 to 4.5.

Example Case

Assume a reverse air baghouse is proposed. Figure 4.9-5 is used for the cost of the baghouse structure. For purposes of illustration, assume the structure requires stainless steel add-on and insulation. The first step is to calculate the total, or gross cloth area.

From Table 4.9-3, Flyash, the A/C ratio = 2.5
Thus A_{nc} = (110,000 acfm)/2.5 = 44,000 ft^2

Obtain the total cloth area using Table 4.9-4. This table indicates A_{nc} should be multiplied by 1.125 to obtain A_{tc}. Thus, A_{tc} = 44,000 (1.125) = 49,500 ft^2. This value is used to obtain the structure cost.

Using Figure 4.9-5 the structure cost equals $380,000 plus $270,000 for stainless steel add-on, plus $40,000 for insulation. The total cost is then $380,000 + $270,000 + $40,000 = $690,000.

Example Case (Cont'd)

Table 4.9-7 is used to obtain the bag cost, C_B. From the example case in Section 4.9-3, choose fiberglass bags with Teflon backing. Assume the bag diameter is 8 inches with rings. The bag cost is given as $0.99/ft^2 (49,500) = $49,000.

Assume auxiliary equipment costs obtained from Section 4.12 are $10,000. The equipment cost (EC) is then $690,000 + $49,000 + $10,000 = $749,000. Table 4.9-8 is used to obtain the purchased equipment cost, PEC as shown below:

Instrumentation = 0.10 (EC) = $74,900
Taxes = 0.03 (EC) = $22,500
Freight = 0.05 (EC) = $37,500

The purchased equipment cost (PEC) is then: $749,000 + $74,900 + $22,500 + $37,500 = $884,000. Table 4.9-8 is then used to obtain the total capital cost (TCC) of the baghouse system. These costs are given in Table 4.9-9.

Table 4.9-8. Capital Cost Factors for Fabric Filters[a]

Direct Costs	Factor
Purchased Equipment Costs:	
Fabric filter	As estimated
Bags	As estimated
Auxiliary equipment	As estimated (EC = Sum of As estimated)
Instruments & controls	0.10 EC
Taxes	0.03 EC
Freight	0.05 EC
Purchased Equipment Cost, PEC	PEC = 1.18 EC
Installation Direct Costs	
Foundation & supports	0.04 PEC
Erection & handling	0.50 PEC
Electrical	0.08 PEC
Piping	0.01 PEC
Insulation for ductwork[b]	0.07 PEC
Painting[c]	0.02 PEC
Site preparation (SP)	As required
Buildings (Bldg.)	As required
	0.72 PEC + SP +Bldg.
Total Direct Cost, DC	1.72 PEC +SP + Bldg.
Indirect Costs	
Engineering & supervision	0.10 PEC
Construction and field expense	0.20 PEC
Construction fee	0.10 PEC
Start-up fee	0.01 PEC
Performance test	0.01 PEC
Contingencies	0.03 PEC
Total Indirect Cost, IC	0.45 PEC
Total Capital Cost (TCC) = DC + IC	2.17 PEC + SP + Building

[a] Reference 11.

[b] If ductwork dimensions have been established, cost may be established based on \$10 to \$12/ft^2 of surface for field application. Fan housings and stacks may also be insulated.

[c] The increased use of special coatings may increase this factor to 0.06 PEC or higher.

4.9.6.2 Annualized Costs for Fabric Filter Systems

The annual costs for a fabric filter system consist of the direct and indirect operating costs these costs are discussed in more detail below. Table 4.9-10 provides the cost factors used to estimate annual costs.

Direct Costs. Direct costs include utilities (electricity, replacement bags, compressed air), operating labor, and maintenance costs.

The cost of electricity is largely a function of the fan power requirement. Equation 4.9-2 can be used to estimate this requirement assuming a 65 percent fan-motor efficiency and a fluid specific gravity of 1.00.

$$F_p = 1.81 \times 10^{-4} (Q_{e,a})(P)(HRS) \qquad (4.9\text{-}2)$$

where:

F_p = fan power requirement, kWh/yr

$Q_{e,a}$ = emission stream flow rate, acfm

P = system pressure drop, in. H_2O

HRS = operating hours,hrs/yr

For mechanical shaking, the additional power requirement can be estimated using Equation 4.9-3.

$$P_{ms} = 6.05 \times 10^{-6} (HRS)(A_{tc}) \qquad (4.9\text{-}3)$$

where:

P_{ms} = mechanical shaking power requirement, kWh/yr

A_{tc} = gross cloth area, ft^2

The annual electricity cost is calculated as the sum of F_p and P_{ms} multiplied by the cost of electricity given in Table 4.9-10.

For a pulse-jet system, the consumption of compressed air is about 2 scfm/1,000 scfm of the emission stream. For example, a 100,000 scfm stream will consume about 200 scfm. This would then need to be multiplied by both 60 and by HRS to obtain the total yearly consumption. This value is then multiplied by the cost of compressed air given in Table 4.9-10 to obtain annual costs. For other cleaning mechanisms, this consumption is assumed to be zero.

The cost of replacement bags is obtained from Equation 4.9-4.

$$C_{RB} = [C_B + C_L]\, CRF_B \qquad (4.9\text{-}4)$$

where:

C_{RB} = bag replacement cost, \$/yr

C_B = initial bag cost, \$

C_L = bag replacement labor, \$ (C_L = \$0.14 A_{nc})

CRF_B = capital recovery factor, 0.5762 (indicates a two year life, 10 percent interest)

The bag replacement labor cost depends on such factors as the number, size, and type of bags, the accessibility of the bags, how they are connected to the tube-sheet, etc. As such, these costs are highly variable. For simplicity, assume a conservatively high cost of \$0.14/ft^2 net bag area, per EPA guidance.[11]

The cost of operating labor is estimated from a labor requirement of 3 hours per 8 hour shift and the operator labor wage rate provided in Table 4.9-10. Supervisory costs are taken as 15 percent of operator labor costs.

The cost of maintenance is estimated from a maintenance labor requirement of 1 hour per 8 hour shift and

Table 4.9-9. Example Case Capital Costs

Direct Costs	Factor	Cost($)
Purchased Equipment Costs:		
Fabric filter	As estimated	$ 690,000
Bags	As estimated	49,000
Auxiliary equipment	As estimated	10,000
	(EC=Sum of As estimated)	$ 749,000
Instruments & controls	0.10 EC	$ 74,900
Taxes	0.03 EC	22,500
Freight	0.05 EC	37,500
Purchased Equipment Cost, PEC	PEC = 1.18 EC	$ 884,000
Installation Direct Costs		
Foundation & supports	0.04 PEC	$ 35,400
Erection & handling	0.50 PEC	442,000
Electrical	0.08 PEC	70,700
Piping	0.01 PEC	8,840
Insulation for ductwork[b]	0.07 PEC	61,900
Painting[c]	0.02 PEC	17,700
Site preparation (SP)	As required	—
Buildings (Bldg.)	As required	—
	0.72 PEC + SP + Bldg.	$ 636,000
Total Direct Costs	1.72 PEC + SP + Bldg.	$ 1,520,000
Indirect Costs		
Engineering & supervision	0.10 PEC	$ 88,400
Construction and field expense	0.20 PEC	177,000
Construction fee	0.10 PEC	88,400
Start-up fee	0.01 PEC	8,840
Performance test	0.01 PEC	8,840
Contingencies	0.03 PEC	26,500
Total Indirect Cost	0.45 PEC	$ 398,000
Total Direct and Indirect Cost = Total Capital Cost (TCC)	2.17 PEC + SP + Bldg.	$ 1,920,000

Table 4.9-10. Annual Costs for Fabric Filters[a]

Cost Item	Factor
Direct Costs, DAC	
Utilities	
Electricity	$0.059/kWh
Compressed air	$0.16/$10^3$ scfm
Replacement Parts, bags	See Section 4.9.6.2
Operating Labor	
Operator	$12.96/hr
Supervisor	15% of operator labor
Maintenance	
Labor	$14.26/hr
Material	100% of maintenance labor
Waste Disposal	Variable. See Section 4.9.6.2
Indirect Costs, IAC	
Overhead	0.60 (Operating labor + maintenance)
Administrative	2% of TCC
Property tax	1% of TCC
Insurance	1% of TCC
Capital recovery[b]	0.1175 (TCC - 0.05C_L - 1.08 C_B)

[a] Reference 11.

[b] Capital recovery factor is estimated as: $i(1+i)^n/(1+i)^n-1$
where: i = interest rate, 10 percent
n = equipment life, 20 years

the wage rate provided in Table 4.9-10. The cost of maintenance materials is assumed to equal the maintenance labor costs.

The cost of dust disposal will vary widely from site to site. The reader should make every effort to obtain accurate costs for this item as this cost will typically be large. Typical costs fall between $20/ton and $30/ton for non-hazardous waste, while hazardous material costs can be 10 times this amount.[11]

Indirect Costs. Indirect costs consist of overhead, administrative costs, property taxes, insurance, and capital recovery. Table 4.9-10 provides the appropriate factors to estimate these costs.

Example Case

Direct Annual Costs

Electricity usage is estimated using Equation 4.9-2. Assume the system pressure drop equals 10 inches H_2O.

F_p = 1.81 x 10^{-4} (110,000) (10) (6,000)
= 1.19 x 10^6

Electricity cost = $0.059 (1.19 x 10^6) = $70,200/yr

Example Case (Cont'd)

Since reverse air is used, $P_{ms} = 0$.
Bag replacement costs are obtained using Equation 4.9-4.

$$C_{RB} = [49{,}000 + 0.14\,(44{,}000)]\,0.5762 = \$31{,}800/\text{yr}$$

Operating labor costs are estimated as:
[(3 hr/shift)/(8 hr/shift)] 6,000 hr/yr = 2,250 hr/yr
2,250 hr/yr ($12.96/hr) = $29,200/yr

Supervisory costs are taken as 15 percent of this total, or $4,370.

Maintenance labor costs are estimated as:
[(1 hr/shift)/8 (hr/shift)]/6,000 hr/yr = 750 hr/yr
750 hr/yr ($14.26/hr) = $10,700/yr

Maintenance materials are taken as 100 percent of this total, or $10,700.

$$\text{Waste Disposal: } 3.2\ \frac{\text{gr}}{\text{ft}^3} \times \frac{1\ \text{lb}}{7000\ \text{gr}} \times \frac{110{,}000\ \text{ft}^3}{\text{min}}$$

$$\times \frac{60\ \text{min}}{\text{hr}} \times \frac{6000\ \text{hr}}{\text{yr}} = 1.81 \times 10^7\ \text{lb/yr}$$

$$1.81 \times 10^7\ \frac{\text{lb}}{\text{yr}} \times \frac{\text{ton}}{2000\ \text{lb}} \times \frac{200}{\text{ton/yr}} = \$1{,}810{,}000$$

Total Direct Annual Costs =

$70,200 + $31,800 + $29,200 + $4,370 + $10,700 + $10,700 + $1,810,000 = $1,970,000

Indirect Annual Costs

These costs are obtained from the factors presented in Table 4.9-10 and the example case presented above.

Overhead = 0.60 ($29,200 + $4,370 + $10,700 + $10,700) = $33,000
Administrative = 0.02 ($1,920,000) = $38,400
Insurance = 0.01 ($1,920,000) = $19,200
Property taxes = 0.01 ($1,920,000) = $19,200
Capital recovery = 0.1175 ($1,920,000) - 1.08 ($49,000) - 0.05 ($0.14)(44,000) = $219,000
Total Indirect Costs = $33,000 + $38,400 + $19,200 + $19,200 + $219,000 = $329,000
Total Annual = $1,970,000 + $329,000
Costs = $2,200,000/yr

4.9.7 References

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4.10 Electrostatic Precipitators

Electrostatic precipitators (ESPs) use an electrostatic field to charge particulate matter contained in the gas stream. The charged particles then migrate to a grounded collecting surface. The collected particles are dislodged from the collector surface periodically by vibrating or rapping the collector surface, and subsequently collected in a hopper at the bottom of the ESP. ESPs typically have a high collection efficiency and are very efficient at controlling submicron (<1.0 um) particles common to metal fumes, for example.

Two basic types of ESPs are: single stage and two stage.[1,2] In the single stage precipitator, which may be wet or dry, ionization and collection are combined, whereas in the two stage precipitator, ionization and collection are done in separate steps. Dry, single stage ESPs are the most common. Several specific types of the single stage ESP are employed. These include the plate wire type (the most common), the flat plate, and the tubular. Wet electrostatic precipitators, while not as common as dry ESPs, can be used to remove both solid and gaseous pollutants and are less sensitive to particle resistivity characteristics as discussed in Section 4.10-3. A brief description of these precipitator types follows.

In a *plate wire ESP,* gases flow between parallel plates of sheet metal and high voltage electrodes. The electrodes consist of long weighted wires hanging between the plates and supported by rigid frames. The gases must pass through the wires as they traverse the ESP unit. This configuration allows many parallel lanes of flow and is well suited for handling large volumes of gas. The cleaning and power supplies for this type are often sectioned, to improve performance. The plate wire ESP is the most popular type.

Flat plate ESPs differ from plate wire types in that the electrodes consist of flat plates rather than wires. A number of smaller precipitators use flat plates instead of wires. These plates increase the average electric field used to collect particles,and provide increased surface collection area, relative to plate wires. A flat plate ESP operates with little or no corona (a region of gaseous ions) which leads to high rapping losses particularly if the emission stream velocity is high. These ESPs perform well with small, high resistivity particles provided the velocity is low.

Tubular ESPs are the oldest type and the least common. Tubular ESPs are typically used in sulfuric acid plants, coke oven by product gas cleaning (tar removal), and iron and steel sinter plants. The tube is usually a circular, square, or hexagonal honeycomb with gas flowing lengthwise through the system. The tubular ESP is most commonly applied where the particles are wet or sticky.

The *two stage ESP* is a series device where the first unit is responsible for ionization, and the second for collection. This results in more time for particle changing and economical construction for smaller (≤50,000 acfm) applications. Two stage units are often used to collect oil mists, smokes, fumes and other sticky particulates because there is little electrical force to hold the collected particles onto the plates.

Ionizing wet scrubbers (IWS) also may be used as a particulate control device. An IWS combines the principle of wet electrostatic particle charging with packed bed scrubbing into a two-stage collection system.[8] Note however, that IWS technology is not the same as a two-stage ESP. A constant DC voltage is applied to the ionizing section, which the emission stream passes through before introduction to the scrubbing section. The electrostatic plates in the ionizing section are continually flushed with water to prevent resistive layer buildup. The cleaned gas exiting the ionizing section is further scrubbed in a packed bed section. Unlike dry ESPs, IWSs are fairly insensitive to particle resistivity. For best performance of IWSs, monitoring of plate voltage and packed bed scrubbing water is recommended. Design and cost equations for this technology are not included, but it is mentioned here to introduce the reader with this emerging technology.

A rigorous design of a given ESP system can become quite complex as it normally includes a consideration of electrical operating points (voltages and currents), particle charging, particle collection, and sneakage and rapping reentrainment. For purposes of this handbook, a simplified design procedure is presented. A more rigorous design procedure is presented in Reference 7. However, for purposes of quickly obtaining an approximate design and cost for a given ESP, the methodology given below should suffice.

The most important variable considered in the design of an ESP presented below is specific collection plate area assuming that the ESP is already provided with an optimum level of secondary voltage and current. Secondary voltage or current is the voltage or current level at the plates themselves, and this voltage and current are responsible for the electric field. Collection plate area is a function of the desired collection efficiency, gas stream flow rate and particle drift velocity.[1,2,3,5,8] Other design details to be estimated by the vendor include (but are not limited to) expected secondary voltage and current, electrical sections alignment, and direction of gas flow.

Particle drift velocity is a complicated function of particle size, gas velocity, gas temperature, particle resistivity, particle agglomerization, and the physical and chemical properties of the particulate matter. The theoretical relationship of the drift velocity to the variables is discussed extensively in the literature.[1,2,3,5] Unfortunately, there are no empirical equations readily available to calculate drift velocity directly from these variables. Therefore, in determining drift velocity for a given emission stream, equipment vendors often rely upon historical data for similar streams and data established from pilot plant tests. Published information on drift velocity (based on design data for actual installations to represent typical gas characteristics) are available for several industrial emission streams.[2,7]

Appendix C.10 provides a worksheet to record the information obtained during the performance of the ESP design and cost procedures.

4.10.1 Data Required

The data necessary to perform the design steps consist of the HAP emission stream data characteristics previously compiled on the "HAP Emission Stream Data Forms" and the required HAP control as determined by the applicable regulations.

Example Case

Electrostatic precipitation was one of the selected control techniques for the municipal incinerator stream. The pertinent data for these procedures are found on the "HAP Emission Stream Data Form" (Figure 3.9).

1. Flow rate, $Q_{e,a}$ = 110,000 acfm
2. Emission stream temperature, T_e = 400°F
3. Particulate content = 3.2 grains/scf - flyash
4. Moisture content, M_e = 5% (vol)
5. HAP content = 10% (mass) cadmium
6. Drift velocity of particles, U_d = 0.31 ft/s
7. Collection efficiency, CE = 99.9% mass
8. System pressure drop, P = 5 in. H_2O

In the case of a permit review for an ESP, the following data should be supplied by the applicant. The design criteria and considerations discussed in this section will be used to evaluate the reasonableness of the applicant's proposed design.

1. Reported collection efficiency = ________%
2. Reported drift velocity of particles = ___ ft/sec
3. Reported collection plate area = _______ ft^2

4.10.2 Pretreatment of the Emission Stream

As discussed in Section 3.2.1, the temperature of the emission streams should be within 50 to 100°F above the stream dew point. Procedures for determining the dew point of an emission stream are provided in Appendix B.1. If the emission stream temperature does not fall within the stated range, pretreatment (i.e., emission stream preheat or cooling) is necessary. Methods of pretreatment are discussed briefly in Appendix B.3. The primary characteristics affecting ESP sizing are drift velocity of the particles and flow rate. Therefore, after selecting a temperature for the emission stream, the new stream flow rate must be calculated. The calculation method depends upon the type of pretreatment performed; use appropriate standard industrial equations. The use of pretreatment mechanical dust collectors may also be appropriate. If the emission stream contains an appreciable amount of large particles (20 to 30 um), pretreatment with mechanical dust collectors is typically performed. Appendix B.3 further describes the use of mechanical dust collectors.

4.10.3 ESP Design Variables

As mentioned earlier, an ESP collects particles by imparting a charge into them and using electrical forces to drive them to a collection plate. The particles are given an electrical charge by forcing them through a region of gaseous ions, called a corona. The corona is generated by applying voltage to electrodes located within the ESP. The ions migrate from the electrode area to the collection surface by following electric field lines. Particles passing through the corona become attached to these ions. Typically the particles must pass through a series of coronas before they are collected.

Upon collection, the particles are dislodged from the collection plate into a hopper. During dislodgement, however, some particles become reentrained in the gas stream reducing the overall collection efficiency. The amount of particle reentrainment significantly affects the collection efficiency of the ESP. Another factor affecting the collection efficiency is called "back corona." Back corona is due to particle buildup on the collection plates. The ion current generated by the electrodes must pass through the particle layer before reaching the ground (collection) plate. This current gives rise to an electric field in the layer, and can become large enough to cause a local electrical breakdown. This breakdown condition causes sparking and is called back corona.

Back corona is prevalent when the resistivity of the layer is high, usually above 2×10^{11} ohm-cm, and reduces collection efficiency due to difficulties in charging the particles. On the other hand, resistivities below 2×10^{8} ohm-cm make holding the particles on the plates difficult and increase reentrainment problems. See Reference 9 for more information on low resistivity performance problems. In general, wet ESPs are much less sensitive to particle resistivity than dry ESPs.

The particle resistivity is a fundamental indicator of the drift velocity of the particles. The drift velocity is an attempt to measure the velocity at which the particles migrate to the collection plate, and is used in the basic design equation presented below. The drift velocity strongly influences the estimate of the collection plate area for an ESP as can be seen in Equation 4.10-1.

For purposes of this manual, estimating the collection plate area is the most important aspect of sizing an ESP. A secondary consideration is the material of construction. For control of HAPs, it is recommended that continuous monitoring of both plate voltage and current be performed.

4.10.3.1 Collection Plate Area and Collection Efficiency

Although precise specification of collection plate area is best left to the vendor, an approximate collection plate area can be calculated using the available drift velocity value for the gas stream. For control of HAP emissions, it is recommended that a more precise computer model be used by the source or vendor to ascertain the required collection plate area. In the absence of this, Equation 4.10-1 can provide an indication of required plate area.

As noted earlier, collection plate area is a function of the emission stream flow rate, the particulate drift velocity, and desired control efficiency. The Deutsch-Anderson equation relates these variables as follows:[1,2,7]

$$SCA = -\ln(1\text{-}CE)/U_d(0.06) \qquad (4.10\text{-}1)$$

where:

SCA = specific collection plate area, ft²/1,000 acfm

CE = required collection efficiency, decimal fraction

U_d = drift velocity of particles, ft/s

The value of SCA, the specific collection area, is the area required per 1000 ft³/min. Thus, for a given application, the SCA must be multiplied by the volumetric flow rate (in units of 1,000 acfm) to obtain the total collecting plate area. This equation estimates the required SCA for a given collection efficiency. As the collection efficiency increases, the SCA also increases, all other things being equal.

Published data on drift velocities as a function of collection efficiency for a plate wire (dry and wet) and flat plate ESPs are presented in Tables 4.10-1 through 4.10-3. These tables may be used to obtain an indication of the drift velocity if no other information is available. They may also be used to serve as a check on drift velocity values submitted by a source. If the emission stream does not match any of the data presented in Tables 4.10-1 through 4.10-3, or information from the source or a vendor is unavailable, a default value of 0.30 ft/s may be used for particles of "average" resistivity (approximately 2×10^8 to 2×10^{10} ohm-cm), and a value of 0.10 ft/s may be used for particles having a high resistivity (10^{11} to 10^{13} ohm-cm).

A plot of Equation 4.10-1 in graphical form is presented in Figure 4.10-1. This enables the reader to quickly obtain an estimate of the SCA as a function of the desired collection efficiency and the drift velocity of the particles. This figure was obtained from Reference 7 and uses a different nomenclature than Equation 4.10-1. The variables p and w_e in Figure 4.10-1 correspond to (1-CE) and U_d used in Equation 4.10-1, respectively.

As mentioned above, particles with low resistivities are difficult to collect and impose special design considerations on an ESP. Such particles (resistivities from 10^4 to 10^7 ohm-cm) are difficult to collect because the particles tend to lose their charge, drop off the collector plate and become reentrained in the gas stream. In such cases, specially designed collecting plates or coatings may be used to reduce reentrainment as well as the use of additivies such as ammonia to the emission stream.[1,2,7,9] Particles with high resistivities also can cause ESP operating difficulties. High resistivity particles accumulate on the collection plates and insulate the collection plate, thus reducing the attraction between the particles and the collecting plate (i.e. back corona). In these cases, oversizing an ESP and more frequent cleaning or rapping of the collector plates are necessary. An alternative to a larger ESP is the use of conditioning agents to reduce the resistivity of the particles. Consult a vendor for advice concerning conditioning agents.

Example Case

Emission stream flow rate, $Q_{e,a}$ = 110,000 acfm

Drift velocity of particles, U_d = 0.31 ft/s (from Figure 3.9)

Collection efficiency, CE = 0.999

From the Deutsch equation:

$$SCA = -\ln(1\text{-}0.999)/0.31(0.06) = 371 \text{ ft}^2/1{,}000 \text{ acfm}$$

$$A_p = 110{,}000\,(371 \text{ ft}^2/1000 \text{ acfm}) = 40{,}800 \text{ ft}^2 \text{ of collection plate area.}$$

4.10.3.2 Materials of Construction

The most common material used in ESP construction is carbon steel. In cases where the gas stream contains high concentrations of SO_3 or where liquid-gas contact areas are involved, stainless steel may be required.[1,2,3,4,5] However, by keeping the emission stream temperature above the dew point and by insulating the ESP (the temperature drop across an insulated ESP should not exceed 20°F) the use of stainless steel should not be necessary.

4.10.4 Evaluation of Permit Application

Using Table 4.10-4, compare the results from this section and the data supplied by the permit applicant. The calculated values are based on the example. In evaluating the reasonableness of ESP design specifications in a permit application, the main task will be to examine each parameter in terms of its compatibility with the gas stream conditions.

Table 4.10-1. Plate-wire ESP Drift Velocities (ft/s)[a]

Particle Source		Design Efficiency, %			
		95	99	99.5	99.9
Bituminous coal fly ash[b]	(no BC)	0.41	0.33	0.31	0.27
	(BC)	0.100	0.080	0.078	0.069
Sub-bituminous coal fly ash in tangential-fired boiler[b]	(no BC)	0.56	0.39	0.34	0.29
	(BC)	0.151	0.102	0.085	0.072
Other coal[b]	(no BC)	0.32	0.26	0.26	0.24
	(BC)	0.095	0.072	0.069	0.062
Cement kiln[c]	(no BC)	0.049	0.049	0.059	0.059
	(BC)	0.020	0.020	0.016	0.016
Glass plant[d]	(no BC)	0.052	0.052	0.050	0.050
	(BC)	0.016	0.016	0.016	0.016
Iron/steel sinter plant dust with mechanical precollector[b]	(no BC)	0.223	0.200	0.216	0.207
	(BC)	0.072	0.050	0.050	0.056
Kraft-paper recovery boiler[b]	(no BC)	0.085	0.082	0.102	0.095
Incinerator fly ash[e]	(no BC)	0.502	0.374	0.348	0.308
Copper reverberatory furnace[f]	(no BC)	0.203	0.138	0.121	0.276
Copper converter[g]	(no BC)	0.180	0.144	0.134	0.118
Copper roaster[h]	(no BC)	0.203	0.180	0.174	0.157
Coke plant combustion stack[i]	(no BC)	0.039 [j]	—	—	—

BC = Back corona.

[a] Reference 7. To convert ft/s to cm/s, multiply ft/s by 30.488.

[b] At 300°F. Depending on individual furnace/boiler conditions, chemical nature of the fly ash, and availability of naturally occurring conditioning agents (e.g., moisture in the gas stream) migration velocities may vary considerably from these values. Likely values are in the range from back corona to no back corona.

[c] At 600°F. [d] At 500°F. [e] At 250°F. [f] 450 to 570°F.
[g] 500 to 700°F. [h] 600 to 660°F. [i] 360 to 450°F.

[j] Data available only for inlet concentrations in the range of 0.02 to 0.2 g/s-m^3 and for efficiencies less than 90 percent.

Table 4.10-2. Wet Plate-Wire ESP Drift Velocities (ft/s)[a]

Particle Source[b]	Design Efficiency, %			
	95	99	99.5	99.9
Bituminous coal fly ash	1.03	1.08	0.817	0.269
Sub-bituminous coal fly ash in tangential-fired boiler	1.31	1.40	1.45	1.03
Other coal	0.692	0.702	0.705	0.558
Cement kiln	0.210	0.184	0.164	0.187
Glass plant	0.151	0.148	0.141	0.125
Iron/steel sinter plant dust with mechanical precollector	0.459	0.449	0.436	0.380

[a] Reference 7. To convert ft/s to cm/s, multiply ft/s by 30.488.

Table 4.10-3. Flat Plate ESP Drift Velocities, ft/s (No back corona)[a]

Particle Source	Design Efficiency, %			
	95	99	99.5	99.9
Bituminous coal fly ash[b]	0.309	0.354	0.436	0.375
Sub-bituminous coal fly ash in tangential-fired boiler[b]	0.670	0.426	0.497	0.415
Other coal[b]	0.494	0.501	0.504	0.133
Cement kiln[c]	0.150	0.105	0.101	0.089
Glass plant[d]	0.108	0.105	0.101	0.089
Iron/steel sinter plant dust with mechanical precollector[b]	0.328	0.321	0.312	0.272
Kraft-paper recovery boiler[b]	0.117	0.110	0.143	0.136
Incinerator fly ash[e]	0.590	0.396	0.494	0.429

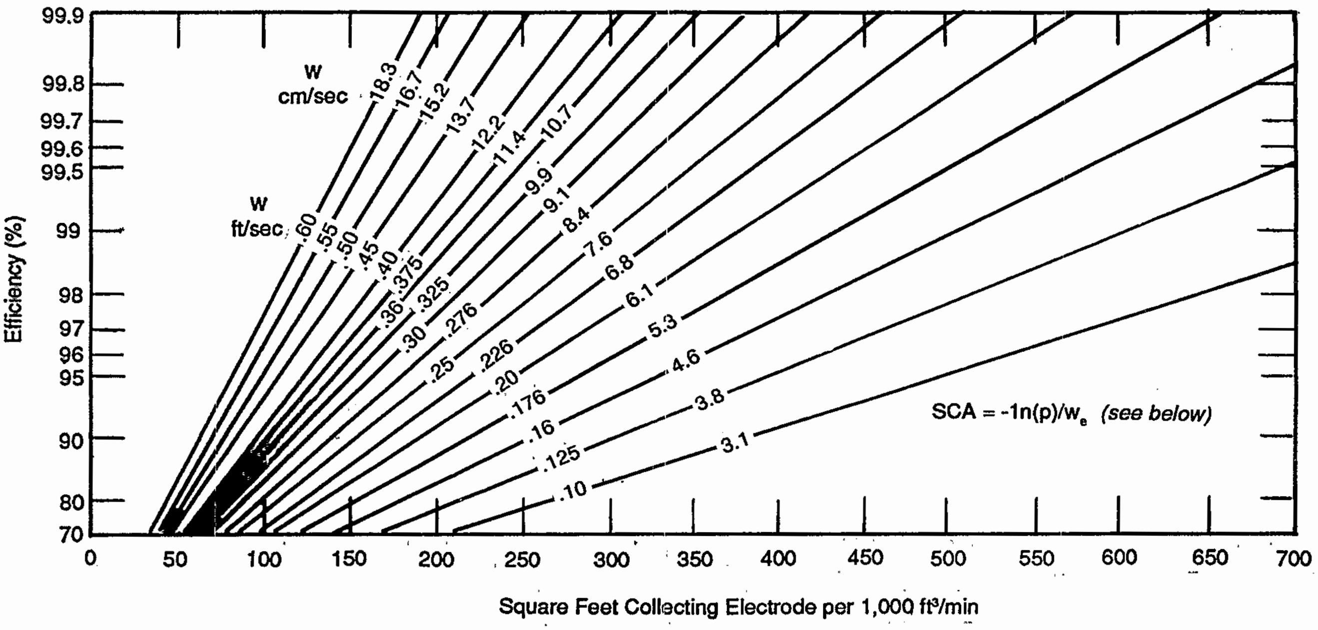
[a] Reference 7. To convert ft/s to cm/s, multiply ft/s by 30.488.

[b] At 300°F.

[c] At 600°F.

[d] At 500°F.

[e] At 250°F.



Where: SCA = specific collection area; p = fractional penetration, or p = 1 - fractional efficiency; w_e = migration velocity
To get SCA in ft²/1,000 acfm, multiply w_e in cm/s by 0.00197 (in ft/s by 0.0600).

Figure 4.10-1. Chart for finding SCA.[7]

If the applicant's collection plate area is different than the calculated area, the discrepancy will most likely be the selected drift velocity. Further discussions with the permit applicant are recommended to evaluate the design assumptions and to reconcile any apparent discrepancies.

Table 4.10-4. Comparison of Calculated Values and Values Supplied by the Permit Applicant for ESPs

Parameter	Calculated Value[a]	Reported Value
Continuous monitoring of plate voltage and current	yes	...
Drift velocity of particles, U_d	0.31	...
Collection efficiency, CE	0.999	...
Collection plate area, A_p	40,800 ft²	...

[a] Based on the municipal incinerator emission stream.

4.10.5 Determination of ESP Operating Parameters

Many times, optimization of an ESPs collection efficiency occurs in the field after construction. The following discussion does not pertain to the preliminary design of an ESP control system. Therefore, this discussion is placed after the evaluation of the permit application. The information presented should be helpful in achieving and maintaining the desired collection efficiency for the installed control system.

4.10.5.1 Electric Field Strength

Current in the form of ions from the charging electrodes actually charge the particles. Once the particles are charged, the electric field strength determines the amount of charge on the particles. Field strength is based on voltage and distance between the collecting plates and electrodes.[1,2,3] ESPs are usually operated at the highest secondary voltage practicable with limited sparking to maximize collection efficiency. Sparking represents an instantaneous drop in voltage, collapse of the electrostatic field, and momentary cessation of particulate collection. Sparking varies with the density of the gas stream, material collected on the electrodes, and humidity and temperature of the gas stream. When automatic controls are used, ESPs usually operate with a small amount of sparking to ensure that the voltage is in the correct range and the field strength is maximized. Automatic voltage controls can control sparking to a specified sparking frequency (typically 50 to 150 sparks per minute per section of ESP).[2] As the spark rate increases, a greater percentage of the input power is wasted in the spark current. Consequently, less useful power is applied to the collecting electrode.

4.10.5.2 Cleaning Frequency and Intensity

Particles accumulating on the collecting plates must be removed periodically. In wet ESPs the liquid flowing down the collector surface removes the particles.[5] In dry ESPs, the particles are removed by vibrating or rapping the collector plates. For dry ESPs this is a critical step in the overall performance because improperly adjusted or operating rappers can cause reentrainment of collected particles or sparking due to excessive particulate buildup on the collection plates or discharge electrodes. In normal operation, dust buildup of 6 to 25 mm is allowed before rapping of a given intensity is initiated.[1] In this way, collected material falls off in large clumps that would not be reentrained. If rapping is initiated more frequently or if the intensity of rapping is lowered, the resulting smaller clumps of particulate matter are more likely to be reentrained, reducing the collection efficiency of the ESP. Optimal adjustment of the ESP can best be made by direct visual inspections through sight ports.

4.10.5.3 ESP Collection Efficiency

ESP collection efficiencies less than permitted can be the result of operational problems, mechanical troubles, or improper design. Typical operational problems include improper electrical settings, badly adjusted rappers, full or nearly full dust hoppers, and process upsets. Mechanical difficulties typically are the result of electrode misalignment or excessive dust buildup on the electrodes. Basic design problems include undersized equipment, reentrainment, or high resistivity particles. The permit applicant should carefully examine each of these items if the ESP is emitting particulate emissions from his facility that are in excess of permitted levels.

4.10.6 Capital and Annual Costs of ESP Systems

This section provides a methodology to estimate the total capital and annual costs for an ESP.

4.10.6.1 ESP Capital Costs

The capital costs consist of equipment costs (including auxiliary equipment) and the direct and indirect costs associated with installing or erecting the ESP. The equipment cost for five types of ESPs are given in 2nd quarter 1987 dollars. While these costs may appear somewhat dated, costs for ESP systems have risen little in the past ten years due to more effective designs and more vendor competition. Therefore, assume these costs are current and do not need to be escalated. If needed, Table 4.12-1 can be used to escalate these costs. The ESP types include plate wire, flat plate, wet, tubular and two-stage. The capital cost direct and indirect installation factors for ESP systems are provided in Table 4.10-5. Equipment cost multipliers for standard options supplied with some ESPs are provided in Table 4.10-6.

The structure cost is primarily a function of plate area, but electrode design and materials of construction can also influence this value. Table 4.10-7 provides equipment cost multipliers for various materials of construction.

The flange-to-flange equipment cost of flat wire rigid electrode and flat plate ESP systems are given in Figure 4.10-2, as a function of the collection plate area.

In Figure 4.10-2, the reader should be aware that the upper and lower lines are simply aids in obtaining more precise estimates of costs with the formulae rather than the rougher estimate obtained from reading the curves directly. The black bars simply indicate the point at which the slopes change (50,000 ft^2). Therefore, the second line from the top is the curve for ESP systems *with* all standard options while the second line from the bottom is for basic ESP systems *without* standard options.

The cost of wet and tubular ESPs are more difficult to estimate because the market is relatively small. In general, flange-to-flange equipment costs of \$65 - \$95/ft^2 of collection area can be used as a rough estimate for wet ESPs, while \$90 - \$120/ft of collection area is a typical cost for wet tubular ESPs.[7]

Table 4.10-5. Capital Cost Factors for ESPs[a]

Cost Item	Factor
Direct Costs	
Purchased Equipment Costs	
ESP + auxiliary equipment, EC	As estimated, EC
Instrumentation	0.10 EC
Sales taxes	0.03 EC
Freight	0.05 EC
Purchased Equipment Cost, PEC	PEC = 1.18 EC
Direct Installation Costs	
Foundations & supports	0.04 PEC
Handling & erection	0.50 PEC
Electrical	0.08 PEC
Piping	0.01 PEC
Insulation for ductwork[b]	0.02 PEC
Painting	0.02 PEC
Direct Installation Cost	0.67 PEC
Site preparation	As required, SP
Buildings	As required, Bldg.
Total Direct Cost, DC	1.67 PEC + SP + Bldg.
Indirect Costs (installation)	
Engineering	0.20 PEC
Construction and field expenses	0.20 PEC
Contractor fees	0.10 PEC
Start-up	0.01 PEC
Performance test	0.01 PEC
Model study	0.02 PEC
Contingencies	0.03 PEC
Total Indirect Cost, IC	0.57 PEC
Total Capital Cost = DC + IC	2.24 PEC + SP + Bldg.

[a] Reference 7.

[b] If ductwork dimensions established, cost may be estimated based on \$10-\$12/ft^2 of surface for field application. Fan housing and stacks may also be insulated.

Table 4.10-6. Equipment Cost Multipliers for ESP Optional Equipment[a]

Option	Factor
Inlet and outlet nozzles and diffuser plates	8-10 percent of ESP cost[b]
Hopper auxiliaries/ heaters, level detectors	8-10 percent of ESP cost[b]
Weather enclosure and stair access	8-10 percent of ESP cost[b]
Structural supports	5 percent of ESP cost[b]
Insulation	8-10 percent of ESP cost[b]

[a] Reference 7.

[b] The ESP cost is the cost obtained from Figure 4.10-2. Note that the upper curve in Figure 4.10-2 contains all above standard options.

Table 4.10-7. Equipment Cost Multipliers for Various Materials of Construction[a,b]

Material	Factor
Carbon Steel	1.0
304 Stainless Steel	1.3
316 Stainless Steel	1.7
Carpenter 20 CB-20	2.5
Monel-400	3.0
Nickel-200	4.2
Titanium	5.8

[a] Reference 7.

[b] These factors multiply the ESP cost obtained from Figure 4.10-2 or 4.10-3.

The flange-to-flange structure cost for a two-stage ESP system is given in Figure 4.10-3. The lower cost curve is for a two-cell unit without a precooler, an installed cell washer, or a fan. The upper curve is for a packaged system with an inlet diffuser plenum, prefilter, cooling coils with coating, coil plenums with access, water flow controls, triple pass configuration, system exhaust fan, outlet plenum, and in-place foam cleaning system.

The equipment cost (EC) for an ESP system is obtained by adding the ESP structure cost and the cost of auxiliary equipment. Auxiliary equipment costs (refer to Section 4.12) include ductwork, dampers, fans, stacks, and cyclones if necessary.

After obtaining the equipment cost, the purchased equipment cost, PEC, is calculated based on the factors provided in Table 4.10-5. The total capital cost is then estimated according to the direct and indirect cost factors given in Table 4.10-5.

Example Case

Assume a basic flat plate rigid electrode ESP system is proposed. Figure 4.10-2 contains the cost of this structure with a plate area of 40,800 ft^2 as $470,000 (from reading the graph). For example purposes, assume 304L stainless steel is used, although it probably is not necessary provided the emission stream temperature is within 50 - 100°F of its dewpoint. From Table 4.10-7, the cost factor for this material is 1.3. This factor multiplies the cost from Figure 4.10-2, yielding a cost of $611,000. Assume auxiliary equipment costs equal $10,000. The equipment cost (EC) is then $621,000.

Table 4.10-5 is used to obtain the purchased equipment cost (PEC) of the ESP system:

Instrumentation = 0.10 (EC) = $ 62,100
Sales tax = 0.03 (EC) = $ 18,600
Freight = 0.05 (EC) = $ 31,100
$112,000

The purchased equipment cost (PEC) is therefore equal to $733,000. Table 4.10-5 is then used to obtain the total capital cost, TCC. These costs are given in Table 4.10-8.

4.10.6.2 ESP Annual Costs

The total annual cost of an ESP system consists of direct and indirect annual costs. The appropriate cost factors used to estimate this cost are provided in Table 4.10-9. The discussion below focuses on the information necessary to correctly use these factors.

Direct Annual Cost. These costs include electricity, operating labor, maintenance costs, plus water costs, wastewater treatment costs, and SO_3 conditioning costs if they apply to the same units.

Electricity costs are primarily associated with the fan needed to move the gas through the ESP. Equation 4.10-2 can be used to obtain an estimate of the fan power needed,assuming a fan-motor efficiency of 65 percent and fluid specific gravity of 1.0:

$$F_p = 1.81 \times 10^{-4} (Q_{e,a}) (P) (HRS) \qquad (4.10\text{-}2)$$

where:

F_p = fan power requirement, kWh/yr
$Q_{e,a}$ = emission stream flow rate, acfm
P = system pressure drop, in. H_2O
HRS = annual operating hours, hr/yr

For wet ESPs the pump power (P_p) can be estimated from Equation 4.10-3.

$$P_p = 0.746 (Q_L)(Z) (S_g) (HRS)/(3960n) \qquad (4.10\text{-}3)$$

where:

P_p = Pump power requirement, kWh/yr
Q_L = Liquid flow rate, gal/min
Z = fluid head, ft
S_g = specific gravity of fluid relative to water at 77° F, 1 atm
HRS = annual operating hours, hr/yr
n = combined pump-motor efficiency, fraction

The power requirement for TR sets and motor-driven or electromagnetic rapper systems can be estimated from Equation 4.10-4:

$$OP = 1.94 \times 10^{-3} (A_p) (HRS) \qquad (4.10\text{-}4)$$

where:

OP = annual ESP operating power, kWh/yr
A_p = collection plate area, ft^2
HRS = annual operating hours, hr/yr

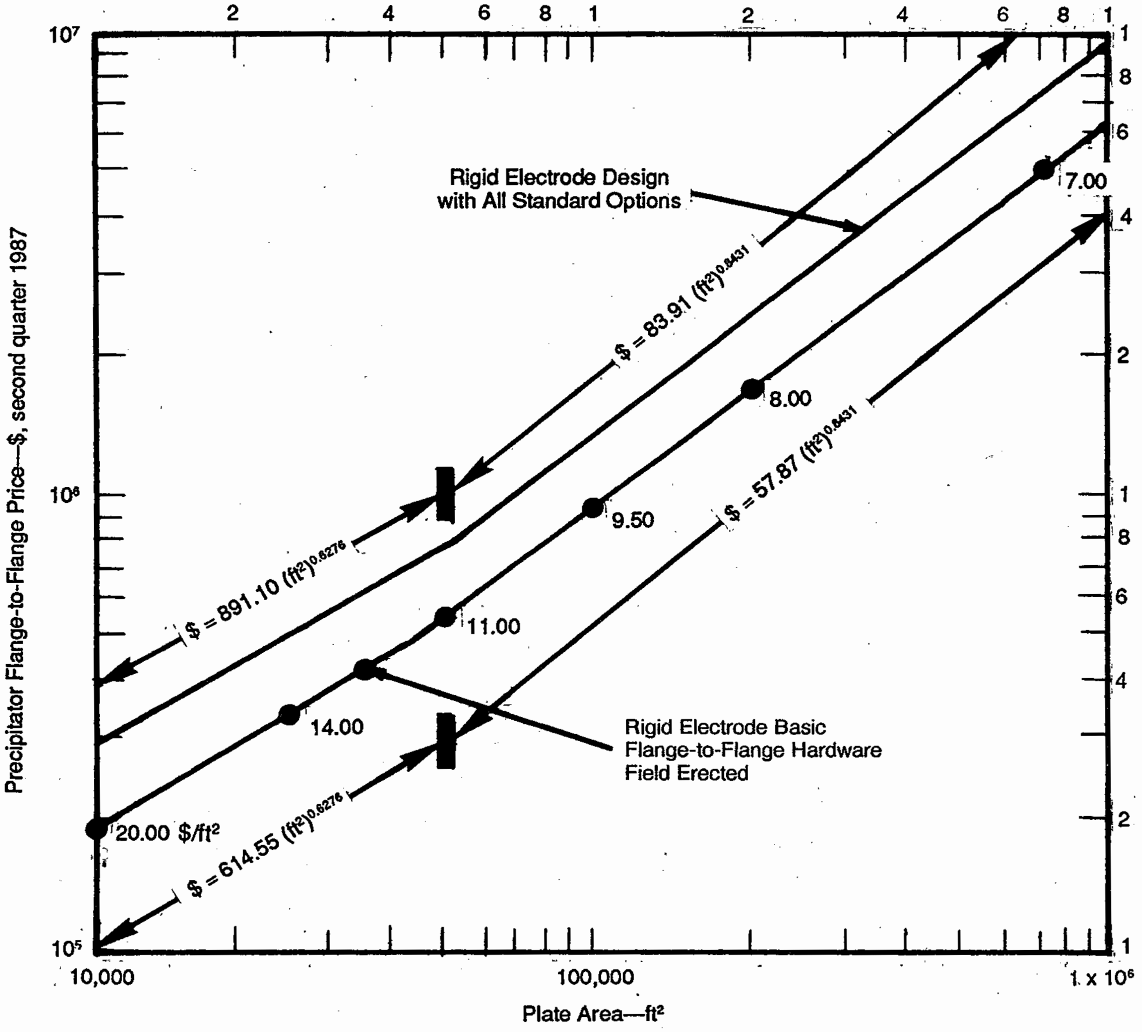


Figure 4.10-2. Cost of plate wire and flat plate ESP structures.[7]

For two-stage ESPs, power requirements range from 25 to 100 W/kacfm, with 40 W/kacfm being typical.

The cost of water for wet ESPs is estimated at 5 gal/min kacfm for large single stage units and 16 gal/min kacfm for two-stage ESPs. Treatment costs for the resulting wastewater may vary from \$1.30 to 2.15/1000 gal. The cost of SO_3 conditioning for a large ESP (2.6 x 10^6 acfm) ranges from \$1.61/10^6 ft³ gas processed for a liquid SO_3 system to \$2.30/10^6 ft³ gas processed for a liquid SO_3 system providing 20 ppm of SO_3. For purposes of this manual, fuel costs are assumed to be zero.

Costs of compressed air for operating rappers are included in Equation 4.10-4. The cost of dust disposal is highly variable and the reader should make every effort to secure these costs on an individual basis. Disposal cost may fall between \$20/ton to \$30/ton for nonhazardous wastes, excluding transportation. For comparison, landfilling hazardous wastes may cost 10 times this amount.[7]

The cost of operating labor is estimated as 0.5 hours per 8 hour shift. The operator labor wage rate is provided in Table 4.10-9. Supervisory costs are estimated as 15 percent of operator labor costs. Some ESP systems have an individual who coordinates the operation, maintenance, and troubleshooting components of an ESP program. His time therefore, becomes an operating expense for the ESP. For purpose of this manual, this expense is assumed to be one-third of the operating labor cost.[7]

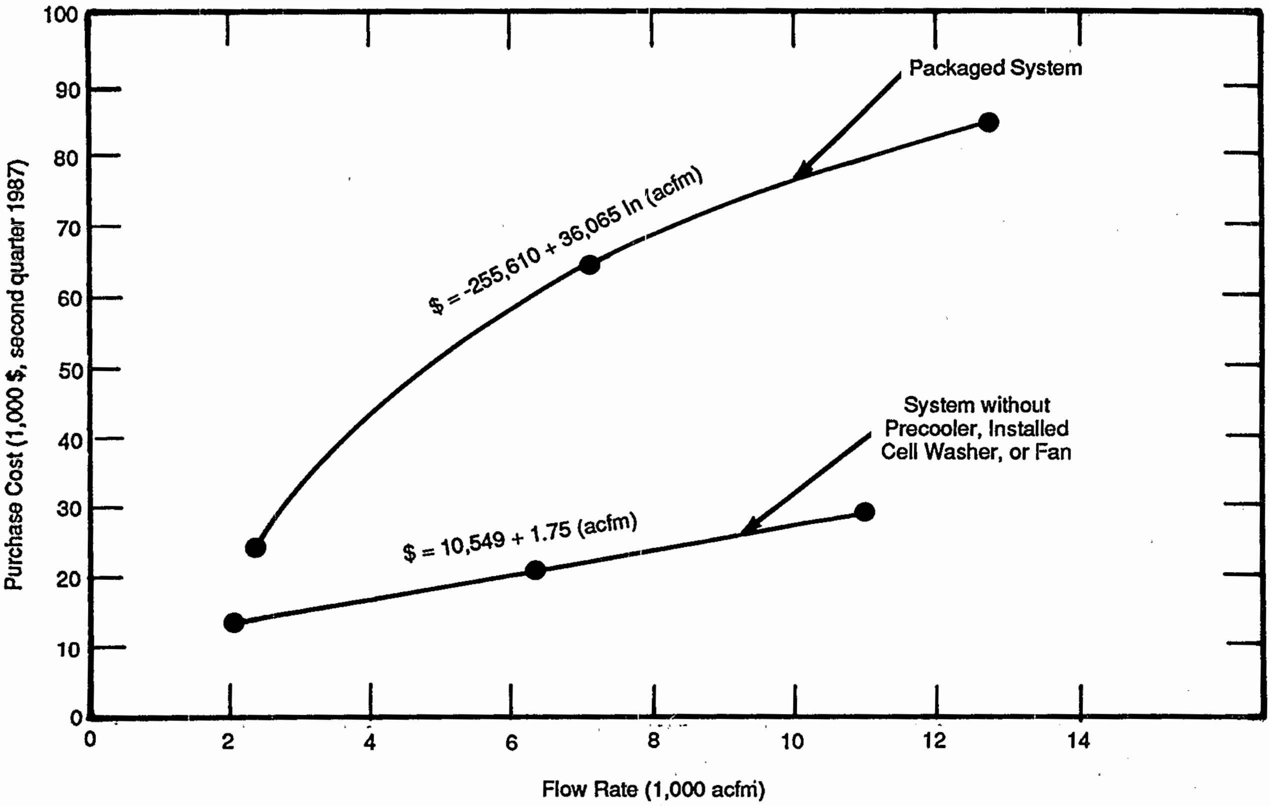


Figure 4.10-3. Cost of two-stage ESP structures.[7]

The annual maintenance labor cost is estimated from Equation 4.10-5:

$$MC = 0.01\,(PEC) + \text{Labor cost} \qquad (4.10\text{-}5)$$

where:

MC = annual maintenance cost, $/yr

PEC = flange-to-flange purchased equipment cost, $

Labor cost = $4,125 if $A_p < 50,000$ ft^2
= $0.0825\,A_p \geq 50,000$ ft^2

where A_p = collection plate area, ft^2

The cost of maintenance materials is taken as 1 percent of the PEC.

Indirect Annual Costs. These costs include the capital recovery cost, overhead, property taxes, insurance and administrative costs. The appropriate factors used to estimate these costs, as a percentage of the total capital cost (TCC), are provided in Table 4.10-9.

Example Case

Direct Annual Costs

Electricity usage for the ESP fan is estimated from Equation 4.10-2:

$$F_p = 1.81 \times 10^{-4}\,(110{,}000)(5)(6000)$$
$$= 5.97 \times 10^5 \text{ kWh/yr}$$

Electricity cost = $0.059 ($5.97 \times 10^5$) = $35,200

Electricity usage for the rapper system is estimated from Equation 4.10-4:

$$OP = 1.94 \times 10^{-3}\,(46{,}900)\,(6{,}000)$$
$$= 5.46 \times 10^5 \text{ kWh/yr}$$

Electricity cost = $0.059 ($5.46 \times 10^5$) = $31,900

Operating labor costs are estimated as:

[(0.5 hr/shift)/(8 hr/shift)] 6,000 hr/yr = 375 hr/yr

375 hr/yr ($12.96/hr) = $4,860/yr

Supervisory costs are taken as 15 percent of this total or $729. The cost of an ESP coordinator is taken as 33 percent of this total or $1,600.

Maintenance costs are estimated using Equation 4.10-5 and Table 4.10-9:

Table 4.10-8. Example Case Capital Costs

Cost Item	Factor	Cost($)
Direct Costs		
Purchased Equipment Costs		
ESP + auxiliary equipment, EC	As estimated, EC	$ 621,000
Instrumentation	0.10 EC	62,100
Sales taxes	0.03 EC	18,600
Freight	0.05 EC	31,100
Purchased Equipment Cost, PEC	PEC = 1.18 EC$	733,000
Direct Iinstallation Costs		
Foundations & supports	0.04 PEC	$29,300
Handling & erection	0.50 PEC	367,000
Electrical	0.08 PEC	58,600
Piping	0.01 PEC	7,330
Insulation for ductwork	0.02 PEC	14,700
Painting	0.02 PEC	14,700
Direct Installation Cost	0.67 PEC	$492,000
Site preparation	As required, SP	
Buildings	As required, Bldg.	
Total Direct Cost, DC	1.67 PEC + SP + Bldg.	$1,220,000
Indirect Costs (installation)		
Engineering	0.20 PEC	$147,000
Construction and field expenses	0.20 PEC	147,000
Contractor fees	0.10 PEC	73,300
Start-up	0.01 PEC	7,330
Performance test	0.01 PEC	7,330
Model study	0.02 PEC	14,700
Contingencies	0.03 PEC	22,000
Total Indirect Cost, IC	0.57 PEC	$419,000
Total Capital Cost = DC + IC	2.24 PEC + SP + Bldg.	$1,640,000

Table 4.10-9. Annual Costs for ESPs[a]

Cost Item	Factor
Direct Annual Costs, DAC	
Utilities	
Electricity	$0.059/kWh
Water	$0.20/10^3 gal
Operating Labor	
Operator	$12.96/hr
Supervisor	15% of operator labor
Coordinator	33% of operator labor
Maintenance	
Labor	See Section 4.10.6.2
Material	% of PEC
Waste Disposal Costs	Variable (see Section 4.10.6.2)
Indirect Annual Costs, IAC	
Overhead	0.60 (Operating labor + maintenance costs)
Administrative	2% of TCC
Property tax	1% of TCC
Insurance	1% of TCC
Capital recovery[b]	0.1175 (TCC)
Total Annual Costs, TAC	DC + IC

Example Case (Cont'd)

MC = 0.01 (733,000) + $4,125 = $11,500

Maintenance materials are estimated as 1 percent of the PEC or $7,330.

Waste Disposal Costs:

$$\frac{3.2\ \text{gr}}{\text{ft}^3} \times \frac{\text{lb}}{7000\ \text{gr}} \times \frac{110{,}000\ \text{ft}^3}{\text{min}} \times \frac{60\ \text{min}}{\text{hr}} \times \frac{6{,}000\ \text{hr}}{\text{yr}}$$

$$= 1.81 \times 10^7\ \text{lb/yr}$$

$$1.81 \times 10^7 \times \frac{\text{lb}}{\text{yr}} \times \frac{\text{ton}}{2000\ \text{lb}} \times \frac{\$200}{\text{ton}}$$

$$= 1.81 \times 10^6\ \$/\text{yr}$$

Total Direct Costs:

$35,200 + $31,900 + $4,860 + $729 + 1,600 + $11,500 + $7,330 + $1,810,000 = $1,900,000

Indirect Annual Costs

These costs are obtained from the factors presented in Table 4.10-9.

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[a] Reference 7.

[b] Capital recovery factor is calculated as: i(1+i)^n/(1+i)^n-1
where: i = interest rate, 10 percent
n = equipment life, 20 years

Example Case (Cont'd)

Overhead
= 0.60 ($4,860 + $729 + $1,600 + $11,500 + 7,330) = $15,600

Administrative
= 0.02 ($1,640,000) = $32,800

Insurance
= 0.01 ($1,640,000) = $16,400

Property taxes
= 0.01 ($1,640,000) = $16,400

Capital recovery
= 0.1175 ($1,640,000) = $193,000

Total Indirect Costs
= $15,600 + $32,800 + $16,400 + $16,400 + $193,000 = $274,000

Total Annual Costs
= $1,900,000 + $274,000 = $2,170,000

4.10.7 References

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4.11 Venturi Scrubbers

Venturi scrubbers are designed to serve as a control device for applications requiring very high collection efficiencies of particles generally between 0.5 to 5.0 um in diameter. They employ gradually converging and then diverging sections to clean an incoming gaseous stream. The section connecting the converging and diverging sections of the scrubber is called the throat. In general, the longer the throat, the higher the collection efficiency at a given pressure drop, provided the throat is not so long that frictional losses become significant.[1] Venturi scrubbers are also available in variable throat designs that allow adjustment to the throat velocity as a means of modifying the pressure drop and efficiency.

Typically, a liquid (usually water) is introduced upstream of the throat and flows down the converging sides into the throat where it is atomized by the gaseous stream; this method is called the "wetted approach." Alternatively, the liquid can be injected into the throat itself by use of nozzles directed at the throat; this approach is called the "nonwetted approach."[1] The nonwetted approach works well when a gas is already close to saturation; however, this method requires that the liquid be free of particles that could clog the nozzles. Where inlet gases are hot and a significant amount of liquid needs to be evaporated, the wetted approach is preferred.

Once the liquid is atomized, it begins to collect particles from the gas impacting into the liquid as a result of the difference in velocities of the gas stream and the atomized droplets. As the mixture decelerates in the expanding section, further impaction occurs causing the droplets to agglomerate. Once the particles have been trapped by the liquid, a separator (e.g. cyclone, demisters, swirl vanes) can readily remove the scrubbing liquid from the cleaned gas stream.

Another type of scrubber that has been successfully installed in industrial applications is called a hydrosonic scrubber. This type of scrubber is very efficient at controlling fine (submicron) particles found in metal fumes, and noxious gas. Literature data from vendors indicates these scrubbers have the potential to control submicron particulates to outlet emissions of 0.006 gr/dscf, corrected to 7 percent O_2.[10] One type of hydrosonic scrubber uses two subsonic nozzles in tandem with a throat separating the nozzles to maximize turbulent mixing and particle agglomerization. The first nozzle section condenses vapors present in the emission stream, removes the larger particles, and initiates smaller particle agglomerization. The second nozzle section collects the smaller particles not collected in the first section.

A different type of hydrosonic scrubber utilizes a supersonic nozzle to agglomerate particles and a subsonic nozzle and mixing section to collect fine particles and noxious gas (SO_2, H_2S, NO_x, etc.) While these types of scrubbers are not as common as venturi scrubbers, they are mentioned here to introduce the reader to these devices. For more information, consult Reference 10.

In recent years, venturi scrubbers have been increasingly supplanted in favor of fabric filters or ESPs. The reasons for this include BACT regulations, advances in filters and cleaning methods resulting in wider application of baghouses, reductions in rapping losses for ESPs, and problems associated with wastewater generation for venturi scrubbers. Therefore, while venturi scrubbers are still a viable choice for particulate control, the likelihood of encountering a venturi scrubber on a given permit application is decreasing. Because of this, readily available cost information on venturi scrubbers was dated. Therefore, purchase cost information has been obtained directly from vendors.

Appendix C.11 provides a worksheet to record the information obtained during the performance of the venturi scrubber design procedures.

4.11.1 Data Required

The data necessary to perform the design steps consist of the HAP emission stream characteristics previously compiled on the "HAP Emission Stream Data Forms," and the required HAP control as determined by the applicable regulations.

Example Case

A venturi scrubber was one of the selected control techniques for the municipal incinerator emission stream. The pertinent data for these procedures are found on the "HAP Emission Stream Data Form" (see Figure 3.9).

1. Flow rate $Q_{e,a}$ = 110,000 acfm
2. Temperature, T_e = 400° F
3. Moisture content, M_e = 5% vol.
4. Required collection efficiency, CE = 99.9%
5. Particle mean diameter, D_p = 1.0 µm
6. Particulate content = 3.2 grams/scf flyash
7. HAP content = 10% (mass) cadmium

In the case of a permit review for a venturi scrubber, the following data should be supplied by the applicant.

1. Reported pressure drop across venturi = ____ in. H_2O
2. Performance curve applicable to the venturi scrubber.
3. Reported collection efficiency ______%

4.11.2 Pretreatment of the Emission Stream

As discussed in Section 3.3.1, the temperature of the emission stream should be within 50 to 100°F above the stream dew point. Procedures for determining the dew point of an emission stream are provided in Appendix B.1. If the emission stream temperature does not fall within the stated range, pretreatment (i.e., emission stream preheating or cooling) is necessary. Methods of pretreatment are briefly discussed in Appendix B.3. If pretreatment is performed, the emission stream characteristics will be altered. The primary characteristic affecting venturi scrubber design are the saturated gas flow rate ($Q_{e,s}$), which is a function of the emission stream temperature (T_e) and flow rate at actual conditions ($Q_{e,a}$), particle size, and throat velocity.[1,11] Thus, if the temperature of the emission stream changes, changing the actual flow rate, the saturated gas flow rate must be based on the new actual flow rate. The calculation method depends upon the type of pretreatment performed; use appropriate standard industrial equations. The use of pretreatment mechanical dust collectors may also be appropriate, depending upon the amount of large particles in the emission stream. Appendix B.3 further describes the use of mechanical dust collectors.

4.11.3 Venturi Scrubber Design Variables

To design a venturi scrubber, any one of three options may be chosen: (1) rely on previous experience with an analogous application, which is best for plants lacking effluent data; (2) test a scrubber on the source itself; or (3) collect sufficient data about source stream characteristics, such as particle size distribution, flow rate, and temperature, to utilize existing "performance curves" for a given venturi scrubber. This section is concerned with the third option. Thus, the most important consideration becomes the pressure drop across the venturi. A secondary consideration is materials of construction.

4.11.3.1 Pressure Drop and Efficiency

Performance curves are typically logarithmic plots relating venturi collection efficiency, pressure drop, and particle size.[2,3,5,6] Collection (control) efficiency is usually plotted versus pressure drop across the venturi for a particle mean diameter (D_p). Figure 4.11-1 is a plot of venturi scrubber pressure drops for a given collection efficiency and particle mean diameter for venturi scrubbers manufactured by a specific vendor. Thus, if the particle mean diameter for an emission stream and required collection efficiency is known, the pressure drop across the venturi can be estimated. Figure 4.11-1 is representative of plots likely to be used by vendors, and does not necessarily represent characteristics for all venturi scrubbers.

A logarithmic relationship between pressure drop and efficiency exists for a given particle size as shown in Figure 4.11-1. This type of figure usually takes the place of design equations for venturi scrubbers. If a particle distribution is known, the overall collection efficiency is the weighted average of the collection efficiency for each particle size.

Estimating the pressure drop gives an indication of whether a venturi scrubber is a feasible control device for a given stream. Venturi scrubbers are used in appli-

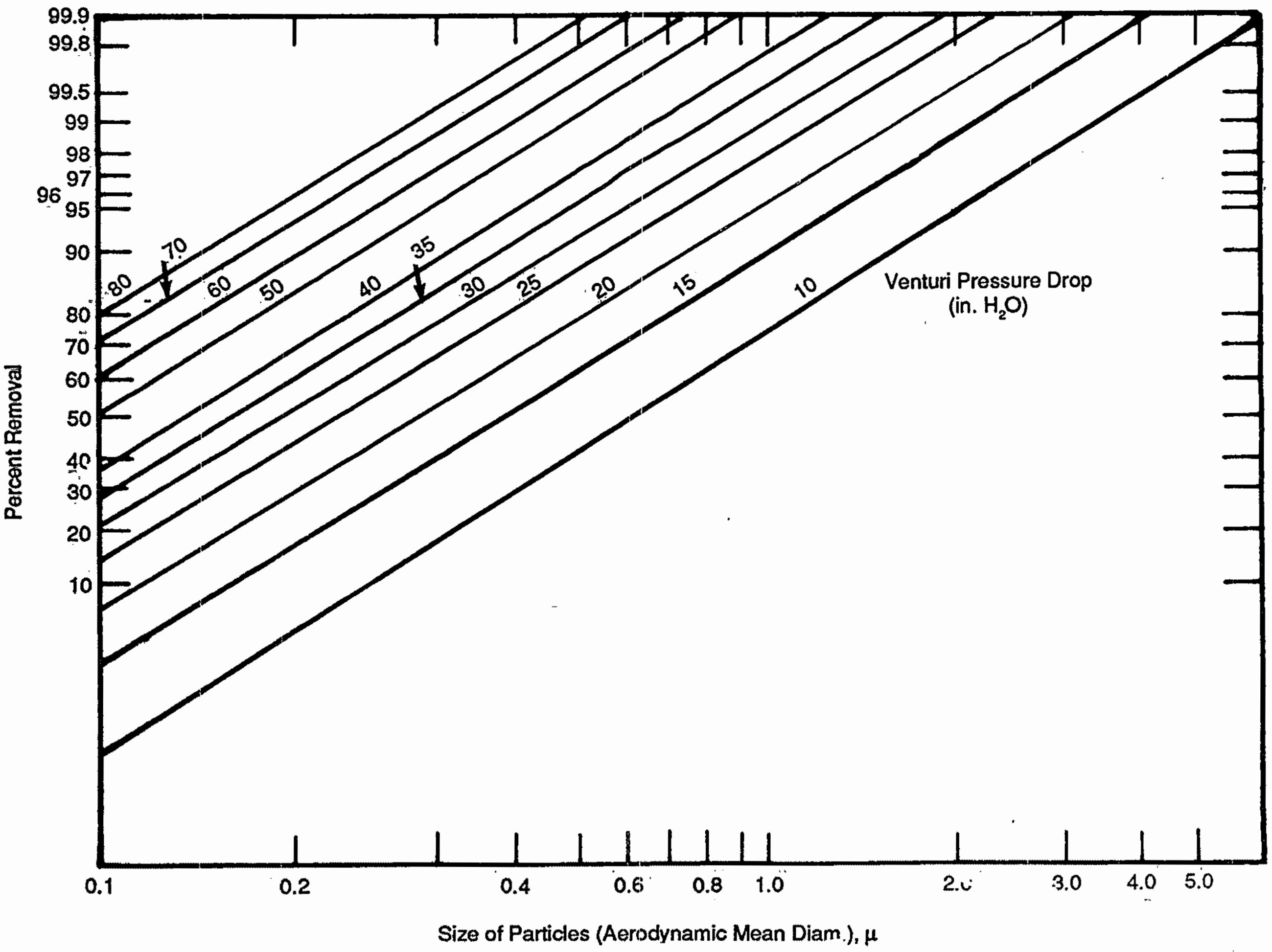

Figure 4.11-1 **Typical Venturi scrubber performance curve.**

cations where pressure drops of between 10 and 80 inches of water gauge occur across the venturi. Venturi scrubbers can operate at pressure drops higher than 80 inches; however, in general, a pressure drop exceeding 80 inches H_2O indicates that a venturi scrubber will have difficulty collecting the particles[1]. Therefore, if the pressure drop indicated on the performance curve is greater than 80 inches H_2O, assume that the venturi scrubber cannot accomplish the desired control efficiency.

For control of HAPs, it is recommended that routine maintenance of the nozzles, liquid pump, and visual inspection of the throat be performed to maintain system design performance.[11]

Typical pressure drops for venturi scrubbers for a variety of applications are listed in Table 4.11-1. The pressure drops are listed to provide general guidance to typical values that occur in industry. The values are not meant to supersede any specific information known, and given application may have a pressure drop outside those listed in Table 4.11-1.

4.11.3.2 Materials of Construction

Proper selection of the materials in constructing a venturi scrubber ensures long-term operation with minimal downtime for repair. The materials are generally chosen based on the corrosive or erosive nature of the emission stream, and to a lesser degree, the temperature of the gas stream. For any given application, a vendor should be contacted to ensure correct selection of materials. A venturi scrubber will generally be constructed of either carbon or stainless steel or a nickel alloy; it may also be lined with another material (e.g., ceramics). Materials of construction for various industries are listed in Table 4.11-2 and serve as a general guide rather than a definitive statement on the types of materials used in industry.

Example Case

The required collection efficiency is 99.9% and the particle mean diameter in the municipal waste incinerator emission stream is estimated to be 1.0 μm; therefore:

P_v = 47 in. H_2O (Figure 4.11-1)

Example Case (Cont'd)

Note that this value is outside the range given in Table 4.11-1. Nonetheless, use the value calculated in Figure 4.11-1 (47 in. H_2O). Since the estimated venturi pressure drop value is not greater than 80 in. H_2O, this venturi scrubber should be able to accomplish the desired control efficiency. As indicated in Table 4.11-2, the venturi scrubber should be constructed of 316L stainless steel.

4.11.4 Sizing of Venturi Scrubbers

If a venturi scrubber is found to be a feasible control choice for a given emission stream, it is then sized. Venturi scrubbers can be sized using either the flow rate at inlet conditions ($Q_{e,a}$) or the saturated gas flow rate ($Q_{e,s}$).[4] Vendors may use either parameter; the cost data presented in Section 4.11.6 are based on $Q_{e,a}$. If needed, $Q_{e,s}$ can be calculated as shown below. A psychrometric chart (Figure 4.11-2) can be used to determine the saturated gas temperature ($T_{e,s}$), and $Q_{e,s}$ can then be calculated using Equation 4.11-1:

$$Q_{e,s} = Q_{e,a} \times (T_{e,s} + 460)/(T_e + 460) + Q_w \quad (4.11\text{-}1)$$

where:

$Q_{e,s}$ = saturated emission stream flow rate, acfm

$T_{e,s}$ = temperature of the saturated emission stream, °F

T_e = temperature of emission stream at inlet, °F

Q_w = volume of water added, ft³/min. Q_w can be calculated from the following formula:

$$Q_w = Q_{e,ad}\,(D_e)\,(L_{w,s} - L_{w,a})\,(1/D_w)$$

where:

$Q_{e,ad}$ = actual flow rate of dry air, acfm (Must account for air at stack conditions of density and moisture. See example case for application)

D_e = density of emission stream, lbs/ft³

$L_{w,s}$ = saturated lb H_2O/lb dry air (from psychrometric chart)

$L_{w,a}$ = inlet lb H_2O/lb dry air (from psychrometric chart)

D_w = density of water vapor, lbs/ft³

The density of any gas can be approximated using the following formula:

$$D = (PM)/(RT)$$

where:

P = pressure of emission stream, atm

M = molecular weight of gas, lb/lb-mole

R = gas constant, 0.7302 atm ft³/lb-mol°R

T = temperature of gas, °R

Table 4.11-1. Pressure Drops for Typical Venturi Scrubber Applications[a]

Application	Pressure drop (in. H_2O)
Boilers	
Pulverized coal	15-40
Stoker coal	10-12
Bark	6-10
Combination	10-15
Recovery	30-40
Incinerators	
Sewage sludge	18-20
Liquid waste	50-55
Solid waste	
Municipal	10-20
Pathological	10-20
Hospital	10-20
Kilns	
Lime	15-25
Soda ash	20-40
Potassium chloride	30
Coal Processing	
Dryers	25
Crushers	6-20
Dryers	
General spray	20-60
Food spray	20-30
Fluid bed	20-30
Mining	
Crushers	6-20
Screens	6-20
Transfer points	6-20
Iron and steel	
Cupolas	30-50
Arc furnaces	30-50
BOFs	40-60
Sand systems	10
Coke ovens	10
Blast furnaces	20-30
Open hearths	20-30
Nonferrous metals	
Zinc smelters	20-50
Copper and brass smelters	20-50
Sinter operations	20
Aluminum reduction	50
Phosphorus	
Phosphoric acid	
Wet process	10-30
Furnace grade	40-80
Asphalt	
Batch plants—dryer	10-15
Transfer points	6-10
Glass	
Container	25-60
Plate	25-60
Borosilicate	30-60
Cement	
Wet process kiln	10-15
Transfer points	6-12

[a] Reference 1.

Table 4.11-2. Construction Materials for Typical Venturi Scrubber Applications[a]

Application	Construction Material
Boilers	
Pulverized coal	316L stainless steel
Stoker coal	316L stainless steel
Bark	Carbon steel
Combination	316L stainless steel
Recovery	Carbon steel or 316L stainless steel
Incinerators	
Sewage sludge	316L stainless steel
Liquid waste	High nickel alloy
Solid waste	
Municipal	316L stainless steel
Pathological	316L stainless steel
Hospital	High nickel alloy
Kilns	
Lime	Carbon steel or stainless steel
Soda ash	Carbon steel or stainless steel
Potassium chloride	Carbon steel or stainless steel
Coal Processing	
Dryers	304 stainless steel or 316L stainless steel
Crushers	Carbon steel
Dryers	
General spray dryer	Carbon steel or stainless steel
Food spray dryer	Food-grade stainless steel
Fluid bed dryer	Carbon steel or stainless steel
Mining	
Crushers	Carbon steel
Screens	Carbon steel
Transfer points	Carbon steel
Iron and Steel	
Cupolas	304-316L stainless steel
Arc furnaces	316L stainless steel
BOFs	Carbon steel (ceramic lined)
Sand systems	Carbon steel
Coke ovens	Carbon steel
Blast furnaces	Carbon steel (ceramic lined)
Open hearths	Carbon steel (ceramic lined)
Nonferrous Metals	
Zinc smelters	Stainless steel or high nickel
Copper and brass smelters	Stainless steel or high nickel
Sinter operations	Stainless steel or high nickel
Aluminum reduction	High nickel
Phosphorus	
Phosphoric acid	
Wet process	316L stainless steel
Furance grade	316L stainless steel
Asphalt	
Batch plants - dryer	Stainless steel
Transfer points	Carbon steel
Glass	
Container	Stainless steel
Plate	Stainless steel
Borosilicate	Stainless steel
Cement	
Wet process kiln	Carbon steel or stainless steel
Transfer points	Carbon steel

[a] Reference 1.

Example Case

Determination of saturated gas flow rate:

Emission stream flow rate, $Q_{e,a}$ = 110,000 acfm

Moisture content, M_e = 5% vol.

Emission stream temperature, T_e = 400°F

Convert M_e to units of lb H_2O/lb dry air, decimal fraction:

$(M_e/100)(18/29) = (5/100)(18/29)$
$= 0.031$ lb H_2O/lb dry air

$T_{e,s}$ = 127°F (Figure 4.11-2)

$L_{w,s}$ = 0.10 lb H_2O/lb dry air (Figure 4.11-2)

$L_{w,a}$ = 0.031 lb H_2O/lb dry air (Figure 4.11-2)

The density of air and water vapor is found below:

D_e = (1 atm) (29 lb/lb-mole)/(0.7302 atm ft^3/lb-mole °R) (127 + 460 °R)
= 0.0676 ft^3/lb

D_w = (1 atm) (18 lb/lb-mole)/(0.7302 atm ft^3/lb-mole °R) (127 + 460 °R)
= 0.042 ft^3/lb

Q_w = (1 - 0.031)(0.0676)(110,000)(0.10 - 0.031) (1/0.042) = 11,800 ft^3/min

and,

$Q_{e,s}$ = {(110,000) x (127 + 460)/(400 + 460)} + 11,800

$Q_{e,s}$ = 75,000 + 11,800 = 86,800 acfm

4.11.5 Evaluation of Permit Application

Using Table 4.11-3, compare the results of this section and the data supplied by the permit applicant. The calculated values in the table are based on the example. Compare the estimated P_v and the reported pressure drop across the venturi, as supplied by the permit applicant.

If the estimated and reported values differ, the differences may be due to the applicant's use of another performance chart, or a discrepancy between the required and reported collection efficiencies. Discuss the details of the design and operation of the system with the applicant. If there are no differences between the estimated and reported values for P_v, the design and operation of the system can be considered appropriate based on the assumptions employed in this manual.

4.11.6 Capital and Annual Costs for Venturi Scrubbers

The capital costs of a venturi scrubber system consists of purchased equipment costs and direct and indirect installation costs. The annual costs consist of direct and indirect annual costs.

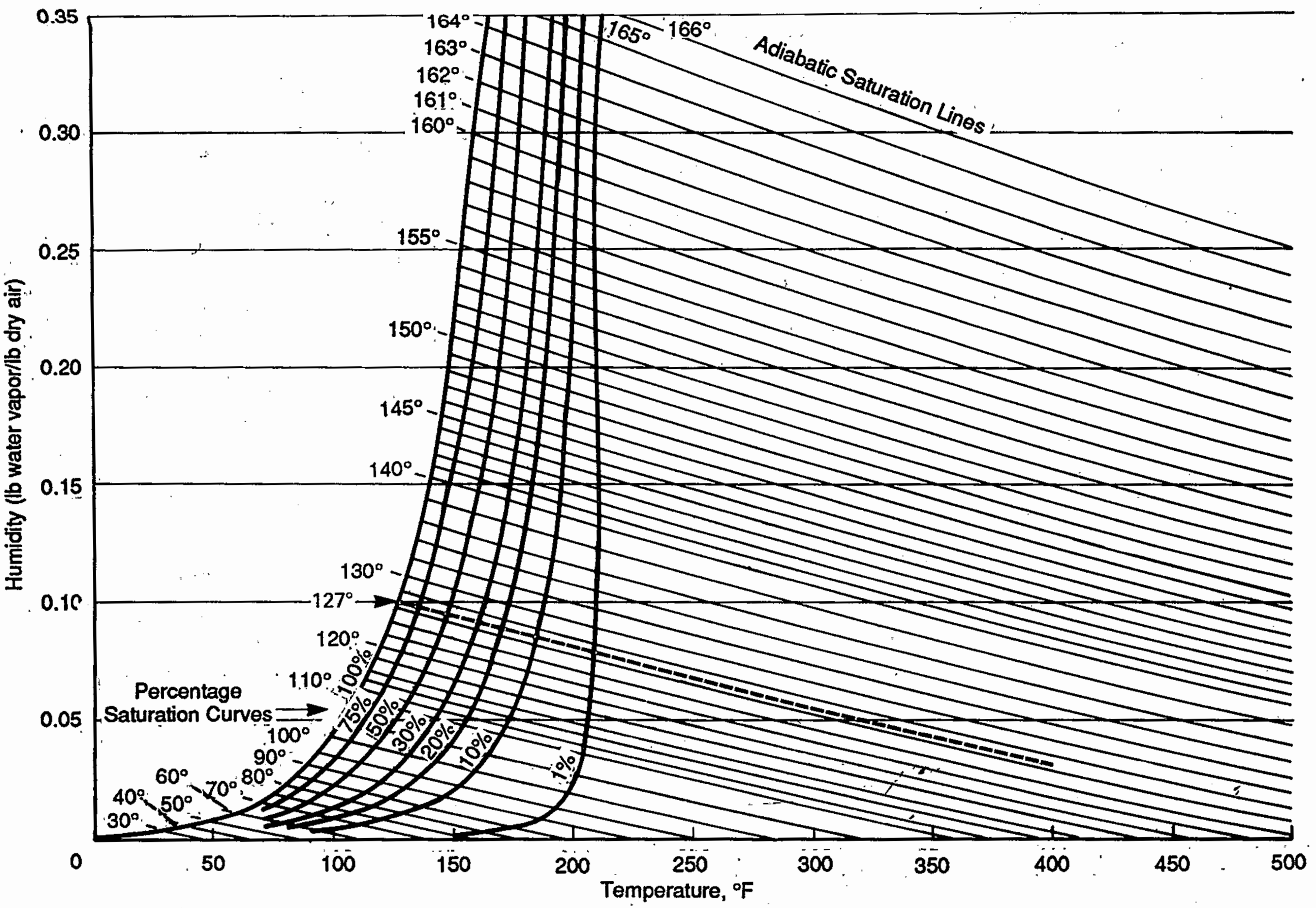

Figure 4.11-2. Psychrometric chart.

Table 4.11-3. Comparison of Calculated Values and Values Supplied by the Permit Applicant for Venturi Scrubbers[a]

Parameter	Calculated Value (Example Case)	Reported Value
Particle mean diameter, D_p	1.0 μm	...
Collection Efficiency, CE	0.999	...
Pressure drop, P_v	47 in. H_2O	...

[a] Based on the municipal incinerator emission stream.

4.11.6.1 Capital Costs of Venturi Scrubbers

Recent equipment cost information on venturi scrubbers was not available. Accordingly, vendor estimates of venturi scrubber costs were obtained as a function of the emission stream flow rate[7,8]. These equipment costs are detailed in Table 4.11-4. These costs include carbon steel construction and instrumentation but do not include auxiliary costs, sales tax, or freight. Refer to Section 4.12 to obtain auxiliary equipment costs which include ductwork, damper, fan, stack, and cyclone (if necessary) costs. If 304L stainless steel construction is used, multiply the carbon steel cost by a factor of 2.3. If 316L stainless steel is used, multiply the carbon steel cost by 3.2.[12] To obtain capital costs, use the direct and indirect installation cost factors taken from previous EPA publications. These factors are provided in Table 4.11-5.

Table 4.11-4. Venturi Scrubber Equipment Costs[a]

Flow rate (acfm)	Venturi Scrubber Cost ($)
$10{,}000 \le Q_{e,a} < 50{,}000$	$VSC = \$7{,}250 + 0.585\,(Q_{e,a})$
$50{,}000 \le Q_{e,a} \le 150{,}000$	$VSC = \$11.10\,(Q_{e,a})^{0.7513}$

[a] Carbon steel construction; includes cost of instrumentation. References 7 and 8.

Example Case

The venturi scrubber cost is obtained using Table 4.11-4, which yields a cost of $66,600 for an inlet flow rate of 110,000 acfm. This is multiplied by 3.2 to account for 316L stainless steel construction, which yields a cost of $213,000. Assume auxiliary equipment costs are $10,000. The equipment cost is thus $223,000. Table 4.11-5 is then used to obtain the purchased equipment cost (PEC). Note that instrumentation is included in the venturi scrubber purchase cost.

Sales tax = 0.03 (223,000) = $ 6,390
Freight = 0.05 (223,000) = 11,200
$17,600

The purchased equipment cost (PEC) is equal to $240,000. Table 4.11-5 is used to obtain the total capital costs of a venturi scrubber system. These costs are given in Table 4.11-6.

Table 4.11-5. Capital Cost Factors for Venturi Scrubber[a]

Cost Item	Factor
Direct Costs, DC	
Purchased Equipment Costs	
Venturi scrubber + auxiliary equipment	As estimated, EC
Instrumentation[b]	Included with EC
Sales tax	0.03 EC
Freight	0.05 EC
Purchased Equipment Cost, PEC	1.08 EC
Direct Installation Costs	
Foundation and supports	0.06 PEC
Erection and handling	0.40 PEC
Electrical	0.01 PEC
Piping	0.05 PEC
Insulation	0.03 PEC
Painting	0.01 PEC
Site preparation	As required, SP
Buildings	As required, Bldg.
Total Direct Costs	1.56 PEC + SP + Bldg.
Indirect Costs, IC	
Engineering	0.10 PEC
Construction	0.10 PEC
Contractor fee	0.10 PEC
Start up	0.01 PEC
Performance test	0.01 PEC
Contingency	0.03 PEC
Total Indirect Cost, IC	0.35 PEC
Total Capital Costs	1.91 PEC + SP + Bldg

[a] References 7 and 8.
[b] If not included with EC, estimate as 10 percent of the EC

4.11.6.2 Annual Costs for Venturi Scrubbers

The annual costs for venturi scrubber systems consist of direct and indirect annual costs. Appropriate factor for these costs are presented in Table 4.11-7.

Direct Annual Costs. Direct annual costs are composed of utility costs (electricity and water), operating labor, and maintenance costs. The costs of wastewater disposal are beyond the scope of this manual.

Electricity costs are a function of the fan power required to move the gas through the system. Equation 4.11-2 is used to estimate the fan power requirement assuming a fan-motor efficiency of 65 percent and a fluid specific gravity of 1.0.

$$F_p = 1.81 \times 10^{-4} (Q_{e,a})(P)(HRS) \qquad (4.11\text{-}2)$$

where:

F_p = fan power requirement, kWh/yr

$Q_{e,a}$ = emission stream flow rate, acfm

P = system pressure drop, in. H_2O

HRS = system operating hours, yr

Table 4.11-6. Example Case Capital Costs

Cost Item	Factor	Cost($)
Direct Costs, DC		
Purchased Equipment Costs		
Venturi scrubber & auxiliary equipment	As estimated, EC	$223,000
Instrumentation	Included with EC	--
Sales tax	0.03 EC	6,690
Freight	0.05 EC	11,200
Purchased Equipment Cost, PEC	1.08 EC	$241,000
Direct Installation Costs		
Foundation and supports	0.06 PEC	$ 14,500
Erection and handling	0.40 PEC	96,400
Electrical	0.01 PEC	2,400
Piping	0.05 PEC	12,000
Insulation	0.03 PEC	7,200
Painting	0.01 PEC	2,400
	0.56 PEC	$134,000
Site Preparation	As required, SP	
Building	As required, Bldg.	
Total Direct Cost, DC	1.56 PEC + SP + Bldg.	$375,000
Indirect Costs, IC		
Engineering	0.10 PEC	$ 24,000
Construction	0.10 PEC	24,000
Contractor fee	0.10 PEC	24,000
Start-up	0.01 PEC	2,400
Performance test	0.01 PEC	2,400
Contingency	0.03 PEC	7,200
Total Indirect Cost, IC	0.35 PEC	$ 84,000
Total Capital Cost, TCC = DC + IC	1.91 PEC + SP + Bldg.	$459,000 + SP + Bldg.

Table 4.11-7. Annual Cost Factors for Venturi Scrubbers[a]

Cost Item	Factor
Direct Annual Costs, DAC	
Utilities	
Electricity	\$0.059/kWh
Water	\$0.20/10^3 gal
Operating Labor	
Operator labor	\$12.96/hr
Supervisory labor	15 percent of operator labor
Maintenance	
Labor	\$14.26/hr
Materials	100 percent of maintenance labor
Wastewater treatment	Variable. Consult source for specific information
Indirect Annual Costs, IAC	
Overhead	0.60 (Operating labor + maintenance)
Administrative	2% of TCC
Insurance	1% of TCC
Property tax	1% of TCC
Capital recovery[b]	0.1628 (TCC)

[a] Reference: 9

[b] The capital recovery cost is estimated as: $i(1+i)^n/(1+i)^n - 1$
where: i = interest rate, 10 percent
n = equipment life, 10 years

The water consumption of a venturi scrubber is estimated from Equation 4.11-3. This equation assumes 0.01 gal of water are required per acf of flow.

$$WR = 0.60\,(Q_{e,a})\,HRS \qquad (4.11\text{-}3)$$

where:

WR = water consumption, gal/yr

The amount of operator labor is estimated as 2 hours per 8 hour shift. The operator labor wage rate is provided in Table 4.11-7. Supervisory costs are assumed to be 15 percent of operator labor costs.

The amount of maintenance labor is estimated as 1 hour per 8 hour shift. The maintenance wage rate is provided in Table 4.11-7. Maintenance materials are assumed to equal maintenance costs.

The cost of wastewater disposal or treatment is variable and not discussed here. Consult the source for an estimate of this cost. Actual costs may be quite high.

Indirect Annual Costs. These costs consist of overhead costs, administrative charges, property tax, and capital recovery costs. Table 4.11-7 provides appropriate factors for these costs.

Example Case

Direct Annual Costs

Electricity usage is estimated using Equation 4.11-2:

$$F_p = 1.81 \times 10^{-4}\,(110{,}000)(47)(6000)$$
$$= 5.61 \times 10^6 \text{ kWh/yr}$$

Electricity cost = \$0.059 (5.61×10^6)
= \$331,000/yr

Water consumption is estimated using Equation 4.11-3:

WR = 0.60 (110,000) (6,000) = 3.96×10^8 gal/yr

Water cost = \$0.20/1,000 gal (3.96×10^8)
= \$79,200/yr

Operating labor is estimated as:

[(2 hr/shift)/(8 hr/shift)] 6000 hr/yr = 1500 hr/yr

1500 hr/yr (\$12.96/hr) = \$19,400/yr

Supervisory costs are taken as 15 percent of this value or \$2,910.

Maintenance labor is estimated as:

[(1 hr/shift)/(8 hr/shift)] 6000 = 750 hr/yr

750 hr/yr (14.26/hr) = \$10,700 hr/yr

Maintenance materials are taken as 100 percent of this total, or \$10,700/yr.

For example purposes, wastewater treatment costs are assumed zero, but actual costs may be quite high.

Total Direct Costs = \$331,000 + \$79,200 + \$19,400 + \$2,910 + \$10,700 + \$10,700 = \$454,000

Indirect Annual Costs

These costs are obtained from the factors given in Table 4.11-7 and the example cases.

Overhead = 0.60 (\$19,400 + \$2,910 + \$10,700 + \$10,700)
= \$26,200

Administrative = 0.02 (\$459,000) = \$9,180

Insurance = 0.01 (\$459,000) = \$4,590

Property taxes = 0.01 (\$459,000) = \$4,590

Capital recovery = 0.1628 (\$459,000)
= \$74,700

Example Case (Cont'd)

Total Indirect Costs = \$26,200 + \$9,180
+ \$4,590 + \$4,590
+ \$74,700
= \$ 119,000

Total Annual Costs = \$454,000 + \$119,000
= \$573,000

4.11.7 References

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11. U.S. EPA. Handbook: Guidance on Setting Permit Conditions and Reporting Trial Burn Results. EPA 625/6-86-019. January 1989.
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4.12 Costs of Auxiliary Equipment

For purposes of this handbook, auxiliary equipment 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 Reference 1.

If equipment costs must be escalated to the current year, the Chemical Engineering (CE) equipment index^2 can be used. Monthly indices for five years are provided in Table 4.12-1.

4.12.1 Fan Purchase Cost

In general, fan costs are most closely correlated with fan diameter. Equations 4.12-1 through 4.12-3 can be used to obtain fan prices. Costs for carbon steel fan motor ranging in horsepower from 1 to 150 hp are provided in Equations 4.12-4 and 4.12-5. Equations 4.12-2 or 4.12-3 are used in conjunction with Equations 4.12-4 or 4.12-5.

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 multi-rating tables. The reader should be able to obtain the fan wheel diameter for a given ductwork diameter by consulting the appropriate multi-rating 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 inches of water, the cost as a function of fan diameter (d_{fan}) in July 1988 dollars is provided by Equation 4.12-1.

$$P_{fan} = 42.3\, d_{fan}^{1.20} \qquad (4.12\text{-}1)$$

where:

P_{fan} = cost of fan system, July 1988 \$

d_{fan} = fan diameter, in. ($12.25'' \le d_{fan} \le 36.5''$)

The cost of a fiber reinforced plastic (FRP) fan, not including the cost of a motor or starter, is provided by Equation 4.12-2. The cost of a motor and starter as obtained in Equation 4.10-4 or 4.10-5 should be added to the fan cost obtained in Equation 4.12-2.

$$P_{fan} = 53.7\, d_{fan}^{1.38} \qquad (4.12\text{-}2)$$

where:

P_{fan} = cost of fan without motor or starter, April 1988 \$

d_{fan} = fan diameter, in ($10.5'' \le d_{fan} \le 73''$)

A correlation for a radial-tip fan with welded, carbon steel construction, and an operating temperature limit of

Table 4.12-1. CE Equipment Index[a]

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] Reference 2.

1,000°F without a motor or starter is provided by Equation 4.12-3. The values for the parameters a and b are provided by Table 4.12-2.

$$P_{fan} = a_f\, d_{fan}^{\,b_f} \qquad (4.12\text{-}3)$$

where:

P_{fan} = cost of fan without motor or starter, July 1988 $

a_f , b_f = obtained from Table 4.12-2

d_{fan} = fan diameter, in.

Table 4.12-2. Equation 4.12-3 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

The cost of fan motors and starters is given in Equation 4.12-4 or 4.12-5 as a function of the horsepower (hp) requirement. The cost obtained from either of these equations should be added to the fan cost obtained in Equation 4.12-2 or 4.12-3. For low horsepower requirements,

$$P_{motor} = 235\ hp^{0.256} \qquad (4.12\text{-}4)$$

where:

P_{motor} = cost of fan motor, belt, and starter, February 1988 $

hp = motor horsepower ($1 \le hp < 7.5$)

For high horsepower requirements,

$$P_{motor} = 94.7\ hp^{0.821} \qquad (4.12\text{-}5)$$

where:

P_{motor} = cost of fan motor, belt and starter, February 1988 $

hp = motor horsepower ($7.5 \le Hp \le 250$)

Example Case

Let the required static pressure equal 8 inches of water with a fan diameter of 30 inches. Equation 4.12-1 can be used to obtain the fan cost as follows:

$$P_{fan} = 42.3\,(30)^{1.20}$$

$$P_{fan} = \$2{,}510$$

4.12.2 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 Equation 4.12-6. This equation assumes a duct velocity (U_{duct}) of 2,000 ft/min.

$$d_{duct} = 12\,[(4/\pi)(Q_{e,a}/U_{duct})]^{0.5} = 0.3028\,(Q_{e,a})^{0.5} \qquad (4.12\text{-}6)$$

The cost of PVC ductwork in $/ft for diameters between 6 and 24 inches is provided in Equation 4.12-7.

$$P_{PVCD} = a_d\, d_{duct}^{\,b_d} \qquad (4.12\text{-}7)$$

where:

P_{PVCD} = cost of PVC ductwork, $/ft (August 1988 $)

d_{duct} = duct diameter, in. (factor of 12 in/ft above)

a_d = 0.877 ($6" \le d_{duct} \le 12"$), or 0.0745 ($14" \le d_{duct} \le 24"$)

b_d = 1.05 ($6" \le d_{duct} \le 12"$), or 1.98 ($14" \le d_{duct} \le 24"$)

For FRP duct having a diameter between 2 and 5 feet, Equation 4.12-8 can be used to obtain the ductwork cost. Note that the duct diameter is in units of feet for this equation.

$$P_{FRPD} = 24\, D_{duct} \qquad (4.12\text{-}8)$$

where:

P_{FRPD} = cost of FRP ductwork, $/ft (August 1988 $)

D_{duct} = duct diameter, ft

It is more difficult to obtain ductwork costs for carbon steel and stainless steel construction because ductwork of this material is almost always custom fabricated. For more information on these costs, consult Reference 1.

Example Case

Let $Q_{e,a}$ = 15,300 acfm. Then the required duct diameter, d_{duct}, is obtained using Equation 4.12-6.

d_{duct} = $0.3028\,(15{,}300)^{0.5}$ = 37.4 inches (or 3.12 feet).

For a duct with this diameter, Equation 4.12-8 is applicable.

$P_{FRPD} = 24\,(3.12)$
$P_{FRPD} = \$74.90/\text{ft}$

Thus, for a 50-foot duct length, the cost of ductwork equals 50 ($74.90) = $3,750.

4.12.3 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 feet) FRP stacks can be roughly estimated as 150 percent 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 approximately 150 percent of the cost of corresponding ductwork (refer to Reference 1 for more information).

For larger stacks (200-600 feet) the cost is typically quite high, ranging from $1,000,000 to $5,000,000 for some applications. Equation 4.12-9 and Table 4.12-3 can be used to obtain costs of large stacks.

$$P_{stack} = a_s\, H_{stack}^{\,b_s} \qquad (4.12\text{-}9)$$

where:

P_{stack} = total capital cost of large stack, 10^6 $
H_{stack} = stack height, ft
a_s, b_s = refer to Table 4.12-3

Table 4.12-3. Parameters for Costs of Large Stacks[a]

Lining	Diameter (ft)	a	b
Carbon-steel 316-L Stainless Steel in top Section	15	0.0120	0.811
	20	0.0108	0.851
	30	0.0114	0.882
	40	0.0137	0.885
Acid resistant Firebrick	15	0.00602	0.952
	20	0.00562	0.984
	30	0.00551	1.027
	40	0.00633	1.036

[a] Reference 1.

Example Case

Assume a 50 foot FRP stack is required. The cost of this stack is approximately 150 percent the cost of an equal length of ductwork. From the example case given in Section 4.12-2, the cost of 50 feet of FRP ductwork is $3,750. The FRP stack cost is then 1.5 ($3,750) = $5,630.

4.12.4 Damper Purchase Cost

Dampers are commonly used to divert air flow in many industrial systems. Two types of dampers are discussed below: backflow and two-way diverter valve dampers. The cost of backflow dampers for duct diameters between 10 and 36 inches is given in Equation 4.12-10.

$$P_{damp} = 7.46\, d_{duct}^{\,0.944} \qquad (4.12\text{-}10)$$

where:

P_{damp} = cost of damper, February 1988 $
d_{duct} = ductwork diameter, in.

The cost of a two-way diverter valve for ductwork diameters between 13 and 40 inches are given in Equation 4.12-11.

$$P_{divert} = 4.84\ d_{duct}^{1.50} \qquad (4.12\text{-}11)$$

where:

P_{divert} = cost of two-way diverter valve, February 1988 \$

d_{duct} = duct diameter, in.

Example Case

Assume a diverter valve is required for a duct diameter of 37 inches. Equation 4.12-11 is used to obtain the damper cost as follows:

P_{damp} = $4.84\ (37)^{1.50}$

P_{damp} = \$1,090

4.12.5 Cyclone Purchase Cost

Cyclones are used upstream of particulate control devices (e.g., fabric filters, ESPs) to remove larger particles entrained in a gas stream. Equation 4.12-12 yields the cost of a carbon steel cyclone with support stand, fan and motor, and a hopper or drum to collect the dust.

$$P_{cyc} = 6{,}520\ A_{cyc}^{0.9031} \qquad (4.12\text{-}12)$$

where:

P_{cyc} = cost of cyclone, August 1988 \$

A_{cyc} = cyclone inlet area, ft^2
($0.200 \leq A_{cyc} \leq 2.64$ ft^2)

The cyclone inlet area can be calculated from Equation 4.12-13. In this equation, d_c is the critical particle size in µm. The critical particle size is the size of the smallest particle the cyclone can remove with 100 percent efficiency. Therefore simply select a critical particle size and then calculate the appropriate cyclone dimensions which will remove 100 percent of all particles that size and larger.

$$A_{cyc} = 3.34\ [Q_{e,a}(r_p - D_G) / \mu]^{1.33}\ (d_c)^{2.67} \qquad (4.12\text{-}13)$$

where:

$Q_{e,a}$ = actual emission stream flow rate, acfm

r_p = density of particles, lb/ft^3

D_G = density of emission stream, lb/ft^3

μ = *emission stream viscosity, lb/ft^3*

d_c = critical particle size, µm

The cost of a rotary air lock for the hopper or drum is given by Equation 4.12-14.

$$P_{ral} = 2{,}730\ A_{cyc}^{0.0965} \qquad (4.12\text{-}14)$$

where:

P_{ral} = Cost of rotary air lock, August 1988 \$

A_{cyc} = Cyclone inlet area, ft^2 ($0.350 \leq A_{cyc} \leq 2.64$ ft^2)

The cost of the complete cyclone unit is given by the sum of P_{cyc} and P_{ral}.

Example Case

Assume an emission stream actual flow rate of 1000 acfm, a 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-sec, and a critical particle size of 20 µm. Using Equation 4.12-13 the cyclone inlet area is:

A_{cyc} = $3.34\ [1{,}000\ (30-0.07)/1.41 \times 10^{-5}]^{1.33}\ [20 \times 10^{-6}]^{2.67}$

A_{cyc} = 2.41 ft^2

The cost of a cyclone is then obtained from Equation 4.12-12 as follows:

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

P_{cyc} = \$14,400

The cost of a rotary air lock for this system is given by Equation 4.12-14:

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

P_{ral} = \$2,970

The cost of a cyclone is the sum of these two costs, or \$17,400.

4.12.6 References

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2. Chemical Engineering. Equipment indices, McGraw-Hill Publishing, New York, NY. (Years indicated).

Appendix A.1
Listing of Compounds Currently Considered Hazardous[1]

CAS Number	HAP Name	CAS Number	HAP Name
83-32-9	Acenaphthene	106-99-0	Butadiene,1,3-
208-96-8	Acenaphthylene	106-97-8	Butane
75-07-0	Acetaldehyde	109-79-5	Butanethiol
64-19-7	Acetic Acid	78-93-3	Butanone,2-
108-24-7	Acetic Anhydride	1338-23-4	Butanoneperoxide,2-
67-64-1	Acetone	106-98-9	Butene,1-
75-05-8	Acetonitrile	140-32-2	Butyl Acrylate
74-86-2	Acetylene	71-36-3	Butyl Alcohol
50-78-2	Acetylsalicylic Acid	85-68-7	Butyl Benzyl Phthalate
107-02-8	Acrolein	123-86-4	Butylacetate,n-
79-06-1	Acrylamide	105-46-4	Butylacetate,sec-
79-10-7	Acrylic Acid	540-88-5	Butylacetate,tert-
107-13-1	Acrylonitrile	141-32-2	Butylacrylate,n-
15972-60-8	Alachlor	78-92-2	Butylalcohol,sec-
107-18-6	Allyl Alcohol	75-65-0	Butylalcohol,t-
7429-90-5	Aluminum	109-73-9	Butylamine,n-
133-90-4	Amiben	128-37-0	Butylated Hydroxytoluene
92-67-1	Aminobiphenyl,4-	2426-08-6	Butylglycidylether,n-
504-29-0	Aminopyridine,2-	138-22-7	Butyllactate,n-
7664-41-7	Ammonia	123-72-8	Butyraldehyde
12124-97-9	Ammonium Bromide	107-92-6	Butyric Acid
12125-02-9	Ammonium Chloride-Fume	7440-43-9	Cadmium
7783-20-2	Ammonium Sulfate	10108-64-2	Cadmium Chloride
628-63-7	Amylacetate,n-	1306-19-0	Cadmium Oxide
62-53-3	Aniline	2223-93-0	Cadmium Stearate
120-12-7	Anthracene	7440-70-2	Calcium
7440-36-0	Antimony	1305-62-0	Calcium Hydroxide
1327-33-9	Antimony Oxide	1305-78-8	Calcium Oxide
11097-69-1	Aroclor 1254	76-22-2	Camphor, Synthetic
7440-38-2	Arsenic and Compounds (as As)	105-60-2	Caprolactam
1303-28-2	Arsenic Pentoxide	133-06-2	Captan
1327-53-3	Arsenic Trioxide	63-25-2	Carbaryl
7784-42-1	Arsine	1563-66-2	Carbofuran
1332-21-4	Asbestos	7440-44-0	Carbon
8052-42-4	Asphalt (Petroleum) Fumes	1333-86-4	Carbon Black
1912-24-9	Atrazine	124-38-9	Carbon Dioxide
7440-39-3	Barium	75-15-0	Carbon Disulfide
10294-40-3	Barium Chromate	630-08-0	Carbon Monoxide
114-26-1	Baygon	56-23-5	Carbon Tetrachloride
56-55-3	Benz(a)Anthracene	353-50-4	Carbonyl Fluoride
98-87-3	Benzal Chloride	120-80-9	Catechol
100-52-7	Benzaldehyde	7782-50-5	Chlorine
71-43-2	Benzene	10049-04-4	Chlorine Dioxide
92-87-5	Benzidine	79-11-8	Chloroacetic Acid
205-99-2	Benzo(b)Fluoranthene	108-90-70	Chlorobenzene
191-24-2	Benzo(ghi)Perylene	75-45-6	Chlorodifluoromethane
207-08-9	Benzo(k)Fluoranthene	53449-21-9	Chlorodiphenyl
50-32-8	Benzo(a)Pyrene	75-00-3	Chloroethane
65-85-0	Benzoic Acid	67-66-3	Chloroform
120-51-4	Benzoic Acid, Benzyl Ester	107-30-2	Chloromethyl Methyl Ether, bis
98-07-7	Benzotrichloride	100-00-5	Chloronitrobenzene,
98-88-4	Benzoyl Chloride	4-76-15-3	Chloropentafluoroethane
94-36-0	Benzoyl Peroxide	3691-35-8	Chlorophacinone
12-05-58	Benzyl Benzoate	75-29-6	Chloropropane,2-
100-44-7	Benzyl Chloride	107-05-1	Chloropropene,3-
7440-41-7	Beryllium	2921-88-2	Chloropyrifos
92-52-4	Biphenyl	123-09-1	Chlorothioanisole
80-05-7	Bisphenol A	108-41-8	Chlorotoluene,M-
7440-42-8	Boron	95-49-8	Chlorotoluene,O-
1303-86-2	Boron Oxide	13907-45-4	Chromate, (CrO_4^{2-})
10294-33-4	Boron Tribromide	68131-98-6	Chrome Tanned Cowhide
7637-07-2	Boron Trifluoride	7738-94-5	Chromic Acid
7726-95-6	Bromine	13548-38-4	Chromic Nitrate
74-97-5	Bromochloromethane	7440-47-3	Chromium

[1] U.S. EPA, Shareef, G.S., M.T. Johnston, E.P. Epner, D. Ocamb, and C. Berry. *Tutorial Manual for CAT (Controlling Air Toxics) Version 1.0.* EPA/600/8-88/092, August 1988.

CAS Number	HAP Name	CAS Number	HAP Name
18540-29-9	Chromium (VI) Compounds (as Cr)	26761-40-0	Diisodecyl Phthalate
1333-82-0	Chromium Oxide	109-87-5	Dimethoxymethane
14977-61-8	Chromyl Chloride	127-19-5	Dimethyl Acetamide
7788-96-7	Chromyl Fluoride	115-10-6	Dimethyl Ether
218-01-9	Chrysene	131-11-3	Dimethyl Phthalate
8001-58-9	Coal Tar	77-78-1	Dimethyl Sulfate
8007-45-2	Coal Tar Pitch Volatiles	75-18-3	Dimethyl Sulfide
7440-48-4	Cobalt	124-40-3	Dimethylamine
1317-42-6	Cobalt Sulfide	60-11-7	Dimethylaminoazobenzene,4-
7440-50-8	Copper	1300-73-8	Dimethylaminobenzene,4-
1317-38-0	Copper Oxide (CuO)	121-69-7	Dimethylaniline,n,n-
13071-79-9	Counter 15 G	68-12-2	Dimethylformamide,n,n-
1319-77-3	Cresol (All Isomers)	123-91-1	Dioxane,1,4-
108-39-4	Cresol,m-	101-84-8	Diphenyl Oxide
95-48-7	Cresol,o-	101-68-8	Diphenylmethane Diisocyanate,4,4'-
106-44-5	Cresol,p-	1314-56-3	Diphosphorus Pentoxide
8021-39-4	Creosote	110-98-5	Dipropylene Glycol
14464-46-1	Cristobalite (SiO_2)	34590-94-8	Dipropylene Glycol Methyl Ether
123-73-9	Crotonaldehyde	64742-47-8	Distillates (Petroleum)
98-82-8	Cumene	106-89-8	Epichlorohydrin
101-14-4	Curene	75-08-1	Ethanethion
420-04-2	Cyanamide	64-17-5	Ethanol
590-28-3	Cyanic Acid, Potassium Salt	110-80-5	Ethoxyethanol,2-
917-61-3	Cyanic Acid, Sodium Salt	111-15-9	Ethoxyethylacetate,2-
57-12-5	Cyanide	141-78-6	Ethyl Acetate
143-33-9	Cyanides	140-88-5	Ethyl Acrylate (Inhibited)
506-68-3	Cyanogen Bromide	541-85-5	Ethyl Amyl Ketone
506-77-4	Cyanogen Chloride	100-41-4	Ethyl Benzene
110-82-7	Cyclohexane	60-29-7	Ethyl Ether
108-93-0	Cyclohexanol	759-94-9	Ethyldipropylcarbamsthioat, s-
108-94-1	Cyclohexanone	109-94-4	Ethyl Formate
110-83-8	Cyclohexene	78-10-4	Ethyl Silicate
542-92-7	Cyclopentadiene	74-85-1	Ethylene
112-31-2	Decanal	106-93-4	Ethylene Dibromide
124-18-5	Decane	107-06-2	Ethylene Dichloride
2238-07-5	di-2,3-Epoxypropyl Ether	107-21-1	Ethylene Glycol
84-74-2	di-n-Butyl Phthalate	110-49-6	Ethylene Glycol Methyl Ether Acetate
117-84-0	di-n-Octyl Phthalate	111-76-2	Ethylene Glycol Monobutyl Ether
123-42-2	Diacetone Alcohol	75-21-8	Ethylene Oxide
39393-37-8	Dialkyl Phthalates	107-15-3	Ethylenediamine
124-09-4	Diaminohexane,1,6-	151-56-4	Ethyleneimine
95-80-7	Diaminotoluene,2,4-	117-81-7	Ethylhexylphthalate,Bis,2-
333-41-5	Diazinon	16219-75-3	Ethylidene-2-Norbornene
53-70-3	Dibenz(a,h)Anthracene	12604-58-9	Ferrovanadium Dust
19287-45-7	Diborane	206-44-0	Fluoranthene
96-12-8	Dibromochloropropane,1,2-,3-	86-73-7	Fluorene
95-50-1	Dichlorobenzene,1,2-	53-96-3	Fluorenylacetamide,n-,2-
91-94-1	Dichlorobenzidine,3,3'-	16984-48-8	Fluorides
110-56-5	Dichlorobutane,1,4-	7782-41-4	Fluorine
75-71-8	Dichlorodifluoromethane	75-69-4	Fluorotrichloromethane
75-34-3	Dichloroethane,1,1-	50-00-0	Formaldehyde
75-35-4	Dichloroethylene,1,1-	75-12-7	Formamide
540-59-0	Dichloroethylene,1,2-,Cis-,Trans-	64-18-6	Formic Acid
156-60-5	Dichloroethylene,1,2-,Trans-	110-00-9	Furan
75-43-4	Dichloromonofluoromethane	98-01-1	Furfural
594-72-9	Dichloronitroethane,1,1,1-	98-00-0	Furfuryl Alcohol
120-83-2	Dichlorophenol,2,4-	110-17-8	Fumaric Acid
94-75-7	Dichlorophenoxyacetic-acid,2,4-	8006-61-9	Gasoline
78-87-5	Dichloropropane,1,2-	111-30-8	Glutaraldehyde
542-75-6	Dichloropropene,1,3-	56-81-5	Glycerol
77-73-6	Dicyclopentadiene	556-52-5	Glycidol
111-42-2	Diethanolamine	111-71-7	Heptanal
96-22-0	Diethyl Ketone	142-82-5	Heptane
84-66-2	Diethyl Phthalate	87-68-3	Hexachloro-1,3- Butadiene
109-89-7	Diethylamine	118-74-1	Hexachlorobenzene
100-37-8	Diethylaminoethanol	77-47-4	Hexachlorocyclopentadiene
111-46-6	Diethylene Glycol	34465-46-8	Hexachlorodibenzodioxin,1,2,3,6,7,8-
111-40-0	Diethylenetriamine	67-72-1	Hexachloroethane
108-83-8	Diisobutyl Ketone	684-16-2	Hexafluoroacetone

Appendix A.1 (cont)

CAS Number	HAP Name	CAS Number	HAP Name
66-25-1	Hexanal	563-80-4	Methyl Isopropyl Ketone
110-54-3	Hexane,n-	74-94-1	Methyl Mercaptan
591-78-6	Hexanone,2-	80-62-6	Methyl Methacrylate
142-92-7	Hexylacetate,sec-	110-43-0	Methyl n-Amyl Ketone
107-41-5	Hexylene Glycol	98-83-9	Methyl Styrene
302-01-2	Hydrazine	78-94-4	Methyl Vinyl Ketone
122-66-7	Hydrazobenzene	137-05-3	Methyl-2-Cyanoacrylate
7647-01-1	Hydrochloric Acid	100-61-8	Methylaniline,n-
10035-10-6	Hydrogen Bromide	583-60-8	Methylcyclohexanone,o-
7647-01-0	Hydrogen Chloride	75-09-2	Methylene Chloride
74-90-8	Hydrogen Cyanide	101-77-9	Methylenedianiline,4,4'-
7664-39-3	Hydrogen Fluoride	108-11-2	Methylisobutylcarbin
7722-84-1	Hydrogen Peroxide(30%)	108-10-1	Methylpentanone,4-,2-
7783-07-5	Hydrogen Selenide	872-50-4	Methylpyrrolidone,n-,2-
7783-06-4	Hydogen Sulfide	12001-26-2	Mica (VAN8CI9CI)
123-31-9	Hydroquinone	7439-98-7	Molybdenum
193-39-5	Indeno(1,2,3-c,d)Pyrene	108-90-7	Monochlorobenzene
7440-74-6	Indium	141-43-5	Monoethanolamine
7553-56-2	Iodine	75-04-7	Monoethylamine
74-88-4	Iodomethane	74-89-5	Monomethylamine
15438-31-0	Iron	110-91-8	Morpholine
1309-37-1	Iron Oxide Fume	107-87-9	n-Methyl Propyl Ketone
123-92-2	Isoamyl Acetate	684-93-5	n-Nitroso-n-Methylurea
110-19-0	Isobutyl Acetate	62-75-9	n-Nitrosodimethylamine
78-83-1	Isobutyl Alcohol	8030-30-6	Naphtha
78-84-2	Isobutyraldehyde	91-20-3	Naphthalene
26952-21-6	Isooctyl Alcohol	134-32-7	Naphthylamine,1-
78-59-1	Isophorone	91-59-8	Naphthylamine,2-
78-79-5	Isoprene	7440-02-2	Nickel
67-63-0	Isopropanol	13463-39-3	Nickel Carbonyl
109-59-1	Isopropoxyethanol	1313-99-1	Nickel Oxide
108-21-4	Isopropyl Acetate	7440-02-0	Nickel Powder
108-20-3	Isopropyl Ether	7697-37-2	Nitric Acid
8001-20-6	Kerosene	10102-43-9	Nitric Oxide
463-51-4	Ketene	100-01-6	Nitroaniline,p-
301-04-2	Lead Acetate	98-95-3	Nitrobenzene
18454-12-1	Lead Chromate	92-93-3	Nitrodiphenyl,4-
1309-60-0	Lead Dioxide	79-24-3	Nitroethane
7439-92-1	Lead Powder	10102-44-0	Nitrogen Dioxide
8032-32-4	Ligroine	55-63-0	Nitroglycerine
1310-65-2	Lithium Hydroxide	75-52-5	Nitromethane
7439-95-4	Magnesium	100-02-7	Nitrophenol,p-
1309-48-4	Magnesium Oxide	108-03-2	Nitropropane,1-
1309-48-8	Magnesium Oxide Fume	79-46-9	Nitropropane,2-
121-75-5	Malathion	99-99-0	Nitrotoluene,p-
108-31-6	Maleic Anhydride	124-19-6	Nonanal
7439-96-5	Manganese	111-84-2	Nonane,n-
104-14-4	Mboca	3268-87-9	Octachlorodibenzo-p-Dioxin
7725-93-1	Mercaptomethylthiazolylmethylketone,2	124-13-0	Octanal
7439-97-6	Mercury	111-65-9	Octane
141-79-7	Mesityl Oxide	8012-95-1	Oil Mist, Mineral
79-41-4	Methacrylic Acid	1317-71-1	Olivine
74-93-1	Methanethiol	144-62-7	Oxalic Acid (Anhydrous)
67-56-1	Methanol	7783-41-7	Oxygen Difluoride
16752-77-5	Methomyl	10028-15-6	Ozone
72-43-5	Methoxychlor	106-51-4	p-Quinone
109-86-4	Methoxyethanol,2-	8002-74-2	Paraffin Wax Fume
79-20-9	Methyl Acetate	87-86-5	Pentachlorophenol
74-99-7	Methyl Acetylene	504-60-9	Pentadiene Isomer
96-33-3	Methyl Acrylate	115-77-5	Pentaerythritol
74-83-9	Methyl Bromide	109-66-0	Pentane
78-78-4	Methyl Butane	79-21-0	Peracetic Acid (40% Solution)
74-87-3	Methyl Chloride	594-42-3	Perchloromethyl Mercaptan
107-30-2	Methyl Chloromethyl Ether	7616-94-6	Perchloryl Fluoride
8022-00-2	Methyl Demeton	64741-88-4	Petro Distill (Heavy)
624-92-0	Methyl Disulfide	8002-05-9	Petroleum Distillates
107-31-3	Methyl Formate	85-01-8	Phenanthrene
110-12-3	Methyl Isoamyl Ketone	108-95-2	Phenol
624-83-9	Methyl Isocyanate	122-60-1	Phenyl Glycidyl Ether

Appendix A1 (cont)

CAS Number	HAP Name	CAS Number	HAP Name
122-39-4	Phenylbenzenamine,n-	13494-80-9	Tellerium and Compounds (as Te)
106-50-3	Phenylenediamine,p-	26140-60-3	Terphenyl
298-02-2	Phorate	75-65-1	t-Butyl Alcohol
75-44-5	Phosgene	634-66-2	Tetrachlorobenzene,1,2,3,4-
7803-51-2	Phosphine	1746-01-6	Tetrachlorodibenzo-p-Dioxin,2,3,7,8-
7664-38-2	Phosphoric Acid	76-12-0	Tetrachlorodifluoroethane,1,1,2,2-,1,2-
7723-14-0	Phosphorous (Yellow)	79-34-5	Tetrachloroethane,1,1,2,2-
10025-87-3	Phosphorous Oxychloride	127-18-4	Tetrachloroethylene
7719-12-2	Phosphorous Trichloride	3689-24-5	Tetraethyl Dithiopyrophosphate
85-44-9	Phthalic Anhydride	78-00-2	Tetraethyl Lead
88-89-1	Picric Acid	1320-37-2	Tetrafluorodichloroethane
80-56-8	Pinene,a-	109-99-9	Tetrahydrofuran
7440-06-4	Platinum	27813-21-4	Tetrahydropthalimide
1336-36-3	Polychlorinated Biphenyls	7722-88-5	Tetrasodium Pyrophosphate
25322-69-4	Polypropylene Glycol	7440-28-0	Thallium, Soluble Compounds (as Tl)
9002-86-2	Polyvinyl Chloride Latex	463-71-8	Thiophosgene
7440-09-7	Potassium	110-02-1	Thiophene
7789-00-6	Potassium Chromate	62-56-6	Thiourea
151-50-8	Potassium Cyanide	137-26-8	Thiram
7778-50-9	Potassium Dichromate	7440-31-5	Tin (as Sn)
1310-58-3	Potassium Hydroxide	13463-67-7	Titanium Dioxide
75-28-5	Propane, 2-Methyl-	108-88-3	Toluene
1120-71-4	Propane Sultone	26471-62-5	Toluene Diisocyanate
57-55-6	Propanediol,1,2-	584-84-9	Toluene,2,4,Diisocyanate
57-57-8	Propiolacetone,b-	95-53-4	Toluidine,o-
123-38-6	Propionaldehyde	126-73-8	Tributyl Phosphate
79-09-4	Propionic Acid	87-61-6	Trichlorobenzene,1,2,3-
71-23-8	Propyl Alcohol	120-82-1	Trichlorobenzene,1,2,4-
109-60-4	Propylacetate,n-	71-55-6	Trichloroethane,1,1,1-
107-10-8	Propylamine	79-00-5	Trichloroethane,1,1,2-
115-07-1	Propylene	79-01-6	Trichloroethylene
6423-43-4	Propylene Glycol Dinitrate	96-18-4	Trichloropropane,1,2,3-
107-98-2	Propylene Glycol Monomethyl Ether	76-13-1	Trichlorotrifluoromethane,1,1,2-
75-56-9	Propylene Oxide	121-44-8	Triethylamine
503-30-0	Propylene Oxide,1,3-	75-63-8	Trifluormonobromomethane
129-00-0	Pyrene	1582-09-8	Trifluralin
121-29-9	Pyrethrin	552-30-7	Trimellitic Anhydride
8003-34-7	Pyrethrum	75-50-3	Trimethylamine
110-86-1	Pyridine	25551-13-7	Trimethylbenzene
14808-60-7	Quartz (Silica Dust)	58784-13-7	Trimethylphenyl n-Methylcarbamate
91-22-5	Quinoline	110-88-3	Trioxane,1,3,5-
108-46-3	Resorcinol	115-86-6	Triphenyl Phosphate
10049-07-7	Rhodium Chloride	7440-33-7	Tungsten and Compounds (as W)
7782-49-2	Selenium Compounds (as Se)	8006-64-2	Turpentine
7803-62-5	Silane	7440-61-1	Uranium
7631-86-9	Silica	51-79-6	Urethane
60676-86-0	Silica Vitreous	7440-62-2	Vanadium
7440-21-3	Silicon	1314-62-1	Vanadium Pentoxide
409-21-2	Silicon Carbide	62-73-7	Vapona
7440-22-4	Silver	108-05-4	Vinyl Acetate
7631-90-5	Sodium Bisulfate	75-01-4	Vinyl Chloride
10588-01-9	Sodium Dichromate	75-02-5	Vinyl Fluoride
7681-49-4	Sodium Fluoride	25013-15-4	Vinyl Toluene
1310-73-2	Sodium Hydroxide	75-05-4	Vinylidene Chloride
7681-57-4	Sodium Metabisulfate	1330-20-7	Xylene
131-52-2	Sodium Pentachloro-	108-38-3	Xylene,m-
10102-18-8	Sodium Selenite	95-47-6	Xylene,o-
1302-67-6	Spinel	106-42-3	Xylene,p-
8052-41-3	Stoddard Solvent	7440-65-5	Yttrium
7789-06-2	Strontium Chromate	7440-66-6	Zinc
100-42-5	Styrene	7699-45-8	Zinc Bromide
7446-09-5	Sulfur Dioxide	7646-85-7	Zinc Chloride, Fume
2551-62-4	Sulfur Hexafluoride	13530-65-9	Zinc Chromate (as Cr)
10025-67-9	Sulfur Monochloride	1314-13-2	Zinc Oxide (Fume)
7446-11-9	Sulfur Trioxide	1314-84-7	Zinc Phosphide
7664-93-9	Sulfuric Acid	13597-46-1	Zinc Selenite
14807-96-6	Talc	557-05-1	Zinc Stearate
7727-43-7	Tbariumsulfate, Total Dust	440-67-2	Zirconium Compounds (as Zr)

Appendix A.2
Toxic Air Pollutant/Source Crosswalk
(Listing of Pollutants by SIC and SCC Classification)

SIC	SIC Code Description	SCC Code	Associated Pollutants
01	AGRICULTURAL PRODUCTION CROPS		Benzene, 1,2-Dichloro- (16); Benzene, 1,3-Dichloro- (16); Benzene, 1,4-Dichloro- (16); Formaldehyde (26); Kestrel (Pesticide) (16); Phenolsulfonic Acids (16)
		2	Formaldehyde (26)
0111	Wheat		Carbon Tetrachloride (7); Ethane, 1,2-Dichloro- (8)
0112	Rice		Carbon Tetrachloride (7); Ethane, 1,2-Dichloro- (8)
0116	Soybeans		Carbon Tetrachloride (7); Ethane, 1,2-Dichloro- (8)
0119	Cash grains, nec		Ethane, 1,2-Dichloro- (8)
0133	Sugarcane and sugar beets		Biphenyl (27); Chlorine (27); Phenol, 2,4-Dichloro- (27); Polycyclic Organic Matter (26); Sodium Hydroxide (27)
		1-02-011-01	Polycyclic Organic Matter (26)
0174	Citrus fruits		Ammonia (27)
018	Horticultural Specialties		Ethane, 1,1,2-Trichloro- (28); Ethylene Oxide (21,22,28); Thiram (22)
0181	Ornamental nursery products		Hydrogen Sulfide (21,22,23,28)
0182	Food crops grown under cover		Ethane, 1,1,1-Trichloro- (28); Polyvinyl Chloride Latex (28)
0191	General farms, primarily crop		Carbon Tetrachloride (7); Ethane, 1,2-Dichloro- (8)
02	AGRICULTURAL PRODUCTION LIVESTOCK		Ethylene Oxide (15)
0211	Beef cattle feedlots		Ammonia (26); Ethane, 1,1,1-Trichloro- (28); Polyvinyl Chloride Latex (28)
		3-02-020-01	Ammonia (26)
0212	Beef cattle, except feedlots		Hydrogen Fluoride (21,22); Silica (22)

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Appendix A.3
Potential HAP's for Solvent Usage Operations

		Solvent Degreasing	Dry Cleaning	Graphic Arts[1]	Waste Solvent Reclaiming	SC[2]-Flatwood Paneling[3]	SC-Machinery[4]	SC-Appliances[5]	SC-Metal Furniture	SC-Auto/Truck[6]	SC-Fabrics	SC-Cans[7]	SC-Paper, Tapes, Labels	Magnetic Tape Coating	SC-Electrical Insulation	SC-Marine Vessels[8]	Vinyl & Acrylic Coatings[9]	SC-Wood Furniture	SC-Trans. Vehicles[10]	Machine Lubricants	Rubber Tire Manufacturing
Aliphatic Hydrocarbons	*Specific Compounds*																				
	Cyclohexane	●												●							
	Generic Compounds																				
	Naptha's mineral spirits	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●		●
	Stoddard solvent			●																	
	Alicyclics		●				●														
Aromatic Hydrocarbons	*Specific Compounds*																				
	Benzene	●	●								●									●	
	Toluene	●		●		●	●	●	●	●		●	●	●		●		●	●		●
	Xylenes	●	●	●		●	●	●	●	●		●	●	●		●		●	●		●
	Napthalene[11]																				
	Generic Compounds																				
	Other aromatics[12]				●	●	●	●	●	●		●	●		●			●	●	●	
Halogenated Hydrocarbons	*Specific Compounds*																				
	Chloromethane[11]																				
	Methylene chloride	●			●																
	Chloroform[11]																				
	Carbon tetrachloride	●	●	●																	
	1,1-dichloroethane										●										
	Trichloroethylene	●	●		●						●										
	1,1,1-trichloroethane	●																			
	Tetrachloroethylene	●	●																		
	Trichlorotrifluoroethane	●	●		●																
	Chlorobenzene	●									●										
	o,p-Dichlorobenzene	●									●										
	Generic Compounds																				
	Halogenated solvents	●			●																
Alcohols Glycols Ethers Epoxides Phenols	*Specific Compounds*																				
	Methanol			●		●				●											●
	Ethylene glycol			●		●		●		●		●	●						●		
	Propylene oxide											●									
	Cresols														●						
	Phenol			●																	
	Generic Compounds																				
	Alcohols	●		●		●	●	●	●	●		●	●	●				●	●		●
	Glycols								●											●	
	Cellusolves			●		●	●	●		●		●	●	●	●	●		●	●		
	Ethers	●		●			●	●													
	Phenols				●															●	
	Epoxides											●									

(continued on next page)

1. Category includes organic compounds associated with inks and solvents used in flexography, lithography, offset printing, and textile printing.
2. SC: surface coating.
3. Category includes coating of other flat stock.
4. Category includes coating of miscellaneous metal parts and coating of machinery and equipment.
5. Category includes all categories of appliances; large and small.
6. Category inlcludes coating of automobiles and light duty trucks as well as automobile refinishing.
7. Category includes surface coating of coils, cans, containers, and closures.
8. Category includes coating of pleasure and commercial marine vessels and maintenance of vessels.
9. Category includes vinyl, acrylic, and nitrocellulose coatings.
10. Category includes surface coating of trucks, buses, railroad cars, and other transportation vehicles.
11. No information on specific categories using these compounds was located.
12. Category includes polycyclic organic matter.

		Solvent Degreasing	Dry Cleaning	Graphic Arts[1]	Waste Solvent Reclaiming	SC[2]-Flatwood Paneling[3]	SC-Machinery[4]	SC-Appliances[5]	SC-Metal Furniture	SC-Auto/Truck[6]	SC-Fabrics	SC-Cans[7]	SC-Paper, Tapes, Labels	Magnetic Tape Coating	SC-Electrical Insulation	SC-Marine Vessels[8]	Vinyl & Acrylic Coatings[9]	SC-Wood Furniture	SC-Trans. Vehicles[10]	Machine Lubricants	Rubber Tire Manufacturing
Ketones Aldehydes	*Specific Compounds*																				
	Formaldehyde									●	●										
	Acetaldehyde[11]																				
	Furfural																●				
	Acetone	●		●		●	●		●	●			●			●		●	●		
	Acrolein (propenal)[11]																				
	Methyl ethyl ketone	●		●		●	●	●	●	●		●	●	●	●	●	●	●	●		
	Methyl isobutyl ketone			●		●	●		●	●		●	●	●		●		●	●		
	Cyclohexanone											●									
	Generic Compounds																				
	Aldehydes											●									
	Ketones			●		●	●	●	●	●		●	●					●	●		●
Esters Amides	*Specific Compounds*																				
	Ethyl acetate			●		●	●		●	●		●	●		●	●		●	●		
	Generic Compounds																				
	Esters			●		●	●	●	●	●		●	●	●				●	●	●	●
	Amides											●									
	Nitrosamines																			●	
Particulates	*Specific Compounds*																				
	Cadmium						●	●	●	●						●			●		
	Chromium						●	●	●	●						●			●		
	Lead						●	●	●	●						●			●		
	Zinc						●	●	●	●						●			●		
Acids Nitriles	*Specific Compounds*																				
	Nitrobenzene[11]																				
	Generic Compounds																				
	Organic acids									●											
	Nitriles				●																
	Nitrocompounds											●									
Heterocyclic Compounds	*Specific Compounds*																				
	Tetrahydrofuran											●		●							
	Furfural																●				
	Generic Compounds																				
	Pyrrolidones								●												
Miscellaneous Trade Solvents	So Cal I + II					●															
	Solvesso 100 + 150									●		●									
	Panasolve											●									
	Hi Sol 100											●									
	Tenneco T-125											●									

Appendix B.1
Gas Stream Parameters Calculations

At many plants, it is common that one pollution control system serves several emission sources. In such situations, the combined emission stream parameters must be calculated from mass and heat balances. Procedures for calculating the combined emission stream and single emission stream parameters listed below are provided in this appendix.

B.1.1 Flow Rate and Temperature
B.1.2 Moisture Content, SO_3 Content, and Dew Point
B.1.3 Particulate Matter Loading
B.1.4 Heat Content

B.1.1 Emission Stream Flow Rate And Temperature Calculations

Only gas volumes at standard conditions (77°F, 1 atm) can be added together. Thus, volumes of all gas streams must first be converted to volumes at standard conditions. This calculation is shown below. (Note: It is assumed that the emission streams are approximately at atmospheric conditions; therefore, pressure corrections are not necessary.)

$$Q_{e1,a} \times \frac{537}{460+T_{e1}} = Q_{e1}$$

where:

$Q_{e1,a}$ = flow rate of gas stream #1 at actual conditions (acfm)
T_{e1} = temperature of gas stream #1 (°F)
Q_{e1} = flow rate of gas stream #1 at standard conditions (scfm)

This calculation is repeated for each emission stream which, when combined, will be served by the control system. The total gas stream volumetric flow rate at standard conditions (Q_e) is calculated by adding all gas streams, as follows:

$$Q_{e1} + Q_{e2} + \ldots = Q_e$$

where:

Q_e = flow rate of combined gas stream (scfm)

The temperature of the combined gas stream (T_e) must be calculated to convert this combined volumetric flow rate at standard conditions (Q_e) to actual conditions ($Q_{e,a}$).

The temperature of the combined gas stream (T_e) is determined by first calculating the enthalpy (sensible heat content) of each individual stream. The calculation procedures are shown below.

$$Q_{e1} \times \frac{0.018\text{Btu}}{\text{ft}^3-{}^\circ\text{F}} \times (T_{e1} - 77) = H_{s1}$$

where:

T_{e1} = temperature of gas stream #1 (°F)
H_{s1} = sensible heat content of gas stream #1 (Btu/min)

This calculation is repeated for each emission stream. The total sensible heat is calculated as follows:

$$H_{s1} + H_{s2} + \ldots = H_s$$

where:

H_s = sensible heat of combined gas stream (Btu/min)

The combined gas stream temperature (T_e) is calculated as follows:

$$H_s \times \frac{\text{ft}^3-{}^\circ\text{F}}{0.018\text{Btu}} \times \frac{1}{Q_e} = T_e$$

where:

T_e = temperature of combined gas stream (°F)

The actual combined gas stream volumetric flow rate at actual conditions ($Q_{e,a}$) is then determined as follows:

$$Q_e \times \frac{460+T_e}{537} = Q_{e,a}$$

where:

$Q_{e,a}$ = flow rate of combined gas stream at actual conditions (acfm)

B.1.2 Moisture Content, SO_3 Content, and Dew Point Calculations

Moisture content is typically reported as a volume percent. The calculation procedures require that the volume percent moisture content of each stream be converted to a lb-mole basis, added together, and then divided by the total combined gas stream volumetric flow rate (Q_e) to obtain the moisture content of the combined gas stream. The moisture content is calculated below both on a volume percent and mass percent basis. The mass basis is to allow for the dew point calculation.

The moisture content is converted from a volume percent basis to a lb-mole basis as follows:

$$M_{e1} \times \frac{1}{100\%} \times Q_{e1} \times \frac{\text{lb-mole}}{392\,\text{scf}} = M_{e1,lm}$$

where:

M_{e1} = moisture content of gas stream #1 (% vol)

$M_{e1,lm}$ = moisture content of gas stream #1 (lb-mole/min)

This calculation is repeated for each emission stream to be combined. The moisture content is the combined gas stream on a volume percent basis (M_e) is calculated by adding, as follows:

$$M_{e1,lm} + M_{e2,lm} + \ldots = M_{e,lm}$$

$$M_{e,lm} \times \frac{392\,\text{scf}}{\text{lb-mole}} \times \frac{1}{Q_e} \times 100\% = M_e$$

where:

$M_{e,lm}$ = moisture content of combined gas stream (lb-mole/min)

M_e = moisture content of combined gas stream (% vol)

The moisture content of the combined stream must be reported on a mass basis ($M_{e,m}$) to determine the dew point. This is calculated as follows:

$$M_{e,lm} \times \frac{18\,\text{lb}}{\text{lb-mole}} = M_{e,m}$$

where:

$M_{e,m}$ = moisture content of combined gas stream (lb/min)

The amount of dry air in the combined gas stream (DA_e) is calculated as follows:

$$Q_e \times \frac{\text{lb-mole}}{392\,\text{scf}} \times \frac{29\,\text{lb}}{\text{lb-mole}} = DA_e$$

where:

DA_e = dry air content of combined gas stream (lb/min)

Calculate the psychrometric ratio as follows:

$M_{e,m}/(DA_e - M_{e,m})$ = psychrometric ratio (lb of water/lb dry air)

Knowing the psychrometric ratio and the gas stream temperature, the dew point temperature is selected from Table B.1.1.

The presence of sulfur trioxide (SO_3) in the gas stream increases the dew point of the stream. If the SO_3 component is ignored during the dew point determination, condensation may occur when not expected. In addition to the problems associated with the entrainment of liquid droplets in the gas stream, the SO_3 will combine with the water droplets to form sulfuric acid, which causes severe corrosion on metal surfaces and deterioration of many fabrics used in baghouses. Therefore, the determination of the stream dew point must consider the presence of SO_3. With information on the SO_3 content (ppm vol) and the moisture content (% vol) of the gas stream, the "acid" dew point temperature can be determined from Figure B.1-1. Figure B.1-1. provides dew points for three

Table B.1-1. Dew Point Temperatures

Psychrometric Ratio	Gas Stream Temperature (°F) 70	80	90	100	120	140	160	180	200	220	240
	Dew Point Temperature (°F)										
0.000	0	0	0	0	0	0	0	0	0	0	0
0.005	54	58	61	65	70	76	81	86	89	93	96
0.010	62	65	68	71	77	82	86	90	94	97	100
0.015	68	72	75	77	82	86	90	94	97	100	103
0.020		77	80	82	87	91	94	97	100	103	106
0.025			85	87	91	94	98	101	103	106	109
0.030			89	91	95	98	100	104	107	109	111
0.035				95	98	101	104	107	109	110	114
0.040				98	101	104	107	109	111	114	116
0.045					104	107	109	112	114	116	118
0.050					107	109	112	114	116	118	120
0.055					109	112	114	116	118	120	122
0.060					111	114	116	118	120	122	124
0.065					114	116	118	120	122	124	125
0.070					116	118	120	122	123	125	130
0.075					118	120	122	124	125	130	150
0.080					119	122	123	125	130	140	170
0.085						123	125	130	143	168	182
0.090						124	130	140	162	180	205
0.095						128	140	165	180	205	225

moisture levels; however, dew points can be estimated for other moisture values.

The SO_3 content of a combined gas stream is calculated by first converting the SO_3 concentration of each individual stream to a lb-mole (lm) basis. The SO_3 content is calculated as follows:

$$S_{e1} \times \frac{1}{10^6} \times Q_{e1} \times \frac{\text{lb-mole}}{392\,\text{scf}} = S_{e1,lm}$$

where:

S_{e1} = SO_3 content of gas stream #1 (ppm vol)

$S_{e1,lm}$ = SO_3 content of gas stream #1 (lb-mole/min)

This is repeated for each separate gas stream. These are then added to obtain the total SO_3 content of the combined gas stream to the control device as follows:

$$S_{e1,lm} + S_{e2,lm} + \ldots = S_{e,lm}$$

$$S_{e,lm} \times \frac{392\,\text{scf}}{\text{lb-mole}} \times \frac{10^6}{Q_e} = S_e$$

where:

$S_{e,lm}$ = SO_3 content of combined gas stream (lb-mole/min)

S_e = SO_3 content of combined gas stream (ppm vol)

With information for the SO_3 content of the combined gas stream (S_e) and the moisture content of the combined gas stream (M_e), the acid dew point is determined from Figure B.1-1.

B.1.3 Particulate Matter Loading

Particulate matter concentrations usually are reported in grains per acf. The procedures below may be used to determine the particulate loading to a control device (in lbs/hr) when gas streams are combined.

$$W_{e1,g} \times Q_{e1,a} \times \frac{60\,\text{min}}{\text{hr}} \times \frac{\text{lb}}{7{,}000\text{gr}} = W_{e1,l}$$

where:

$W_{e1,g}$ = particulate loading for gas stream #1 (gr/acf)

$W_{e1,l}$ = particulate loading for gas stream #1 (lb/hr)

This is repeated for each gas stream and the results are added to obtain the particulate loading for the combined gas stream.

$$W_{e1,l} + W_{e2,l} + \ldots = W_{e,1}$$

where:

$W_{e1,l}$ = particulate loading for combined gas stream (lb/hr)

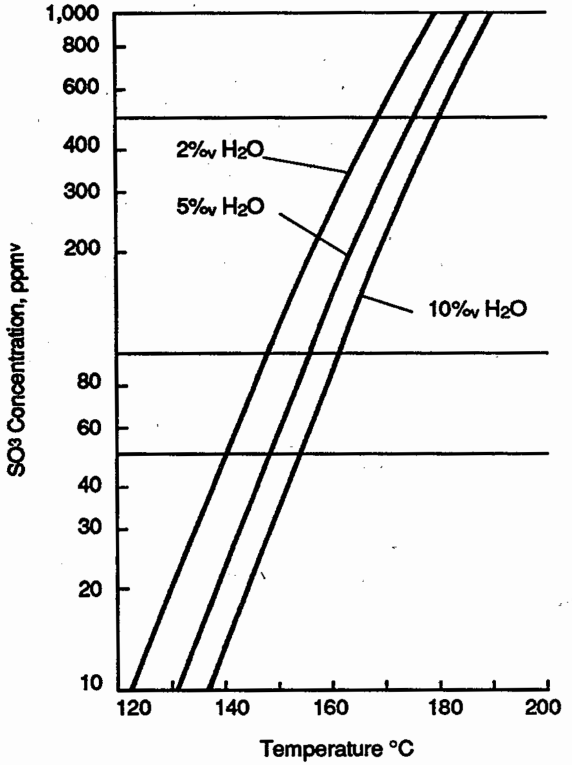

Figure B.1-1. "Acid" Dew Points in Stack Gases

The particulate loading of the combined gas stream can be converted to a concentration as follows:

$$W_{e,1} \times \frac{7{,}000\text{gr}}{\text{lb}} \times \frac{1\,\text{hr}}{60\,\text{min}} \times \frac{1}{Q_{e,a}} = W_{e,g}$$

where:

$W_{e,g}$ = particulate loading for combined gas stream (gr/acf)

B.1.4 Heat Content Calculation

The heat content of gas stream #1 (h_{e1}) can be determined from the heat of combustion of its components using the following equation:

$$h_{e1} = (0.01) \sum_{i=1}^{n} y_{e1,i} \times h_{e1,i}$$

where:

h_{e1} = heat content in gas stream #1 (Btu/scf)

$Y_{e1,i}$ = volume percent of component "i" in gas stream #1 (% vol)

$h_{e1,i}$ = heat of combustion of component "i" in gas stream #1: see Table B.1-2 (Btu/scf)

n = number of components in gas stream #1

The heat content of a combined emission stream can be determined from the heat content of the individual emission streams as follows:

$$H_e = (0.01) \sum_{j=1}^{m} y_{ej} \times h_{ej}$$

where:

H_e = combined emission stream heat content (Btu/scf)

Y_{ej} = volume percent of stream "j" in combined gas stream (% vol)

h_{ej} = heat content of stream "j" in combined gas stream: see previous discussion (Btu/scf)

m = number of individual gas streams in combined gas stream

The heat content of a stream in Btu/scf can be converted to Btu/lb by dividing the value in Btu/scf by the density of the emission stream at standard conditions (typically, 0.0739 lb/ft^3).

Table B.1.2. Heats of Combustion and Lower Explosive Limit (LEL) Data for Selected Compounds[a]

Compound	LEL (ppmv)	Net Heat of Combustion[b,c] (Btu/scf)
Methane	50,000	882
Ethane	30,000	1,588
Propane	21,000	2,274
n-Butane	16,000	2,956
Isobutane	18,000	2,947
n-Pentane	15,000	3,640
Isopentane	14,000	3,631
Neopentane	14,000	3,616
n-Hexane	11,000	4,324
Ethylene	27,000	1,472
Propylene	20,000	2,114
n-Butane	16,000	2,825
l-Pentene	15,000	3,511
Benzene	13,000	3,527
Toluene	12,000	4,196
Xylene	11,000	1,877
Acetylene	25,000	1,397
Naphthalene	9,000	5,537
Methyl alcohol	67,000	751
Ethyl alcohol	33,000	1,419
Ammonia	160,000	356
Hydrogen sulfide	40,000	583

[a]Sources: *Steam/Its Generation and Use.* The Babcock & Wilcox Company. New York, NY. 1975

Fire Hazard Properties of Flammable Liquids, Gases, Volatile Solids-1977. National Fire Protection Association. Boston, MA. 1977.

[b]Lower heat of combustion.

[c]Based on 70°F and 1 atm.

Example Case

Calculate the heat content of an emission stream from a paper coating operation (gas stream #1) with the following composition data: methane (100 ppmv), and toluene (960 ppmv). Let subscripts "1" and "2" denote methane and toluene, respectively.

$h_{e1} = (0.01)(Y_{e1,1} \times H_{e1,1} + Y_{e1,2} \times H_{e1,2})$

Convert the concentrations to volume percent basis:

Methane: $Y_{e1,1} = 0.0100$

Toluene: $Y_{e1,2} = 0.0960$

From Table B.1-2:

Methane: $H_{e1,1} = 882$ Btu/scf

Toluene: $H_{e1,2} = 4,196$ Btu/scf

Substituting these values in the above equation yields:

$h_{e1} = 4.11$ Btu/scf or 55.6 Btu/lb.

Table B.1-3. Properties of Selected Organic Compounds[a]

Compound	Molecular Weight (lb/lb-mole)	Boiling Point (°F)
Acetone	58	133
Benzene	78	176
n-Butyl acetate	116	257
n-Butyl alcohol	74	243
Carbon tetrachloride	154	170
Chloroform	119	142
Cyclohexane	54	176
Ethyl acetate	88	171
Ethyl alcohol	46	173
Heptane	100	209
Hexane	86	156
Isobutyl alcohol	74	225
Isopropyl acetate	103	191
Isopropyl alcohol	60	181
Methyl acetate	74	135
Methyl alcohol	32	148
Methylene chloride	85	104
Methyl ethyl ketone	72	175
Methyl isobutyl ketone	100	244
Perchloroethylene	166	250
Toluene	92	231
Trichloroethylene	131	189
Trichlorotrifluoroethane	187	118
Xylene	106	281-292

[a]Source: *Chemical Engineer's Handbook.* Perry, R.H. and Chilton, C.H. (eds). Fifth Edition. McGraw-Hill Book Company, New York, NY. 1973.

Appendix B.2
Dilution Air Requirements

B.2.1 Dilution Air Calculations

The quantity of dilution air (Q_d) needed to decrease the heat content of the emission stream to h_d is given by the following equation:

$$Q_d = [(h_e/h_d) - 1]Q_e \tag{1}$$

where:

Q_d = dilution air flow rate, scfm
h_e = emission stream heat content before dilution, Btu/scf
h_d = emission stream heat content after dilution, Btu/scf
Q_e = emission stream flow rate before dilution, scfm

The concentrations of the various components and flow rate of the emission stream have to be adjusted after dilution as follows:

$$O_{2,d} = O_2\,(h_d/h_e) + 21\,[1 - (h_d/h_e)] \tag{2}$$
$$M_{e,d} = M_e\,(h_d/h_e) + 2\,[1 - (h_d/h_e)] \tag{3}$$
$$Q_{e,d} = Q_e\,(h_e/h_d) \tag{4}$$

where:

$O_{2,d}$ = oxygen content of diluted emission stream, vol%
$M_{e,d}$ = moisture content of diluted emission stream, vol%
$Q_{e,d}$ = flow rate of the diluted emission stream, scfm

The factor 21 in Equation 2 denotes the volumetric percentage of oxygen in air and the factor 2 in Equation 3 is the volumetric percentage of moisture in air at 70°F and 80 percent humidity. Calculations for the moisture content are given for the readers' information, but are not usually needed for the equations used in this handbook.

After dilution, the HAP emission stream characteristics are redesignated as follows:

O_2 = $O_{2,d}$ = ________ %
M_e = $M_{e,d}$ = ________ %
h_e = h_d = ________ But/scf
Q_e = $Q_{e,d}$ = ________ scfm

Appendix C.2 is a worksheet for calculating dilution air requirements.

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Appendix B.3
Gas Stream Conditioning Equipment

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 control device. Preconditioning equipment, installed upstream of the control device, consists of mechanical dust collectors, wet or dry gas coolers, and gas 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 larger particles.[1] Gas cooling devices are used to reduce the temperature of the gas stream to within the operating temperature of the filter fabric, to reduce the volume of flue gas to be treated, or to increase the HAP collection efficiency. Gas preheaters are used to increase the temperature of the gas stream to eliminate moisture condensation problems. Gas conditioning equipment is discussed below. Design procedures for gas conditioning equipment are not included in this manual. These procedures are straightforward and readily available from vendors and common literature sources.

B.3.1 Mechanical Collectors

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. Theoretically, the higher the velocity or the smaller the inlet diameter, the greater the collection efficiency and pressure drop. Cyclones remove the majority of dust particles above 20 to 30 μm in size to reduce the loading and wear on the subsequent control device.[2]

In general, the particulate size distribution for the gas stream will determine the need for a cyclone collector. If the particle size distribution shows a significant amount of particulate above 20 to 30 μm then use of an upstream cyclone is necessitated for fabric filters and ESP's. "Wetted" venturi scrubbers (see p. 4.11-1 for definition) do not generally experience operating problems in collecting large (20 to 30 μm) particles assuming correct scrubber design and operation. Use of a pretreatment mechanical dust collector may be necessary if a "nonwetted" venturi scrubber (see p. 4-11.1 for definition) is used, since this scrubbing method requires that the liquid be free of particles that could clog the nozzles.

B.3.2 Gas Coolers

Gas coolers can be used to reduce the volume of the gas stream or to maximize the collection of HAP's by electrostatic precipitators and fabric filters. Venturi scrubbers are less sensitive to high gas stream temperatures, since the scrubber cools the gas prior to particle collection. As the temperature of an emission stream is decreased, the HAP's in vapor form will also decrease. However, care must be exercised so that the gas stream temperature does not fall below the emission stream dew point. To ensure a margin for error and process fluctuations, the emission stream temperature should fall between 50 to 100°F above its dew point. Appendix B.1 presents procedures to determine an emission stream's dew point.

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 humidity 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. Selection of the type of gas cooling equipment to be used in based on cost and dew point consideration. For example, a wet-type cooler would not be appropriate if cooling would increase the likelihood of condensation within the fabric filter system.

If a gas cooler is used, a recalculation of the gas stream parameters will have to be performed using standard industrial equations. For instance, if wet-type coolers are used, a new actual gas flow rate and moisture content will have to be calculated.

B.3.3 Gas Preheaters

Gas preheaters are used to increase the emission stream temperature. Condensation causes corrosion of metal surfaces, and it is of particular concern in fabric filter applications where moisture can cause plugging, or "blinding", of the fabric pores; therefore, gas preheaters can be used to elevate the temperature of an emission stream above its dew point. Methods commonly used to increase gas temperature are direct-fired afterburners, heat exchangers, and stream tracing. Afterburners are devices in which an auxiliary fuel is used to produce a flame that preheats a gas stream and that can also combust organic constituents that might otherwise blind the filter bags. Heat exchangers use a heated gas stream in a shell-and-tube type arrangement to preheat gases. With stream tracking, plants that have steam available run gas lines inside the steam lines to preheat the gases.

Emission streams containing HAP's should be preheated only to 50 to 100°F above the dew point, thus minimizing the vapor component of the HAP and enabling a baghouse or an ESP to control the HAP as effectively as possible. Appendix B.1 presents procedures to determine an emission stream's dew point.

If a gas preheater is used, a recalculation of the stream parameters will have to be performed using standard industrial equations. For example, increased gas stream temperature will increase the actual gas flow rate to be controlled.

B.3.4 References

[1] Liptak, B.G. Ed. *Environmental Engineers' Handbook, Volume II: Air Pollution.* Chilton Book Company. Radnor, Pennsylvania. 1974.

[2] U.S. EPA. Handbook. *Control Technologies for Hazardous Air Pollutants.* EPA 625/6-86-014. September 1986. (NTIS PB91-228809).

Appendix C.1

HAP EMISSION STREAM DATA FORM*

Company ____________________
Location (Street) ____________________
(City) ____________________
(State, Zip) ____________________

Plant Contact ____________________
Telephone No. ____________________
Agency Contact ____________________
No. of Emission Streams Under Review ____________________

A. Emission Stream Number/Plant Identification ____________________

B. HAP Emission Source	(a)	(b)	(c)
C. Source Classification	(a)	(b)	(c)
D. Emission Stream HAP's	(a)	(b)	(c)
E. HAP Class and Form	(a)	(b)	(c)
F. HAP Content (1,2,3)**	(a)	(b)	(c)
G. HAP Vapor Pressure (1,2)	(a)	(b)	(c)
H. HAP Solubility (1,2)	(a)	(b)	(c)
I. HAP Adsorptive Prop. (1,2)	(a)	(b)	(c)
J. HAP Molecular Weight (1,2)	(a)	(b)	(c)

K. Moisture Content (1,2,3) ____________________
L. Temperature (1,2,3) ____________________
M. Flow Rate (1,2,3) ____________________
N. Pressure (1,2) ____________________
O. Halogen/Metals (1,2) ____________________

P. Organic Content (1)*** ____________________
Q. Heat/O_2 Content (1) ____________________
R. Particulate Content (3) ____________________
S. Particle Mean Diam. (3) ____________________
T. Drift Velocity/SO_3 (3) ____________________

U. Applicable Regulation(s) ____________________
V. Required Control Level ____________________
W. Selected Control Methods ____________________

---

*The data presented are for an emission stream (single or combined streams) prior to entry into the selected control method(s). Use extra forms if additional space is necessary (e.g., more than three HAP's) and note this need.

**The numbers in parentheses denote what data should be supplied depending on the data in lines C and E:
1 = organic vapor process emission
2 = inorganic vapor process emission
3 = particulate process emission

***Organic emission stream combustibles less HAP combustibles shown on Lines D and F.

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Appendix C.2
Calculation Sheet for Dilution Air Requirements

Dilution air flow rate:

$Q_d = [(h_e/ h_d) - 1]Q_e$

$Q_d =$ __________ scfm

Diluted emission stream characteristics:

$O_{2,d} = O_2 (h_d/h_e) + 21 [1 - (h_d/h_e)]$

$O_{2,d} =$ __________ %

$M_{e,d} = M_e (h_d/h_e) + 2 [1 - (h_d/h_e)]$

$M_{e,d} =$ __________ %

$Q_{e,d} = Q_e (h_e/ h_d)$

$Q_{e,d} =$ __________ scfm

Redesignate emission stream characteristics:

$O_2 = O_{2,d} =$ __________ %

$M_e = M_{e,d} =$ __________ %

$h_e = h_d =$ __________ Btu/scf

$Q_e = Q_{e,d} =$ __________ scfm

(Note: The moisture content for incinerator calculations is not necessary. It is provided for information purposes.)

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Appendix C.3
Calculation Sheet for Thermal Incineration

4.2.1 Data Required*

HAP emission stream characteristics:[a]

1. Maximum flow rate, Q_e = __________ scfm
2. Temperature, T_e = __________ °F
3. Heat content, h_e = __________ Btu/scf
4. Oxygen content,[b] O_2 = __________ %
5. Halogenated organics: Yes __________ No __________

Required destruction efficiency, DE = __________ %

In the case of a permit review, the following data should be supplied by the applicant:

Thermal incinerator system variables at standard conditions (77°F, 1 atm):

1. Reported destruction efficiency, $DE_{reported}$ = __________ %
2. Temperature of emission stream entering the incinerator,

   T_e = __________ °F (if no heat recovery);

   T_{he} = __________ °F (if a heat exchanger is employed)
3. Combustion temperature, T_c = __________ °F
4. Residence time, t_r = __________ sec
5. Maximum emission stream flow rate, Q_e = __________ scfm

---

[a] If dilution air is added to the emission stream upon exit from the process, the data required are the resulting characteristics after dilution.

[b] The oxygen content depends on the oxygen content of the organic compounds (fixed oxygen) and the free oxygen in the emission stream. Since emission streams treated by thermal incineration are generally dilute VOC and air mixtures, the fixed oxygen in the organic compounds can be neglected.

*Numbering in the remainder of Appendices C is provided to match numbering in the main text. The only exception is for <u>new</u> material only (e.g. see page C.7-10 which has Table C.7-1). This is intended to assist the reader in using the correct calculation formula.

6. Fuel heating value, h_f = __________ Btu/lb (assume natural gas)

7. Combustion chamber volume, V_c = __________ ft^3

8. Flue gas flow rate, Q_{fg} = __________ scfm

4.2.2 *Pretreatment of the Emissions Stream: Dilution Air Requirements*

Typically, dilution will not be required. However, if the emission stream heat content (h_e) is greater than 176 Btu/lb or 13 Btu/scf with an oxygen concentration less than 20 percent, see equation 4.2-1 or Appendix C.2 where a blank calculation sheet for determining dilution air requirements is provided.

$$Q_d = [(h_e/h_d)-1]Q_e \qquad 4.2\text{-}1$$

Q_d = __________ scfm

4.2.3 *Design Variables, Destruction Efficiency, and Typical Operational Problems*

Based on the required destruction efficiency (DE), select appropriate values for T_c and t_r from Table 4.2-2.

T_c = __________ °F

t_r = __________ sec

For a permit evaluation, if the applicant's values for T_c and t_r are sufficient to achieve the required DE (compare the reported values with the values presented in Table 4.2-2), proceed with the calculations. If the applicant's values for T_c and t_r are not sufficient, the applicant's design is unacceptable. The reviewer may then use the values for T_c and t_r from Table 4.2-2.

T_c = __________ °F

t_r = __________ sec

(Note: If DE is less than 98 percent, obtain information from literature and incinerator vendors to determine appropriate values for T_c and t_r.)

4.2.4 *Determination of Incinerator Operation Variables*

4.2.4.1 Supplementary Fuel Requirements

To estimate the supplementary fuel flow rate, use equation 4.2-2.

$$Q_f = \frac{D_e\,(Q_e)\,[(Cp_{air})\,(1.1\,T_c - T_{he} - 0.1\,(T_r) - h_e)]}{D_f\,[h_f - 1.1\,Cp_{air}\,(T_c - T_r)]} \qquad 4.2\text{-}2$$

The values for the parameters in this equation can be determined as follows:

Q_e, h_e Input data.

D_e 0.0739 lb/scf.

D_f 0.0408 lb/scf.

h_f Assume a value of 21,600 Btu/lb if no other information is available.

Cp_{air} See Table C.8-1 for values of Cp_{air} at various temperatures.

T_c Obtain value from Table 4.2-2 or from permit applicant.

T_{he} Use the following equation if the value for T_{he} is not specified:

$$T_{he} = (HR/100)\ T_c + [1 - (HR/100)]\ T_e$$

where HR = heat recovery in the heat exchanger (percent). Assume a value of 70 percent for HR if no other information is available.

T_r 77°F

Q_f = __________ scfm

4.2.4.2 Flue Gas Flow Rate

1. For dilute emission streams, use Equation 4.2-3:

$$Q_{fg} = Q_e + Q_f + Q_d \tag{4.2-3}$$

where:

Q_d is the dilution air value obtained from Appendix C.2.

Q_{fg} = __________ scfm

4.2.4.3 Combustion Chamber Volume

a. Use Equation 4.2-4 to convert Q_{fg} (standard conditions) to Q_{fg} (actual conditions):

$$Q_{fg,a} = Q_{fg}\ [(T_c + 460)/537] \tag{4.2-4}$$

$Q_{fg,a}$ = __________ acfm

b. Use Equation 4.2-5 to calculate combustion chamber volume:

$$V_c = [(Q_{fg,a}/60)\ t_r]\ 1.05 \tag{4.2-5}$$

Obtain value for t_r from Table 4.2-2 or from permit applicant.

V_c = __________ ft^3

4.2.5 *Evaluation of Permit Application*

Compare the calculated values and reported values using Table 4.2-4. The combustion volume (V_c) is calculated from flue gas flow rate (Q_{fg}) and Q_{fg} is determined by emission stream flow rate (Q_e), supplementary fuel flow rate (Q_f), and dilution air requirement (Q_d). Therefore, if there are differences between the calculated and reported values for V_c and Q_{fg}, these are dependent on the differences between the calculated and reported values for Q_d and Q_f.

If the calculated and reported values are different, the differences may be due to the assumptions involved in the calculations. Discuss the details of the design and operation of the system with the applicant.

If the calculated and reported values are not different, then the design and operation of the system can be considered appropriate based on the assumptions employed in this handbook.

Table 4.2-4 Comparison of Calculated Values and Values Supplied by the Permit Applicant for Thermal Incineration

	Calculated Value	Reported Value
Continuous monitoring of combustion temperature	. . .	. . .
Supplementary fuel flow rate, Q_f	. . .	. . .
Dilution air flow rate, Q_d	. . .	. . .
Flue gas flow rate, Q_{fg}	. . .	. . .
Combustion chamber size, V_c	. . .	. . .

4.2.6 *Capital and Annual Costs of Thermal Incinerators*

4.2.6.1 Thermal Incinerator Capital Costs

Use the appropriate equation given in Table 4.2-5 to obtain the thermal incinerator cost, TC.

TC = $ __________

Use the factors given in Table 4.2-6 and the auxiliary equipment cost provided in Section 4.12 to obtain the purchased equipment cost, PEC.

PEC = TC + Auxiliary equipment + Sales tax + Freight

PEC = $ __________

After estimating the PEC, simply use the factors given in Table 4.2-7 to obtain the total capital cost (TCC) estimate.

TCC = 1.61 PEC + SP + Bldg.

TCC = $ __________

4.2.6.2 Thermal Incinerator Total Annual Costs, TAC

The TAC consist of direct and indirect annual costs. Direct annual costs include fuel, electricity, operating and supervisory labor, and maintenance labor and materials. Indirect annual costs include overhead, administrative, property taxes, insurance, and capital recovery costs.

Direct Annual Costs

1. Fuel usage

The fuel usage is calculated in Section 4.2.4.1. Take this quantity (in scfm) and multiply by 60 to obtain scfh and multiply this by the annual operating hours and the fuel cost.

Annual fuel cost = $Q_f \times 60 \times HRS \times \$3.30/1{,}000\ ft^3$

Annual fuel cost = $ __________

2. Electricity costs

Use Equation 4.2-6 to estimate the fan power requirement, F_p

$F_p = 1.81 \times 10^{-4} (Q_{fg})(P)(HRS)$

F_p = __________ kWh/yr

Electricity costs = $0.059 ($F_p$)

Electricity costs = $ __________

3. Operating costs

Operating labor costs = [(0.5 hr/shift)/(8 hr/shift)](HRS)($12.98/hr)

Operating labor costs = $ __________

Supervisory costs = 0.15 (Operating labor costs)

Supervisory costs = $ __________

4. Maintenance costs

Maintenance labor costs = [(0.5 hr/shift)/(8 hr/shift)](HRS)($14.26/hr)

Maintenance labor costs = $ __________

Maintenance materials = 1.0 (Maintenance labor costs)

Maintenance materials = $ __________

Total Direct Costs = $ __________

Indirect Annual Costs

These costs are obtained from factors given in Table 4.2-7.

Overhead = $ __________

Administrative = $ __________

Property taxes = $ __________

Insurance = $ __________

Capital recovery = $ __________

Total Indirect Costs = $ __________

Total Annual Costs = Total Direct Costs + Total Indirect Costs

Total Annual Costs = $ __________

Appendix C.4
Calculation Sheet for Catalytic Incineration

4.3.1 Data Required

HAP emission stream characteristics:[a]

1. Maximum flow rate, Q_e = ____________ scfm
2. Temperature, T_e = ____________ °F
3. Heat content, h_e = ____________ Btu/lb
4. Oxygen content[b], O_2 = ____________ %

Required destruction efficiency, DE = ____________ %

In the case of a permit review, the following data should be supplied by the applicant:

Catalytic incinerator system variables at standard conditions (77°F, 1 atm):

1. Reported destruction efficiency, $DE_{reported}$ = ____________ %
2. Temperature of emission stream entering the incinerator,

   T_e = ____________ °F (if no heat recovery);

   T_{he} = ____________ °F (if emission stream is preheated)
3. Temperature of flue gas leaving the catalytic bed,

   T_{co} = ____________ °F
4. Temperature of combined gas stream (emission stream + supplementary fuel combustion products) entering the catalyst bed,[c]

   T_{ci} = ____________ °F

---

[a] If dilution air is added to the emission stream upon exit from the process, the data required are the resulting characteristics after dilution.

[b] The oxygen content depends on the oxygen content of the organic compounds (fixed oxygen) and the free oxygen in the emission stream. Since emission streams treated by catalytic incineration are generally dilute VOC and air mixtures, the fixed oxygen in the organic compounds can be neglected.

[c] If no supplementary fuel is used, the value for this variable will be the same as that for the emission stream.

5. Space velocity, SV = ____________ hr^{-1}

6. Supplementary fuel gas flowrate, Q_f = ____________ scfm

7. Flow rate of combined gas stream entering the catalyst bed,

   Q_{com} = ____________ scfm

8. Dilution air flow rate, Q_d = ____________ scfm

9. Catalyst bed requirement, V_{bed} = ____________ ft^3

10. Fuel heating value, h_f = ____________ Btu/lb

4.3.2 Pretreatment of the Emission Stream: Dilution Air Requirements

For emission streams treated by catalytic incineration, dilution air typically will not be required. However, if the emission stream heat content is greater than 135 Btu/lb or 10 Btu/scf for air + VOC mixtures or if the emission stream heat content is greater than 203 Btu/lb or 15 BTU/scf for inert + VOC mixtures, dilution air is necessary. For emission streams that cannot be characterized as air + VOC or inert + VOC mixtures, assume that dilution air will be required if the heat content is greater than 12 Btu/scf. In such cases, refer to Equation 4.3-1 presented below or see Appendix C.2 where a blank calculation sheet for determining dilution air requirements is provided.

$$Q_d = [(h_e/h_d)-1]Q_e \qquad 4.3\text{-}1$$

Q_d = ____________ scfm

4.3.3 Design Variables, Destruction Efficiency, and Typical Operational Problems

Based on the required destruction efficiency (DE), specify the appropriate ranges for T_{ci} and T_{co} and select the value for SV from Table 4.3-1.

T_{ci} (minimum) = 600°F

T_{co} (minimum) = 1,000°F

T_{co} (maximum) = 1,200°F

SV = ____________ hr^{-1}

In a permit review, determine if the reported values for T_{ci}, T_{co}, and SV are appropriate to achieve the required destruction efficiency. Compare the applicant's values with the values in Table 4.3-1 and check if:

$$T_{ci}\text{ (applicant)} \geq 600°F \text{ and } 1{,}200°F \geq T_{co}\text{ (applicant)} \geq 1{,}000°F$$

and

SV (applicant) ≤ SV (Table 4.3-1)

If the reported values are appropriate, proceed with the calculations. Otherwise, the applicant's design is considered unacceptable. The reviewer may then wish to use the values in Table 4.3-1.

4.3.4 Determination of Incinerator Operating Parameters

4.3.4.1 Supplementary Heat Requirements

1. For dilute emission streams that require no additional combustion air:

   a. Use Equation 4.3-2 to determine if $T_{ci} = 600°F$ from Table 4.3-1 is sufficient to ensure an adequate overall reaction rate without damaging the catalyst, i.e., check if T_{co} falls in the interval 1,000° - 1,200°F:

   $$T_{co} = 600 + 50\ h_e \qquad 4.3\text{-}2$$

   T_{co} = ____________ °F

   If T_{co} falls in the interval 1,000° - 1,200°F, proceed with the calculations. If T_{co} is less than 1,000°F, assume T_{co} is equal to 1,000°F and use Equation 4.3-3 to determine an appropriate value for T_{ci}; and then proceed with the calculations:

   $$T_{ci} = 1{,}000 - 50\ h_e \qquad 4.3\text{-}3$$

   T_{ci} = ____________ °F

   (Note: If T_{co} is greater than 1,200°F, a decline in catalyst activity may occur due to exposure to high temperatures.)

   b. Use Equation 4.3-4 to determine supplementary fuel requirements:

   $$Q_f = \frac{D_e\ Q_e\ [Cp_{air}\ (1.1\ T_{ci} - T_{he} - 0.1\ T_r)]}{D_f\ [h_f - 1.1\ Cp_{air}\ (T_{ci} - T_r)]} \qquad 4.3\text{-}4$$

   The values for the variables in this equation can be determined as follows:

Q_e	Input data.
D_e	0.0739 lb/ft^3
D_f	0.0408 lb/ft^3
h_f	Assume a value of 21,600 Btu/lb (for natural gas) if no other information is available.

Cp_{air} See Table C.8-1 for values of Cp_{air} at various temperatures.

T_{ci} Obtain value from part "a" above or from permit applicant.

T_{he} For no heat recovery case, $T_{he} = T_e$. For heat recovery case, use the following equation if the value for T_{he} is not specified:

$$T_{he} = (HR/100)T_{co} + [1 - (HR/100)]\,T_e \qquad 4.3\text{-}5$$

where HR = heat recovery in the heat exchanger (percent). Assume a value of 50 percent for HR if no other information is available.

T_r 77°F

Q_f = ____________ scfm

4.3.4.2 Flow Rate of Combined Gas Stream Entering the Catalyst Bed

1. For dilute emission streams that require no additional combustion air, use Equations 4.3-6:

$$Q_{com} = Q_e + Q_f + Q_d \qquad 4.3\text{-}6$$

Q_{com} = ____________ scfm

4.3.4.3 Flow Rate of Flue Gas Leaving the Catalyst Bed

a. Use the result from the previous calculation:

$$Q_{fg} = Q_{com}$$

Q_{fg} = ____________ scfm

If Q_{fg} is less than 2,000 scfm, define Q_{fg} as 2,000 scfm.

b. Use Equation 4.3-7 to calculate $Q_{fg,a}$.

$$Q_{fg,a} = Q_{fg}\,[(T_{co} + 460)/537] \qquad 4.3\text{-}7$$

$Q_{fg,a}$ = ____________ acfm

4.3.5 Catalyst Bed Requirement

Use Equation 4.3-8 to estimate the catalyst bed volume.

$$V_{bed} = 60\,Q_{com}/SV \qquad 4.3\text{-}8$$

V_{bed} = ____________ ft^3

4.3.6 Evaluation of Permit Application

Compare the calculated values supplied by the applicant using Table 4.3-2.

If the calculated values for H_f, Q_c, Q_{com}, and V_{bed} differ from the applicant's values, the differences may be due to the assumptions involved in the calculations. Discuss the details of the design and operation of the system with the applicant.

If the calculated and reported values are not different, then the design and operation of the system can be considered appropriate based on the assumptions employed in this handbook.

Table 4.3-2 Comparison of Calculated Values and Values Supplied by the Permit Applicant for Catalytic Incineration

	Calculated Value	Reported Value
Continuous monitoring of combustion temperature rise and pressure drop across catalyst bed	. . .	. . .
Supplementary fuel flow rate, Q_f	. . .	. . .
Dilution air flow rate, Q_d	. . .	. . .
Flue gas stream flow rate, Q_{com}	. . .	. . .
Catalyst bed volume, V_{bed}	. . .	. . .

4.3.7 Capital and Annual Costs of Catalytic Incinerators

4.3.7.1 Catalytic Incinerator Capital Costs

Use the appropriate equation given in Table 4.3-3 to obtain the catalytic incinerator cost, CC.

CC = $ ____________

Use the factors given in Table 4.3-4 and the auxiliary equipment cost provided in Section 4.12 to obtain the purchased equipment cost, PEC.

PEC = CC + Auxiliary equipment + Sales tax + Freight

PEC = $ ____________

After estimating the PEC, simply use the factors given in Table 4.3-4 to obtain the total capital cost (TCC) estimate.

TCC = 1.61 PEC + SP + Bldg.

TCC = $ ____________

4.3.7.2 Catalytic Incinerator Total Annual Costs, TAC

The TAC consist of direct and indirect annual costs. Direct annual costs include fuel, electricity, catalytic replacement, operating and supervisory labor, and maintenance labor and materials. Indirect annual costs include overhead, administrative, property taxes, insurance, and capital recovery costs.

Direct Annual Costs

1. Fuel usage

   The fuel usage is calculated in Section 4.3.4.1. Take this quantity (in scfm) and multiply by 60 to obtain scfh and multiply this by the annual operating hours and the fuel cost.

   Annual fuel cost = $Q_f \times 60 \times HRS \times \$3.30/1{,}000\ ft^3$

   Annual fuel cost = $ ____________

2. Electricity costs

   Use Equation 4.3-9 to estimate the fan power requirement, F_p

   $F_p = 1.81 \times 10^{-4}\,(Q_{fg})(P)(HRS)$ 4.3-9

   F_p = ____________ kWh/yr

   Electricity costs = $0.059 ($F_p$)

   Electricity costs = $ ____________

3. Catalyst replacement costs

   The catalyst volume is obtained in Section 4.3.5. Multiply this volume by the appropriate cost for base metal oxide ($650/ft^3) or noble metal ($3,000/ft^3) and by 0.5762, the capital recovery factor.

   Catalyst replacement cost = $(V_{bed})(\$650/ft^3 \text{ or } \$3{,}000/ft^3)(0.5762)$

   Catalyst replacement cost = $ ____________

4. Operating costs

   Operating labor costs = [(0.5 hr/shift)/(8 hr/shift)](HRS)($12.96/hr)

Operating labor costs = $ ____________

Supervisory costs = 0.15 (Operating labor costs)

Supervisory costs = $ ____________

5. Maintenance costs

Maintenance labor costs = [(0.5 hr/shift)/(8 hr/shift)](HRS)($14.26/hr)]

Maintenance labor costs = $ ____________

Maintenance materials = 1.0 (Maintenance labor costs)

Maintenance materials = $ ____________

Total Direct Costs = $ ____________

Indirect Annual Costs

These costs are obtained from factors given in Table 4.3-6.

Overhead = $ ____________

Administrative = $ ____________

Property taxes = $ ____________

Insurance = $ ____________

Capital recovery = $ ____________

Total Indirect Costs = $ ____________

Total Annual Costs = Total Direct Costs + Total Indirect Costs

Total Annual Costs = $ ____________

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Appendix C.5
Calculation Sheet for Flares

4.4.1 Data Required

HAP emission stream characteristics:

1. Expected emission stream flowrate, Q_e = __________ scfm
2. Emission stream temperature, T_e = __________ °F
3. Heat content, h_e = __________ Btu/scf
4. Mean molecular weight of emission stream MW_e = __________ lb/lb-mole

Flare tip diameter, D_{tip} = __________ in

Required destruction efficiency, DE = __________ %

In the case of a permit review, the following data should be supplied by the applicant:

Flare system design parameters at standard conditions (77°F, 1 atm):

1. Steam flowrate, Q_s = __________ lb/min
2. Flare gas exit velocity, U_{flg} = __________ ft/sec
3. Supplementary fuel flow rate, Q_f = __________ scfm
4. Supplementary fuel heat content, h_f = __________ Btu/scf
5. Temperature of flare gas, T_{flg} = __________ °F
6. Flare gas flowrate, Q_{flg} = __________ scfm
7. Flare gas heat content, h_{flg} = __________ Btu/scf

4.4.2 Determination of Flare Operating Variables

Based on studies conducted by EPA, relief gases having heating values less than 300 Btu/scf are not assured of achieving 98 percent destruction efficiency when they are flared in stream- or air-assisted flares.[1]

In a permit review case, if h_e is below 300 Btu/scf and no supplementary fuel is used, then the application is rejected. The reviewer may then wish to proceed with the calculations below. If h_e is equal to or above 300 Btu/scf, then the reviewer should skip to Section 4.4.2.3.

---

[1] For unassisted flares, the lower limit is 200 Btu/scf.

4.4.2.1 Supplementary Fuel Requirements

For emission streams with heat contents less than 300 Btu/scf, additional fuel is required. Use Equation 4.4-1 to calculate natural gas requirements:

$$Q_f = [(300 - h_e)\ Q_e]/582 \qquad 4.4\text{-}1$$

$Q_f = \underline{\hspace{3cm}}$ scfm

4.4.2.2 Flare Gas Flow Rate and Heat Content

a. Use Equation 4.4-2 to calculate the flare gas flow rate:

$$Q_{flg} = Q_e + Q_f \qquad 4.4\text{-}2$$

$Q_{flg} = \underline{\hspace{3cm}}$ scfm

b. Determine the flare gas heat content as follows:

$h_{flg} = 300$ Btu/scf if $Q_f > 0$

$h_{flg} = h_e$ if $Q_f = 0$

$h_{flg} = \underline{\hspace{3cm}}$ Btu/scf

4.4.2.3 Flare Gas Exit Velocity

a. Use Table 4.4-1 to calculate U_{max}:

If $300 \leq h_{flg} < 1{,}000$ use the following equation:

$$U_{max} = 3.28\ [10^{(0.00118 h_{flg} + 0.908)}]$$

$U_{max} = \underline{\hspace{3cm}}$ ft/sec

If $h_{flg} \geq 1{,}000$ Btu/scf, $U_{max} = 400$ ft/sec

b. Use Equation 4.4-3 to calculate U_{flg}:

$$U_{flg} = (5.766 \times 10^{-3})(Q_{flg})(T_{flg} + 460)/(D_{tip}^2) \qquad 4.4\text{-}3$$

$U_{flg} = \underline{\hspace{3cm}}$ ft/sec

c. Compare U_{flg} and U_{max}:

If $U_{flg} \leq U_{max}$, the desired destruction efficiency level of 98 percent can be achieved. (Note: U_{flg} should exceed 0.03 ft/sec for flame stability.) If $U_{flg} > U_{max}$, 98 percent destruction efficiency cannot be achieved. When evaluating a permit, reject the application in such a case.

4.4.2.4 Steam Requirements

a. Assume that the amount of steam required is 0.4 lb steam/lb flare gas. Use equation 4.4-4 to calculate Q_s:

$$Q_s = 1.03 \times 10^{-3} \times Q_{flg} \times MW_{flg} \qquad 4.4\text{-}4$$

Q_s = __________ lb/min

4.4.3 Evaluation of Permit Application

Compare the calculated and reported values using Table 4.4-2. If the calculated values of Q_f, U_{flg}, Q_{flg}, and Q_s are different from the reported values for these variables, the differences may be due to the assumptions (e.g., heating value of fuel, ratio of steam to flare gas, etc.) involved in the calculations. Discuss the details of the design and operation of the system with the applicant. If the calculated and reported values are not different, then the operation of the system can be considered appropriate based on the assumptions employed in the handbook.

Table 4.4-2 Comparison of Calculated Values and Values Supplied by the Permit Applicant for Flares

	Calculated Value	Reported Value
Appropriate continuous monitoring of system	. . .	. . .
Emission stream heating value, h_e	. . .	. . .
Supplementary fuel flow rate, Q_f	. . .	. . .
Flare gas exit velocity, U_{flg}	. . .	. . .
Flare gas flow rate, Q_{flg}	. . .	. . .
Steam flow rate, Q_s	. . .	. . .

4.4.4 Capital and Annual Costs for Flares

4.4.4.1 Capital Costs of Flares

Calculate the flame angle θ using Equation 4.4-6 which is derived from Equation 4.4-5.

$$\theta = \text{TAN}^{-1}\,(88.2/U_{flg}) \qquad 4.4\text{-}6$$

Next, calculate the flare height H using Equation 4.4-7.

$$H = [(0.01285)\,(Q_{flg} \times h_{flg})^{1/2} - 6.05 \times 10^{-3}\,(D_{tip})\,(U_{flg})\,(\text{Cos}(\theta))] \qquad 4.4\text{-}7$$

Once H is calculated, select the appropriate value for H as a multiple of 5 with a minimum of 30 feet. The flare cost FC is estimated using equations 4.4-8, 4.4-9, or 4.4-10.

$$FC = [78 + 9.14\,(D_{tip}) + 0.749\,(H)]^2 \qquad 4.4\text{-}8$$

where: FC = flare cost for self support

$$FC = [103 + 8.68\,(D_{tip}) + 0.470\,(H)]^2 \qquad 4.4\text{-}9$$

where: FC = flare cost for guy support

$$FC = [76.4 + 2.72\,(D_{tip}) + 1.64\,(H)]^2 \qquad 4.4\text{-}10$$

where: FC = flare cost for derrick support

The equipment cost (EC) is obtained by adding the auxiliary equipment cost and the flare cost, FC.

EC = FC + Aex

EC = $ __________

The purchased equipment cost (PEC) is obtained using the factors given in Table 4.4-3.

PEC = EC + Instrumentation & Sales tax & Freight

PEC = $ __________

After estimating the PEC, simply use the factors given in Table 4.4-3 to obtain the total capital costs (TCC).

TCC = 1.92 PEC + SP + Bldg.

TCC = $ __________

4.4.4.2 Flare Total Annual Costs, TAC

The TAC consist of direct and indirect annual costs. Direct annual costs include fuel, electricity, steam, operating labor, and maintenance labor. Indirect annual costs consist of overhead, administrative, property taxes, insurance, and capital recovery costs.

Direct Annual Costs

1. Fuel usage

   The fuel usage is calculated in Section 4.4.2.1. Take this value and multiply it by 60 to obtain scfh, by the annual operating hours per year, and the cost of fuel.

   Annual fuel cost = $Q_f \times 60 \times HRS \times \$3.30/1{,}000\ ft^3$

Annual fuel cost = $ __________

2. Electricity costs

   Equation 4.4-11 is used to estimate the power requirement. This value is then multiplied by the cost of electricity to obtain the Annual Electricity Cost.

   $F_p = 1.81 \times 10^{-4} (Q_{flg,a})(P)(HRS)$ 4.4-11

   F_p = __________ kWh/yr

   Annual electricity cost = \$0.059 (F_p)

   Annual electricity cost = $ __________

3. Steam requirement

   The steam requirement for a flare is calculated in Section 4.4.2.4. Take this quantity (Q_s) and multiply by 60, by the annual operating hours, and by the cost of steam to obtain annual costs.

   Annual steam costs = $Q_s \times 60 \times HRS \times \$6.00/1{,}000$ lb

   Annual steam costs = $ __________

4. Operating costs

   Operating labor costs = [(0.5 hr/shift)/(8 hr/shift)](HRS)(\$12.96/hr)

   Operating labor costs = $ __________

   Supervisory costs = 0.15 (Operating labor costs)

   Supervisory costs = $ __________

5. Maintenance costs

   Maintenance labor costs = [(0.5 hr/shift)/(8 hr/shift)](HRS)(\$14.26/hr)

   Maintenance labor costs = $ __________

   Maintenance materials = 1.0 (Maintenance labor costs)

   Maintenance materials = $ __________

Total Direct Costs = $ __________

Indirect Annual Costs

These costs are obtained from factors given in Table 4.3-6.

Overhead = $ ___________

Administrative = $ ___________

Property taxes = $ ___________

Insurance = $ ___________

Capital recovery = $ ___________

Total Indirect Costs = $ ___________

Total Annual Costs = Total Direct Costs + Total Indirect Costs

Total Annual Costs = $ ___________

Appendix C.6
Calculation Sheet for Carbon Adsorption

4.6.1 Data Required

HAP emission stream characteristics:

1. Maximum flow rate, Q_e = __________ scfm
2. Temperature, T_e = __________ °F
3. Relative humidity, R_{hum} = __________ %
4. HAP = __________
5. Maximum HAP content, HAP_e = __________ ppmv

Required removal efficiency, RE = __________ %

In the case of a permit review, the following data should be supplied by the applicant:

Carbon adsorber (fixed-bed) system variables at standard conditions (77°F, 1 atm):

1. Reported removal efficiency, $RE_{reported}$ = __________ %
2. HAP inlet loading rate, M_{HAP} = __________ lb/hr
3. HAP content, HAP_e = __________ ppmv
4. Emission stream flow rate, Q_e = __________ scfm
5. Working capacity of carbon bed, W_c = __________ lb HAP/lb carbon
6. Number of beds, N = __________
7. Amount of carbon required, C_{req} = __________ lb
8. Cycle time for adsorption, θ_{ad} = __________ hr
9. Cycle time for regeneration, θ_{reg} = __________ hr
10. Emission stream velocity through the bed, U_e = __________ ft/min
11. Vessel length L_v = __________ ft
12. Vessel diameter, D_v = __________ ft
13. Steam used for regeneration, Q_s = __________ lb steam/min

4.6.2 Adsorption Theory

1. Partial pressure of HAP, P

   $P = (HAP_e) \times 14.696 \times 10^{-6}$ psia

   P = __________ psia

2. Equilibrium and working capacity, W_e and W_c

   $W_e = kP^m$

   Obtain k and m from Table 4.6-1 or appropriate reference

   W_e = __________ lbs HAP/lbs carbon

   W_c = __________ lbs HAP/lbs carbon ($W_c = 0.5\ W_e$ if no information available)

   Note: $W_c = 0.100$ if no information available.

4.6.4 Pretreatment of the Emission Stream

Cooling

T_e = __________ °F

If the temperature of the emission stream is higher than 130°F, a heat exchanger is needed to cool it to 130°F or less. Refer to a suitable reference for the calculation procedure.

Dehumidification

R_{hum} = __________ %

If the relative humidity level is above 50 percent and the HAP concentration is less than 1000 ppmv, a condenser may be required to cool and condense the water vapor in the emission stream. Refer to Section 4.8 for more details.

High VOC Concentrations

HAP_e = __________ ppmv

If flammable vapors are present in the emission stream, the VOC content should be limited to below 25 percent of the LEL.

LEL = __________ ppmv (from Table 4.2-1)

25% of LEL = $0.25 \times$ LEL (ppmv) = __________ ppmv

The maximum practical inlet concentration for carbon beds is about 10,000 ppmv. If HAP_e is greater than 10,000 ppmv, carbon adsorption may not be applicable.

4.6.6 Fixed Bed Regenerative Systems

4.6.6.1 Fixed Bed Design

a. Use Equation 4.6-1 to calculate the required carbon amount C_{req}:

$$C_{req} = \frac{M_{HAP}\,\Theta_{ad}\,(1 + {}^{ND}\!/_{NA})}{W_c} \qquad 4.6\text{-}1$$

C_{req} = __________ lbs

$C'_{req} = C_{req}/NA$

C'_{req} = __________

b. Obtain M_{HAP} if not given using formula 4.6-2.

$$M_{HAP} = 6.0 \times 10^{-5}\,(HAP_e)(Q_e)(D_{HAP}) \qquad 4.6\text{-}2$$

M_{HAP} = __________ lb/hr

where:

$D_{HAP} = PM/RT$

D_{HAP} = __________ lbs/ft^3

Equations 4.6-3, 4.6-4, and 4.6-5 are used to obtain the vessel diameter, D_v, and the vessel length, L_v, and the vessel size, S:

$$D_v = (0.127)(C'_{req})(U_e)/(Q'_{e,a}) \qquad 4.6\text{-}3$$

where:

$Q_{e,a} = Q_e(T_e + 460)/537$

$Q_{e,a}$ = __________ acfm

$Q'_{e,a} = Q_{e,a}/NA$

$Q'_{e,a}$ = __________

D_v = __________ ft

$L_v = (7.87)(Q'_{e,a}/U_e)^2/C'_{req}$ 4.6-4

$L_v =$ ___________ ft

$S = \pi D_v(L_v + D_v/2)$ 4.6-5

$S =$ ___________ ft^2

4.6.6.2 Carbon Adsorber Efficiency

Use Table 4.6-2 to determine the adsorption time θ_{ad}, the regeneration time θ_{reg}, and the steam requirement St, for a given outlet concentration.

$\theta_{ad} =$ ___________ hr

$\theta_{reg} =$ ___________ hr

St = ___________ lb steam/lb carbon

4.6.6.3 Steam Required for Regeneration

Use Equation 4.6-6 to calculate steam requirements:

$Q_s = NA\,[St \times C'_{req}/(\theta_{reg} - \theta_{dry\text{-}cool})]/60$ 4.6-6

Assume $\theta_{dry\text{-}cool} = 0.25$ hrs, if no information available.

$Q_s =$ ___________ lb/min

Calculate Q_s/A_{bed}:

$A_{bed} = Q'_{e,a}/U_e$

$A_{bed} =$ ___________

$Q_s/A_{bed} =$ ___________ lb steam/min-ft^2

If Q_s/A_{bed} is greater than 4 lb steam/min-ft^2, fluidization of the carbon bed may occur.

4.6.7 Evaluation of Permit Application

Compare the results from the calculations and the reported values using Table 4.6-3.

If the calculated values of C_{req}, D_v, L_v, S, and Q_s are different from the reported values, the differences may be due to the assumptions involved in the calculations. Discuss the details of the design and operation of the system with the applicant.

If the calculated values agree with the reported values, then the design and operation of the proposed carbon adsorber system may be considered appropriate based on the assumptions made in this handbook.

Table 4.6-3 Comparison of Calculated Values and Values Supplied by the Permit Applicant for Carbon Adsorption

Variable	Calculated Value	Reported Value
Continuous Effluent Monitoring	. . .	. . .
Carbon Requirement, C_{reg}	. . .	. . .
Vessel Diameter, D_v	. . .	. . .
Vessel Length, L_v	. . .	. . .
Vessel Size, S	. . .	. . .
Steam Regeneration Rate, Q_s	. . .	. . .

4.6.8 Capital and Annual Costs of Fixed Bed Regenerative Adsorbers

4.6.8.1 Costs of Carbon

Equation 4.6-7 is used to obtain the carbon costs, C_c:

$$C_c = \$2.00\,(C_{req}) \qquad 4.6\text{-}7$$

C_c = $ __________

4.6.8.2 Vessel Costs

Use Equation 4.6-8 to obtain the vessel costs.

$$C_v = 271\ S^{0.7712} \qquad 4.6\text{-}8$$

C_v = $ __________

If necessary, multiply C_v by the appropriate construction factor given in Table 4.6-4:

$$C_v = F_m\,C_v$$

C_v = $ __________

4.6.8.3 Purchased Equipment Cost, PEC

Equation 4.6-9 is used to obtain the equipment cost EC:

$$EC = R_c[C_c + C_v\ (NA + ND)] + \text{Ductwork and dampers} \qquad 4.6\text{-}9$$

where:

$$RC = 5.82\ Q_{e,a}^{\ -0.133}$$

Thus,

RC = __________

EC = $ __________

Use the factors provided in Table 4.6-5 to obtain the purchased equipment cost, PEC.

$$PEC = 1.08\ EC$$

PEC = $ __________

4.6.8.4 Total Capital Cost, TCC

Use the factor provided in Table 4.6-5 to obtain the total capital cost, TCC.

$$TCC = 1.61\ PEC + SP + Bldg.$$

TCC = $ __________

4.6.8.5 Fixed Bed Carbon Adsorption Annual Cost Estimates

The annual cost estimate consists of the sum of direct and indirect costs, as well as recovery credits.

Direct Annual Costs

1. Steam costs, C_s

Equation 4.6-10 is used to estimate this cost.

$$C_s = Q_s(60)(HRS)(P_s)/1{,}000 \qquad 4.6\text{-}10$$

C_s = $ __________

2. Cooling water costs, C_{cw}

Equation 4.6-4 is used to estimate this cost.

$$C_{cw} = 3.43\ (C_s/P_s)(P_{cw}) \qquad 4.6\text{-}11$$

$C_{cw} = \$$ __________

3. Electricity cost, AEC

a. Pressure drop through the bed, P_b

$P_b = [0.03679\ U_e + 1.107 \times 10^{-4}\ U_e^{\ 2}][0.0333\ C'_{req}/L_vD_v]$ 4.6-12

$P_b =$ __________ inches H_2O

b. System fan horsepower, hp_{sf}

$hp_{sf} = 2.5 \times 10^{-4}\ (Q_{e,a})(P_b+1)$ 4.6-13

$hp_{sf} =$ __________ hp

c. Bed drying/cooling fan

Operating time θ_{dcf}:

$\theta_{dcf} = 0.4\ \theta_{reg}\ (NA)(HRS)/\theta_{ad}$ 4.6-14

$\theta_{dcf} =$ __________

Flowrate, FR_{dcf}

$FR_{dcf} = (100(C'_{req}))/\theta_{dry\text{-}cool}$ 4.6-15

$FR_{dcf} =$ __________

Power requirement, P_{dcf}

$P_{dcf} = 1.86 \times 10^{-4}\ (FR_{dcf})(P_b+1)\ (\theta_{dcf})$ 4.6-16

$P_{dcf} =$ __________ kWh/yr

d. Cooling water pump horsepower, hp_{cwp}

$hp_{cwp} = (2.52 \times 10^{-4}\ q_{cw}\ H\ S_g)/n$ 4.6-17

$hp_{cwp} =$ __________ hp

e. Electricity usage, F_p

$F_p = 0.746\ [hp_{sf} + hp_{cwp}]\ HRS + P_{dcf}$ 4.6-18

$F_p =$ __________ kWh/yr

f. Annual electricity cost, AEC

$AEC = 0.059\ (F_p)$ 4.6-19

AEC = $ __________

4. Carbon replacement cost, CRC_c

$CRC_c = CRF_c\ (1.08\ C_c + C_{cl})$

$CRC_c = 0.2638\ (1.08\ C_c + 0.05\ C_{req})$

CRC_c = $ __________

5. Operating costs

Operating labor costs = [(0.5 hr/shift)/(8 hr/shift)](HRS)($12.96/hr)

Operating labor costs = $ __________

Supervisory costs = 0.15 (Operating labor costs)

Supervisory costs = $ __________

6. Maintenance costs

Maintenance labor costs = [(0.5 hr/shift)/(8 hr/shift)](HRS)($14.26/hr)

Maintenance labor costs = $ __________

Maintenance materials = 1.0 (Maintenance labor costs)

Maintenance materials = $ __________

Total Direct Annual Costs = $ __________

Indirect Annual Costs

Use the factors provided in Table 4.6-7 to estimate these costs:

Overhead = $ __________

Property tax = $ __________

Insurance = $ __________

Administrative = $ __________

Capital recovery = $ __________

Total Indirect Annual Costs = $ __________

Recovery Credits

Use Equation 4.6-20 to estimate the quantity of recovered HAP.

$$Q_{rec} = (M_{HAP})(HRS)(RE/100) \quad 4.6\text{-}20$$

Q_{rec} = __________ lb/yr

To obtain the value of recovery credits, simply multiply Q_{rec} by the value of the recovered HAP.

$$\text{Recovery Credits} = (Q_{rec})(\text{Value of HAP})$$

Recovery Credits = $ __________

Total Annual Costs = Total Direct Costs + Total Indirect Costs - Recovery Credits

Total Annual Costs: $ __________

4.6.9 Carbon Canister System Design

4.6.9.1 Carbon Requirement

Use Equation 4.6-22 to estimate the carbon requirement for a canister system:

$$C_{req} = (M_{HAP})(\theta_{ad})/(W_c) \quad 4.6\text{-}22$$

C_{req} = __________ lb

If not given, M_{HAP} can be obtained using Equation 4.6-2.

$$M_{HAP} = 6.0 \times 10^{-5} (HAP_e)(Q_e)(D_{HAP}) \quad 4.6\text{-}2$$

M_{HAP} = __________ lb/hr

To calculate the required canister number (RCN) divide C_{req} by the amount of carbon contained in a single canister and round up to the next whole number (typically 150 lbs).

$$RCN = C_{req}/150$$

RCN = __________

4.6.9.2 Evaluation of Permit Application

Use Table 4.6-9 to evaluate the permit application by comparing the results from the calculations to the reported values.

If the calculated values of θ_{ad}, C_{req}, M_{HAP}, and RCN are different than the reported values, the differences may be due to the assumptions involved with the calculations.

If the calculated values agree with the reported values, then the design and operation of the proposed canister system may be considered appropriate based on the assumptions made in this handbook.

Table 4.6-9 Comparison of Calculated Values and Values Supplied by the Permit Applicant for Carbon Canister Systems

Variable	Calculated Value	Reported Value
Adsorption time, θ_{ad}	. . .	. . .
M_{HAP}, lb/hr	. . .	. . .
Carbon Requirement, C_{req}	. . .	. . .
Required Canister Number, RCN	. . .	. . .

4.6.10 Capital and Annual Costs of Canister Systems

4.6.10.1 Capital Costs of Canister Systems

Use Equation 4.6-23 and Table 4.6-10 to estimate the total capital cost of a canister system.

$$TCC = 1.2\,(CEC) \qquad 4.6\text{-}23$$

where: $CEC = (1.1)(1.08)(RCN)(EC)$

TCC = $ __________

4.6.10.2 Annual Costs for Canister Systems

The annual costs of a canister system are the sum of the direct and indirect annual cost. No recovery credits are available for a canister system.

Direct Costs

1. Electricity

    a. Pressure drop, P_c

Use Equation 4.6-24 to estimate the pressure drop.

$$P_c = 0.0471\, Q'_{e,a} + 9.29 \times 10^{-4} [Q_{e,'a}]^2 \qquad 4.6\text{-}24$$

P_c = __________ in. H_2O

b. Once P_c is estimated, use Equation 4.6-25 to calculate the horsepower requirements hp_{sf}.

$$hp_{sf} = 2.5 \times 10^{-4} [P_c + 1][Q_{e,a}] \qquad 4.6\text{-}25$$

hp_{sf} = __________ hp

c. The required electricity usage F_p is found from Equation 4.6-26.

$$F_p = 0.746\, (hp_{sf})\, HRS \qquad 4.6\text{-}26$$

F_p = __________ kWh/yr

d. The annual electricity cost is then obtained by multiplying F_p by the cost of electricity.

Annual electricity cost = \$0.059 (F_p)

Annual electricity cost = \$ __________

2. Solid waste disposal

This cost can vary significantly from site to site. For purposes of this manual, this cost has been estimated at \$65/canister.

Disposal costs = \$65/canister [RCN]

Disposal costs = \$ __________

There are no operating or maintenance costs assumed for carbon canister systems.

Indirect Costs

These costs are obtained from the factors provided in Table 4.6-5.

Property tax = \$ __________

Insurance = \$ __________

Administrative = \$ __________

Capital recovery = $ ___________

Canister expense = $ ___________

Total Indirect Costs = $ ___________

Total Annual Costs = Total Direct Costs + Total Indirect Costs

Total Annual Costs = $ ___________

Appendix C.7
Calculation Sheet for Absorption

4.7.1 Data Required

HAP emission stream characteristics:

1. Maximum flow rate, Q_e = ____________ scfm
2. Temperature flow rate, Te = ____________ °F
3. HAP = ____________
4. HAP concentration, HAP_e = ____________ ppmv
5. Pressure, P_e = ____________ mm Hg

Required removal efficiency, RE = ____________ %

In the case of a permit review, following data should be supplied by the applicant:

Absorption system variables at standard conditions (77°F, 1 atm):

1. Reported removal efficiency, $RE_{reported}$ = ____________ %
2. Emission stream flow rate, Q_e = ____________ scfm
3. Temperature of emission stream, T_e = ____________ °F
4. Molecular weight of emission stream = ____________ lb/lb-mole
5. HAP = ____________
6. HAP concentration, HAP_e = ____________ ppmv
7. Solvent used = ____________
8. Slope of the equilibrium curve, m = ____________
9. Solvent flow rate, L_{gal} = ____________ gal/min
10. Density of the emission stream, D_e = ____________ lb/ft^3
11. Schmidt No. for the HAP/emission stream and HAP/solvent systems:

    Sc_G = ____________

    Sc_L = ____________

(Refer to Reference 1, or Reference 3 in Section 4.7 for definition and calculation of Sc_G and Sc_L)

12. Properties of the solvent:

Density, D_L = ____________ lb/ft^3

Viscosity, μ_L = ____________ centipoise

13. Type of packing used = ____________

14. Packing constants:

a = ____________ b = ____________ c = ____________ d = ____________

e = ____________ Y = ____________ s = ____________ g = ____________

r = ____________

15. Column diameter, D_{column} = ____________ ft

16. Tower height, (packed) Ht_{column} = ____________ ft

17. Pressure drop, P_{total} = ____________ in. H_2O

4.7.3 Determination of Absorber System Design and Operating Variables

4.7.3.1 Solvent Flow Rate

a. Assume a value of 1.6 for AF.

Determine "m" from the equilibrium data for the HAP/solvent system under consideration (see References 1, 3, and 6 in Section 4.7 for equilibrium data).

m = ____________

Use Equation 4.7-3:

Q_e = ____________ scfm 4.7-3

$G_{mol} = 0.155\ Q_e$

G_{mol} = ____________ lb moles/hr

b. Use Equation 4.7-2:

$L_{mol} = 1.6\ m\ G_{mol}$ 4.7-2

L_{mol} = ______________ lb-moles/hr

c. Use Equation 4.7-5:

$$L_{gal} = 0.036\ L_{mol} \qquad 4.7\text{-}5$$

L_{gal} = ______________ gal/min

4.7.3.2 Column Diameter

a. Use Figure 4.7-2:

Calculate the abscissa (ABS) using Equation 4.7-6:

$MW_{solvent}$ = ______________ lb/lb-mole

$L = L_{mol} \times MW_{solvent}$

L = ______________ lb/hr

MW_e = ______________ lb/lb-mole

$G = G_{mol} \times MW_e$

G = ______________ lb/hr

D_G = ______________ lb/ft^3 (refer to Section 4.7.3.2 to calculate this variable)

D_L = ______________ lb/ft^3 (from reference 1, Section 4.7)

$$ABS = (L/G)(D_G/D_L)^{0.5} \qquad 4.7\text{-}6$$

ABS = ______________

b. From Figure 4.7-2, determine the value of the ordinate (ORD) at flooding conditions.

ORD = ______________

c. For the type of packing used, determine the packing constants from Reference 11, Section 4.7:

a = ______________

e = ______________

Determine μ_L (from reference 1):

μ_L = ______________ cp

d. Use Equation 4.7-8 to calculate $G_{area,f}$:

$G_{area,f} = \{[ORD\ D_G D_L\ g_c]/[(a/e^3)(\mu_L)^{0.2}]\}^{0.5}$ 4.7-8

$G_{area,f}$ = ______________ lb/sec-ft^2

e. Assume a value for the fraction of flooding velocity for the proposed design:

f = ______________ (typically, $0.60 \leq f \leq 0.75$)

Use Equation 4.7-9 to calculate G_{area}:

$G_{area} = f\ G_{area,f}$ 4.7-9

G_{area} = ______________ lb/hr-ft^2

f. Use Equation 4.7-10 to calculate the column cross-sectional area:

$A_{column} = G/(3{,}600\ G_{area})$ 4.7-10

A_{column} = ______________ ft^2

g. Use Equation 4.7-11 to calculate the column diameter:

$D_{column} = 1.13\ (A_{column})^{0.5}$ 4.7-11

D_{column} = ______________ ft

4.7.3.3 Column Height

a. Use Equation 4.7-13 or Figure 4.7-3 to calculate N_{OG}:

Using Equation 4.7-13 and 4.7-14:

HAP_e = ______________ ppmv

$HAP_o = HAP_e\ (1 - RE/100)$ 4.7-14

HAP_o = ______________ ppmv

$N_{og} = \ln\{(HAP_e/HAP_o)[1 - (1/AF)] + (1/AF)\}/[1 - (1/AF)]$ 4.7-13

N_{og} = ______________

Using Figure 4.7-3:

HAP_e/HAP_o = ______________

At HAP_e/HAP_o and $1/AF = 1/1.6 = 0.63$, determine N_{og}:

N_{og} = _____________

b. Use Equations 4.7-16, -17, and -15 to calculate H_G, H_L, and H_{og}. Determine the packing constants in Equations 4.7-16 and 4.7-17 using Tables C.7-1 and C.7-2.

b = _____________ c = _____________ d = _____________

Y = _____________ s = _____________

Determine Sc_G and Sc_L using Tables C.7-3 and C.7-4:

Sc_G = _____________

Sc_L = _____________

$L'' = L / A_{column}$ 4.7-18

L" = _____________ lb/hr-ft²

μ_L'' = _____________ lb/hr-ft (from reference 1)

Calculate H_G and H_L:

$H_G = [b\,(3{,}600\, G_{area})^c/(L'')^d](Sc_G)^{0.5}$ 4.7-16

H_G = _____________ ft

$H_L = Y(L''/\mu_L'')^s(Sc_L)^{0.5}$ 4.7-17

H_L = _____________ ft

Calculate H_{og} using AF = 1.6:

$H_{og} = H_G + (1/AF)H_L$ 4.7-15

H_{og} = _____________ ft

c. Use Equation 4.7-12 to calculate Ht_{column}:

$Ht_{column} = N_{og}H_{og}$ 4.7-12

Ht_{column} = _____________ ft

d. Use Equation 4.7-19 to calculate Ht_{total}:

$Ht_{total} = Ht_{column} + 2t\ (0.25\ D_{column})$ 4.7-19

$Ht_{total} =$ ______________ ft

e. Use Equation 4.7-20 to calculate $V_{packing}$:

$V_{packing} = 0.785(D_{column})^2 \times Ht_{column}$ 4.7-20

$V_{packing} =$ ______________ ft^3

4.7.3.4 Pressure Drop Through the Column

a. Use Equation 4.7-21 to calculate P_a:

Determine the constants using Table C.7-5:

g = ______________

r = ______________

$P_a = g \times 10^{-8}[10(rL''/D_L)](3{,}600\ G_{area})^2/D_G$ 4.7-21

$P_a =$ ______________ lb/ft^2-ft

b. Use Equation 4.7-22 to calculate P_{total}:

$P_{total} = P_a \times (Ht_{column})$ 4.7-22

$P_{total} =$ ______________ lb/ft^2

$(P_{total}/5.2) =$ ______________ in. H_2O

4.7.4 Evaluation of Permit Application

Compare the results from the calculations and the values supplied by the permit applicant using Table 4.7-1. If the calculated values are different from the reported values, the differences may be due to the assumptions involved in the calculations. Therefore, discuss the details of the proposed design with the applicant.

If the calculated values agree with the reported values, then the design of the proposed absorber system may be considered appropriate based on the assumptions made in this handbook.

4.7.5 Capital and Annual Costs of Absorbers

4.7.5.1 Capital Costs of Absorbers

Use Figure 4.7-4 to obtain the cost of the absorber tower. Table 4.7-2 can be used to estimate the cost of packing based on the volume of packing calculated in 4.7.3.3. The cost of auxiliary equipment is obtained from Section 4.12. The equipment cost is the sum of these three costs.

Table 4.7-1 Comparison of Calculated Values and Values Supplied by the Permit Applicant for Absorption

	Calculated Value	Reported Value
Solvent flow rate, L_{gal}	. . .	. . .
Column diameter, D_{column}	. . .	. . .
Column height, Ht_{column}	. . .	. . .
Total column height, Ht_{total}	. . .	. . .
Packing volume, $V_{packing}$	. . .	. . .
Pressure drop, P_{total}	. . .	. . .

1. Absorber tower cost = $ ____________
2. Packing cost = $ ____________
3. Auxiliary equipment cost = $ ____________
4. Equipment cost, EC = 1. + 2. + 3. =$ ____________

The purchased equipment cost, PEC, is obtained from the equipment cost calculated above and the factors provided in Table 4.7-3.

PEC = EC + Instrumentation + Sales tax + Freight

PEC = $ ____________

The total capital cost (TCC) is estimated using the PEC and the factors given in Table 4.7-3.

TCC = 2.20 PEC + SP + Bldg.

TCC = $ ____________

4.7.5.2 Annual Costs for Absorbers

The annual costs of an absorber system consists of direct and indirect annual costs. For purposes of this manual, recovery credits are assumed zero.

Direct Costs.

1. Electricity cost

A. Use Equation 4.7-23 to estimate the fane power requirements, F_p.

$$F_p = 1.81 \times 10^{-4} (Q_{e,a})(P_{total})(HRS) \qquad 4.7\text{-}23$$

$F_p =$ ____________ kWh/hr

where:

$Q_{e,a} = Q_e (T_e + 460)/537$

$Q_{e,a} =$ ____________ acfm

B. The annual electricity cost is then:

Annual electricity cost = \$0.059 (F_p)

Annual electricity cost = \$ ____________

2. Solvent cost

Equation 4.7-24 is used to estimate the annual solvent requirement.

$$\text{Annual solvent requirement} = (60)(L_{gal})(HRS) \qquad 4.7\text{-}24$$

Annual solvent requirement = ____________ gal/yr

The solvent cost is obtained from multiplying the annual solvent requirement and the solvent cost, given in Table 4.7-5.

Annual solvent cost = \$0.20/1,000 gal x (Annual solvent requirement)

Annual solvent cost = \$ ____________

3. Operating labor cost

Operating labor = [(0.5 hr/shift)/(8 hr/shift)](HRS)(\$12.96/hr)

Operating labor = \$ ____________

Supervisory costs = 0.15 (Operating labor)

Supervisory costs = \$ ____________

4. Maintenance costs

Maintenance labor = [(0.5 hr/shift)/(8 hr/shift)](HRS)(\$14.26/hr)

Maintenance labor = \$ ____________

Maintenance materials = 1.0 (Maintenance labor)

Maintenance materials = $ ____________

Total Direct Costs = $ ____________

Indirect Costs

These costs are obtained from the factors provided in Table 4.7-5.

Overhead = $ ____________

Property tax = $ ____________

Insurance = $ ____________

Administrative = $ ____________

Capital recovery = $ ____________

Total Indirect Costs = $ ____________

Total Annual Costs = Total Direct Costs + Total Indirect Costs

Total Annual Costs = $ ____________

Table C.7-1 Constants for Use in Determining Height of a Gas Film Transfer Unit[a]

Packing	b	c	d	Range of 3,600 G_{area} (lb/hr-ft^2)	Range of L" (lb/hr-ft^2)
Raschig rings					
3/8 in.	2.32	0.45	0.47	200 to 500	500 to 1,500
1 in.	7.00	0.39	0.58	200 to 800	400 to 500
	6.41	0.32	0.51	200 to 600	500 to 4,500
1-1/2 in.	17.30	0.38	0.66	200 to 700	500 to 1,500
	2.58	0.38	0.40	200 to 700	1,500 to 4,500
2 in.	3.82	0.41	0.45	200 to 800	500 to 4,500
Berl saddles					
1/2 in.	32.40	0.30	0.74	200 to 700	500 to 1,500
	0.81	0.30	0.24	200 to 700	1,500 to 4,500
1 in.	1.97	0.36	0.40	200 to 800	400 to 4,500
1-1/2 in.	5.05	0.32	0.45	200 to 1,000	400 to 4,500
3-in partition rings	650	0.58	1.06	150 to 900	3,000 to 10,000
Spiral rings (stacked staggered)					
3-in. single spiral	2.38	0.35	0.29	130 to 700	3,000 to 10,000
3-in. triple spiral	15.60	0.38	0.60	200 to 1,000	500 to 3,000
Drip-point grids					
No. 6146	3.91	0.37	0.39	130 to 1,000	3,000 to 6,500
No. 6295	4.56	0.17	0.27	100 to 1,000	2,000 to 11,500

[a] Reference 11 of Section 4.7.

Table C.7-2 Constants for Use in Determining Height of a Liquid Film Transfer Unit[a]

Packing	Y	S	Range of L" (lb/hr-ft^2)
Raschig rings			
3/8 in.	0.00182	0.46	400-15,000
1/2 in.	0.00357	0.35	400-15,000
1 in.	0.0100	0.22	400-15,000
1-1/2 in.	0.0111	0.22	400-15,000
2 in.	0.0125	0.22	400-15,000
Berl Saddles			
1/2 in.	0.00666	0.28	400-15,000
1 in.	0.00588	0.28	400-15,000
1-1/2 in.	0.00625	0.28	400-15,000
3-in. Partition rings (stacked, staggered)	0.0625	0.09	3,000-14,000
Spiral rings (stacked, staggered)			
3-in. single spiral	0.00909	0.28	400-15,000
3-in. triple spiral	0.0116	0.28	3,000-14,000
Drip-point grids (continuous flue)			
Style 6146	0.0154	0.23	3,500-30,000
Style 6295	0.00725	0.31	2,500-22,000

[a] Reference 11 of Section 4.7.

Table C.7-3 Schmidt Numbers for Gases and Vapors in Air at 77°F and 1 ATM[a]

Substance	$(Sc_G)^b$	Substance	$(Sc_G)^b$
Ammonia	0.66	Valeric acid	2.31
Carbon dioxide	0.94	i-Caproic acid	2.58
Hydrogen	0.22	Diethyl amine	1.47
Oxygen	0.75	Butyl amine	1.53
Water	0.60	Aniline	2.14
Carbon disulfide	1.45	Chloro benzene	2.12
Ethyl ether	1.66	Chloro toluene	2.38
Methanol	0.97	Propyl bromide	1.47
Ethyl alcohol	1.30	Propyl iodide	1.61
Propyl alcohol	1.55	Benzene	1.76
Butyl alcohol	1.72	Toluene	1.84
Amyl alcohol	2.21	Xylene	2.18
Hexyl alcohol	2.60	Ethyl benzene	2.01
Formic acid	0.97	Propyl benzene	2.62
Acetic acid	1.16	Diphenyl	2.28
Propionic acid	1.56	n-Octane	2.58
i-Butyric aid	1.91	Mesitylene	2.31

---

[a] Reference 13 of Section 4.7.

[b] $Sc_G = \mu_G/P_G D_G$ where D_G and μ_G are the density and viscosity of the gas stream and P_G is the diffusivity of the vapor in the gas stream.

Table C.7-4 Schmidt Numbers for Compounds in Water at 68°F[a]

Solute[b]	(Sc_L)[c]	Solute[b]	(Sc_L)[c]
Oxygen	558	Glycerol	1,400
Carbon dioxide	559	Pyrogallol	1,440
Nitrogen Oxide	665	Hydroquinone	1,300
Ammonia	570	Urea	946
Bromine	840	Resorcinol	1,260
Hydrogen	196	Urethane	1,090
Nitrogen	613	Lactose	2,340
Hydrogen chloride	381	Maltose	2,340
Hydrogen sulfide	712	Mannitol	1,730
Sulfuric acid	580	Raffinose	2,720
Nitric acid	390	Sucrose	2,230
Acetylene	645	Sodium chloride	745
Acetic acid	1,140	Sodium hydroxide	665
Methanol	785	Carbon dioxide[d]	445
Ethanol	1,005	Phenol[d]	1,900
Propanol	1,150	Chloroform[d]	1,230
Butanol	1,310	Acetic acid[e]	479
Allyl alcohol	1,080	Ethylene dichloride[e]	301
Phenol	1,200		

---

[a] Reference 13 of Section 4.7.

[b] Solvent is water except where indicated.

[c] Sc_L - $\mu_L/P_L D_L$ where μ_L and P_L are the viscosity and density of the liquid and D_L is the diffusivity of the solute in the liquid.

[d] Solvent is ethanol.

[e] Solvent is benzene.

Table C.7-5 Pressure Drop Constants for Tower Packing[a]

Packing	Nominal size, (in.)	g	r	Range of L" (lb/hr-ft^2)
Raschig rings	1/2	139	0.00720	300 to 8,600
	3/4	32.90	0.0045	1,800 to 10,800
	1	32.10	0.00434	360 to 27,000
	1-1/2	12.08	0.00398	720 to 18,000
	2	11.13	0.00295	720 to 21,000
Berl saddles	1/2	60.40	0.00340	300 to 14,100
	3/4	24.10	0.00295	360 to 14,400
	1	16.10	0.00295	720 to 78,800
	1-1/2	8.10	0.00225	720 to 21,600
Intalox saddles	1	12.44	0.00277	2,520 to 14,400
	1-1/2	5.66	0.00225	2,520 to 14,400
Drip-point grid tiles	No. 6146 Continuous flue	1.045	0.00214	3,000 to 17,000
	Cross flue	1.218	0.00227	300 to 17,500
	No. 6295 Continuous flue	1.088	0.00224	850 to 12,500
	Cross flue	1.435	0.00167	900 to 12,500

[a] Reference 13 of Section 4.7.

Appendix C.8
Calculation Sheet for Condensation

4.8.1 Data Required

HAP emission stream characteristics:

1. Maximum flow rate, Q_e = ____________ scfm
2. Temperature, T_e = __________ °F
3. HAP = __________
4. HAP concentration, HAP_e = __________ ppmv
5. Moisture content, M_e = __________ %
6. Pressure, P_e = __________ mm Hg

In the case of a permit review for a condenser, the following data should be supplied by the applicant:

Condenser system variables at standard conditions (77°F, 1 atm):

1. Reported removal efficiency, $RE_{reported}$ = __________ %
2. Emission stream flow rate, Q_e = __________ scfm
3. Temperature of emission stream, T_e = __________ °F
4. HAP = __________
5. HAP concentration, HAP_e = __________ ppmv
6. Moisture content, M_e = __________ %
7. Temperature of condensation, T_{con} = __________ °F
8. Coolant used = __________
9. Temperature of inlet coolant, $T_{cool,i}$ = __________ °F
10. Coolant flow rate, $Q_{coolant}$ = __________ lb/hr
11. Refrigeration capacity, Ref = __________ tons
12. Condenser surface area, A_{con} = __________ ft^2
13. Specific Heat of HAP, Cp_{HAP} = __________ Btu/lb-mol°F

14. Heat of vaporization of HAP, ΔH = __________ Btu/lb-mol

4.8.2 Pretreatment of the Emission Stream

Check to see if moisture content of the emission stream is high. If it is high, dehumidification is necessary. This can be carried out in a heat exchanger prior to the condenser.

4.8.3 Condenser System Design Variables

The key design variable is the condensation temperature. Coolant selection will be based on this temperature.

4.8.3.1 Estimating Condensation Temperatures

a. Use Equation 4.8-1 to calculate $P_{partial}$:

$$P_{partial} = 760\{(1 - 0.01\ RE)/[1 - (RE \times 10^{-8}\ HAP_e)]\}HAP_e \times 10^{-6} \qquad 4.8\text{-}1$$

$P_{partial}$ = __________ mm Hg

b. Use Figure 4.8-2 to determine T_{con}:

T_{con} = __________ °F

4.8.3.2 Selection of Coolant

Use Table 4.8-1 to specify the coolant (also see references 3 and 7):

Coolant = __________

In evaluating a permit application, use Table 4.8-1 to determine if the applicant's values for T_{con}, coolant type, and $T_{cool,i}$ are appropriate:

T_{con} = __________ °F

Coolant type = __________

$T_{cool,i}$ = __________ °F

If they are appropriate, proceed with the calculations. Otherwise, reject the proposed design.

4.8.3.3 Condenser Heat Load

1. a. Use Equation 4.8-2 to calculate $HAP_{e,m}$:

$$HAP_{e,m} = (Q_e/392)\ HAP_e \times 10^{-6} \qquad 4.8\text{-}2$$

$HAP_{e,m}$ = __________ lb-moles/min

b. Use Equation 4.8-3 to calculate $HAP_{o,m}$:

$$HAP_{o,m} = (Q_e/392)[1-(HAP_e \times 10^{-6})][P_{vapor}/(P_e - P_{vapor})] \qquad 4.8\text{-}3$$

where: $P_{vapor} = P_{partial}$

$HAP_{o,m}$ = __________ lb-moles/min

c. Use Equation 4.8-4 to calculate HAP_{con}:

$$HAP_{con} = HAP_{e,m} - HAP_{o,m}$$

HAP_{con} = __________ lb-moles/min 4.8-4

2. a. Calculate heat of vaporization (ΔH) of the HAP from the slope of the graph $[\ln(P_{vapor})]$ vs $[1/(T_{con} + 460)]$ for the P_{vapor} and T_{con} ranges of interest (Fig. 4.8-2).

ΔH = __________ Btu/lb-mole

b. Use Equation 4.8-5 to calculate H_{con}:

$$H_{con} = HAP_{con}[DH+Cp_{HAP}\,(T_e - T_{con})] \qquad 4.8\text{-}5$$

where Cp_{HAP} can be obtained from References 3 and 7, or Table C.8-1.

H_{con} = __________ Btu/min

c. Use Equation 4.8-6 to calculate H_{noncon}:

$$H_{noncon} = [(Q_e/392)-HAP_{e,m}]\ Cp_{air}\,(T_e - T_{con}) \qquad 4.8\text{-}6$$

where Cp_{air} can be obtained from References 3 and 7, or Table C.8-1.

H_{noncon} = __________ Btu/min

3. a. Use Equation 4.8-7 to calculate H_{load}:

$$H_{load} = 1.1 \times 60\ (H_{con} + H_{noncon}) \qquad 4.8\text{-}7$$

H_{load} = __________ Btu/hr

4.8.3.4 Condenser Size

Use Equation 4.8-9 to calculate A_{con}:

$$A_{con} = H_{load}/U\ \Delta T_{LM} \qquad 4.8\text{-}9$$

where T_{LM} is calculated as follows:

$$\Delta T_{LM} = [(T_e - T_{cool,o}) - (T_{con} - T_{cool,i})]/\ln[(T_e - T_{cool,o})/(T_{con} - T_{cool,i})]$$

Assume: $T_{cool,i} = T_{con}-15$, and $T_{cool,o} - T_{cool,i} = 25°F$

$T_{cool,i}$ = ___________ °F

$T_{cool,o}$ = ___________ °F

ΔT_{LM} = ___________ °F

Assume: U = 20 Btu/hr-ft^2-°F (if no other estimate is available).

A_{con} = ___________ ft^2

Table C.8-1 Average Specific Heats of Vapors[a,b]

Average Specific Heat, Cp (Btu/scf-°F)[c,d]

Temperature (°F)	Air	H_2O	O_2	N_2	CO	CO_2	H_2	CH_4	C_2H_4	C_2H_6
77	0.0180	0.0207	0.0181	0.0180	0.0180	0.0230	0.0178	0.0221	0.0270	0.0326
212	0.0180	0.0209	0.0183	0.0180	0.0180	0.0239	0.0179	0.0232	0.0293	0.0356
392	0.0181	0.0211	0.0186	0.0181	0.0181	0.0251	0.0180	0.0249	0.0324	0.0395
572	0.0183	0.0212	0.0188	0.0182	0.0183	0.0261	0.0180	0.0266	0.0353	0.0432
752	0.0185	0.0217	0.0191	0.0183	0.0184	0.0270	0.0180	0.0283	0.0379	0.0468
932	0.0187	0.0221	0.0194	0.0185	0.0186	0.0278	0.0181	0.0301	0.0403	0.0501
1,112	0.0189	0.0224	0.0197	0.0187	0.0188	0.0286	0.0181	0.0317	0.0425	0.0532
1,292	0.0191	0.0228	0.0199	0.0189	0.0190	0.0292	0.0182	0.0333	0.0445	0.0560
1,472	0.0192	0.0232	0.0201	0.0190	0.0192	0.0298	0.0182	0.0348	0.0464	0.0587
1,652	0.0194	0.0235	0.0203	0.0192	0.0194	0.0303	0.0183	0.0363	0.0481	0.0612
1,832	0.0196	0.0239	0.0205	0.0194	0.0196	0.0308	0.0184	0.0376	0.0497	0.0635
2,012	0.0198	0.0243	0.0207	0.0196	0.0198	0.0313	0.0185	0.0389	0.0512	0.0656
2,192	0.0199	0.0246	0.0208	0.0197	0.0199	0.0317	0.0186	0.0400	0.0525	0.0676

[a] Source: Reference 3 (see Section 4.8.6).

[b] Average for the temperature interval 77°F and the specified temperature.

[c] Based on 70°F and 1 atm.

[d] To convert to Btu/lb-°F basis, multiply by 392 and divide by the molecular weight of the compound. To convert to Btu/lb-mol°F, multiply by 392.

4.8.3.5 Coolant Flow Rate

Use Equation 4.8-10 to calculate $Q_{coolant}$:

$$Q_{coolant} = H_{load}/[Cp_{coolant} (T_{cool,o} - T_{cool,i})] \qquad 4.8\text{-}10$$

The value for $Cp_{coolant}$ for different coolants can be obtained from References 3 or 7. If water is used as the coolant, Cp_{water} can be taken as 1 Btu/lb-°F.

$Cp_{coolant}$ = __________ Btu/lb-°F

$Q_{coolant}$ = __________ lb/hr

4.8.3.6 Refrigeration Capacity

Use Equation 4.8-11 to calculate Ref:

$$Ref = H_{load}/12{,}000 \qquad 4.8\text{-}11$$

Ref = __________ tons

4.8.3.7 Recovered Product

Use Equation 4.8-12 to calculcate Q_{rec}:

$$Q_{rec} = 60 \times HAP_{con} \times MW_{HAP} \qquad 4.8\text{-}12$$

Q_{rec} = __________ lb/hr

4.8.4 Evaluation of Permit Application

Compare the results from the calculations and the values supplied by the permit applicant using Table 4.8-2. If the calculated values T_{con}, coolant type, $Q_{coolant}$, A_{con}, Ref, and Q_{rec} are different from the reported values for these variables, the differences may be due to the assumptions involved in the calculations. Discuss the details of the proposed design with the permit applicant.

If the calculated values agree with the reported values, then the design and operation of the proposed condenser system may be considered appropriate based on the assumptions made in this handbook.

4.8.5 Capital and Annual Costs of Condensers

4.8.5.1 Capital Costs of Condensers

The capital cost of a condenser system is composed of the purchased equipment cost (PEC) and the direct and indirect installation costs.

Figure 4.8-3 or 4.8-4 can be used to estimate the cost of a chilled water condenser. The equipment cost is the sum of the condenser cost obtained from Figure 4.8-3 or 4.8-4 and the auxiliary equipment cost obtained from Section 4.12. The PEC is then estimated using the factors given in Table 4.8-3.

Table 4.8-2 Comparison of Calculated Values and Values Supplied by the Permit Applicant for Condensation

	Calculated Value	Reported Value
Continuous monitoring of exit stream temperature	. . .	. . .
Condensation temperature, T_{con}	. . .	. . .
Coolant type	. . .	. . .
Coolant flow rate, $Q_{coolant}$	. . .	. . .
Condenser surface area, A_{con}	. . .	. . .
Refrigeration capacity, Ref	. . .	. . .
Recovered product, Q_{rec}	. . .	. . .

Condenser cost = $ __________

Auxiliary equipment cost = $ __________

Equipment cost, EC = Condenser cost + Auxiliary equipment cost

Equipment cost, EC = $ __________

The Purchased Equipment Cost, PEC, is estimated as follows:

PEC = EC + Instrumentation & Sales tax & Freight

PEC = $ __________

The total capital cost (TCC) is estimated using the PEC and the factors given in Table 4.8-3.

TCC = 1.74 PEC + SP + Bldg.

TCC = $ __________

If a condenser needs a refrigerant system, the escalated total capital cost of the refrigerant system obtained from Figure 4.8-4 is added to the TCC obtained above.

4.8.5.2 Annual Costs for Condensers

The annual cost for a condenser system consists of direct and indirect annual costs minus recovery credits.

Direct Annual Costs

Direct annual costs consist of utilities, operating labor, and maintenance labor.

The electricity cost is estimated using the cost factor given in Table 4.8-5 and the annual electricity usage (F_p), calculated using Equation 4.8-13.

$$F_p = 1.81 \times 10^{-4} (Q_{e,a})(P)(HRS) \qquad 4.8\text{-}13$$

where: $Q_{e,a} = Q_e (T_e + 460)/537$

F_p = __________ kWh/yr

Annual electricity cost = \$0.059 (F_p)

Annual electricity cost = \$ __________

The cost of replacing the refrigerant will vary, but is typically low. For purposes of this report, this cost is assumed to equal zero.

The operating labor cost is estimated using a labor requirement of 0.5 hr/shift and the labor rate given in Table 4.8-5. Supervisory costs are assumed to equal 15 percent of operating labor costs.

Operating labor = [(0.5 hr/shift)/(8 hr/shift)](HRS)(\$12.96/hr)

Operating labor = \$ __________

Supervisory costs = 0.15 (Operating labor)

Supervisory costs = \$ __________

Maintenance labor costs are estimated using a labor requirement of 0.5 hr/shift and the wage rate given in Table 4.8-5. Maintenance materials are assumed to be 100 percent of this cost.

Maintenance labor = [(0.5 hr/shift)/(8 hr/shift)](HRS)(\$14.26/hr)

Maintenance labor \$ __________

Maintenance materials = 1.0 (Maintenance labor)

Maintenance materials = \$ __________

Total Direct Costs = \$ __________

Indirect Costs

These costs are obtained from the factors provided in Table 4.8-5.

Overhead = $ __________

Administrative = $ __________

Insurance = $ __________

Property tax = $ __________

Capital recovery = $ __________

Total Indirect Costs = $ __________

Recovery credits may be significant, but are highly variable and depend on site specific conditions. The reader will need to obtain this credit on a site specific basis.

TAC = Total Direct Costs + Total Indirect Costs - Recovery Credits

TAC = $ __________

Appendix C.9
Calculation Sheet for Fabric Filters

4.9.1 Data Required

HAP emission stream characteristics:

1. Flow rate, $Q_{e,a}$ = __________ acfm
2. Moisture content, M_e = __________ % (vol)
3. Temperature, T_e = __________ °F
4. Particle mean diameter, D_p = __________ µm
5. SO_3 content = __________ ppm (vol)
6. Particulate content = __________ grains/scf
7. HAP content = __________ % (mass)

In the case of a permit review, the following data should be supplied by the applicant:

1. Filter fabric material __________
2. Cleaning method (mechanical shaking, reverse air, pulse-jet) __________
3. Air-to-cloth ratio __________ ft/min
4. Baghouse construction configuration (open pressure, closed pressure, closed suction) __________
5. System pressure drop range __________ in. H_2O

4.9.2 Pretreatment Considerations

If emission stream temperature is not from 50° to 100°F above the dew point, pretreatment is necessary (see Section 3.3.1 and Appendix B.1). Pretreatment will cause two of the pertinent emission stream characteristics to change; list the new values below.

1. Maximum flow rate at actual conditions, $Q_{e,a}$ = __________ acfm
2. Temperature, T_e = __________ °F

4.9.3 Fabric Filter System Design Variables

1. Fabric Type(s) (use Table 4.9-1):

   a. __________

b. __________

c. __________

2. Cleaning Method(s) (Section 4.9.3.2):

a. __________

b. __________

3. Air-to-cloth ratio (Table 4.9-3) __________ ft/min

4. Net cloth area, A_{nc}:

$$A_{nc} = Q_{e,a} / (\text{A/C ratio}) \qquad 4.9\text{-}1$$

where:

A_{nc} = net cloth area, ft^2

$Q_{e,a}$ = maximum flow rate at actual conditions, acfm

where:

$Q_{e,a} = Q_e (T_e + 460)/537$ (used if given Q_e instead of $Q_{e,a}$)

A/C ratio = air-to-cloth ratio, ft/min

A_{nc} = __________ / __________

A_{nc} = __________ ft^2

5. Gross cloth area, A_{tc}:

$$A_{tc} = A_{nc} \times \text{Factor}$$

where:

A_{tc} = gross cloth area, ft^2

Factor = value from Table 4.9-4, dimensionless

A_{tc} = __________ × __________

A_{tc} = __________ ft^2

6. Baghouse configuration __________

7. Materials of construction __________

4.9.4 Determination of Baghouse Operating Parameters

1. Collection efficiency, CE = __________

2. System pressure drop range __________ in. H_2O

4.9.5 Evaluation of Permit Application

Using Table 4.9-5, compare the results from this section and the data supplied by the permit applicant. As pointed out in the discussion on fabric filter design considerations, the basic design parameters are generally selected without the involved, analytical approach that characterizes many other control systems, such as an absorber system (Section 4.7). Therefore, in evaluating the reasonableness of any system specifications on a permit application, the reviewer's main task will be to examine each parameter in terms of its compatibility with the gas stream and particulate conditions and with the other selected parameters. The following questions should be asked:

1. Is the temperature of the emission stream entering the baghouse within 50° to 100°F above the stream dew point?

2. Is the selected fabric material compatible with the conditions of the emission stream; that is, temperature and composition (see Table 4.9-1)?

3. Is the baghouse cleaning method compatible with the selected fabric material and its construction; that is, material type and woven or felted construction (see Section 4.9.3.2 and Table 4.9-2)?

4. Will the selected cleaning mechanism provide the desired control?

5. Is the A/C ratio appropriate for the application; that is, type of dust and cleaning method used (see Table 4.9-3)?

6. Are the values provided for the gas flow rate, A/C ratio, and net cloth area consistent? The values can be checked with the following equation:

$$\text{A/C ratio} = \frac{Q_{e,a}}{A_{nc}}$$

where:

A/C ratio = air-to-cloth ratio, ft/min

$Q_{e,a}$ = emission stream flow rate at actual conditions, acfm

A_{nc} = net cloth area, ft^2

7. Is the baghouse configuration appropriate; that is, is it a negative-pressure baghouse?

Table 4.9-5 Comparison of Calculated Values and Values Supplied by the Permit Applicant for Fabric Filters

	Calculated Value	Reported Value
Continuous monitoring of system pressure drop	. . .	. . .
Emission Stream Temp. Range	. . .	. . .
Selected Fabric Material	. . .	. . .
Baghouse Cleaning Method	. . .	. . .
A/C ratio $= \frac{Q_{e,a}}{A_{nc}}$	. . .	. . .
Baghouse Configuration	. . .	. . .

4.9.6 Capital and Annual Costs of Fabric Filters

4.9.6.1 Total Capital Costs

The total capital cost (TCC) of a baghouse system includes the baghouse structure, cost of bags, auxiliary equipment, and the direct and indirect installation costs.

Table 4.9-6 provides a guide that enables the reader to use the correct cost figure for a given baghouse. Figures 4.9-1 through 4.9-6 are used to estimate the cost of the baghouse structure, but do not include the bag cost. The bag cost (C_B) is estimated using Table 4.9-7 and the gross cloth area calculated in Section 4.9.3.3.

The cost of auxiliary equipment is obtained from Section 4.12.

The sum of the cost of the baghouse structure, bags and auxiliary equipment is the equipment cost, EC. Table 4.9-8 contains the factors necessary to estimate the purchased equipment cost (PEC) from the equipment cost:

Baghouse structure cost = $ __________

Bag cost, C_B = $ __________

Auxiliary equipment cost = $ __________

Equipment cost, EC = $ __________

Purchased equipment cost = 1.18 (EC)

Purchased equipment cost, PEC = $ __________

The factors given in Table 4.9-8 are used to estimate the total capital cost (TCC) of a baghouse system.

TCC = 2.17 (PEC) + SP + Bldg.

TCC = $ __________

4.9.6.2 Annual Costs of Fabric Filters

The annual cost of a fabric filter system consists of direct and indirect annual costs.

Direct Costs

The direct costs include utilities, operating labor, and maintenance costs.

The annual electricity cost is the product of the annual electricity usage, and the electricity cost. The annual electricity usage is estimated using Equation 4.9-2.

$$F_P = 1.81 \times 10^{-4} (Q_{e,a})(P)(HRS) \qquad 4.9\text{-}2$$

Annual electricity cost = $0.059 ($F_P$)

Annual electricity cost = $ __________

If a mechanical shaking is used, the additional power requirement (P_{ms}) in kWh/yr must be added to F_P to estimate the total annual electricity usage.

$$P_{ms} = 6.05 \times 10^{-6}(HRS)(A_{tc}) \qquad 4.9\text{-}3$$

and,

Annual electricity cost = $0.059 ($F_P + P_{ms}$)

Annual electricity cost = $ __________

If a pulse jet cleaning is used, the consumption of compressed air can be estimated using a factor of 2 scfm compressed air/1,000 scfm emission stream. The equation below can be used to estimate the yearly compressed air consumption.

Annual consumption = (Q_e)(0.002)(60)(HRS) ft^3/yr

The cost of compressed air is estimated using the factor provided in Table 4.9-10.

Annual compressed air cost = $0.16/1,000 scfm × (Annual consumption)

Annual compressed air cost = $ __________

Equation 4.9-4 is used to estimate the cost of replacement bags, C_{RB}.

$$C_{RB} = [C_B + C_L]\ CRF_B = [C_B + 0.14\ A_{nc}]\ 0.5762 \qquad 4.9\text{-}4$$

C_{RB} = $ __________

The operating labor cost is estimated using a labor requirement of 3 hr/shift and the wage rate given in Table 4.9-10. Supervisory costs are assumed to equal 15 percent of the operating labor cost.

Operating labor = [(3 hr/shift)/(8 hr/shift)] (HRS) ($12.96/hr)

Operating labor = $ __________

Supervisory costs = 0.15 (Operating labor)

Supervisory costs = $ __________

Maintenance costs are estimated using a maintenance requirement of 1 hour per shift and the wage rate given in Table 4.9-10. Maintenance materials are assumed to equal 100 percent of this cost.

Maintenance labor = [(1 hr/shift)/(8 hr/shift)] (HRS) ($14.26/hr)

Maintenance labor = $ __________

Maintenance materials = 1.0 (Maintenance labor)

Maintenance materials = $ __________

Waste disposal costs should be estimated for each facility on a case-by-case basis, as these costs vary widely. If no information can be found this cost can be estimated using a factor of $200/ton for hazardous wastes.

Waste disposal costs = $ __________

Total Direct Costs = $ __________

Indirect Costs

These costs are obtained from the factors provided in Table 4.9-9.

Overhead = $ __________

Property tax = $ __________

Administrative = $ __________

Insurance = $ __________

Capital recovery = $ __________

Total Indirect Costs = $ __________

Recovery credits may be significant, but are highly variable and depend on site specific conditions. The reader will need to obtain this credit on a site specific basis.

TAC = Total Direct Costs + Total Indirect Costs - Recovery Credits

TAC = $ __________

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Appendix C.10
Calculation Sheet for Electrostatic Precipitators

4.10.1 Data Required

HAP emission stream characteristics

1. Flow rate, $Q_{e,a}$ = __________ acfm
2. Emission stream temperature, T_e = __________ °F
3. Particulate content = __________ grains/scf
4. Moisture content, M_e = __________ % (vol)
5. HAP content = __________ % (mass)

In case of a permit review, the following data should be supplied by the applicant. The design considerations in this section will then be used to check the applicant's design.

1. Reported collection efficiency = __________ %
2. Reported drift velocity of particles = __________ ft/sec
3. Reported collection plate area = __________ ft^2
4. System pressure drop = __________ in. H_2O

4.10.2 Pretreatment of Emission Stream

If the emission stream temperature is not from 50° to 100°F above the dew point, pretreatment is necessary (see Section 3.3.1 and Appendix B.1). Pretreatment will cause two of the pertinent emission stream characteristics to change; list the new values below.

1. Maximum flow rate at actual conditions, $Q_{e,a}$ = __________ acfm
2. Temperature, T_e = __________ °F

4.10.3 ESP Design Variables

4.10.3.1 Collection Plate Area and Collection Efficiency

Collection plate area is a function of the emission stream flow rate, drift velocity of the particles (Table 4-17), and desired control efficiency. The variables are related using Equation 4.10-1:

$$SCA = -\ln(1-CE)/U_d\,(0.06) \qquad 4.10\text{-}1$$

where:

SCA = specific collection plate area ft^2/1,000 acfm

U_d = drift velocity of particles, ft/sec (see Tables 4.10-1 through 4.10-3)

CE = required collection efficiency, decimal fraction

SCA = __________ ft^2

4.10.4 Evaluation of Permit Application

Using Table 4.10-4, compare the results from this section and the data supplied by the permit applicant. In evaluating the reasonableness of ESP design specifications in a permit application, the main task will be to examine each parameter in terms of its capability with the gas stream conditions.

If the applicant's collection plate area is less than the calculated area, the discrepancy will most likely be the selected drift velocity. Further discussions with the permit applicant are recommended to evaluate the design assumptions and to reconcile any apparent discrepancies.

Table 4.10-4 Comparison of Calculated Values and Values Supplied by the Permit Applicant for ESPs

Parameter	Calculated Value	Reported Value
Continuous monitoring of plate voltage and current	. . .	. . .
Drift velocity of particles, U_d	. . .	. . .
Collection efficiency, CE	. . .	. . .
Collection plate area, A_p	. . .	. . .

4.10.5 Capital and Annual Costs of ESP Systems

4.10.5.1 ESP Capital Costs

The capital cost of an ESP system consists of the purchased equipment costs and the direct and indirect installation cost factors given in Table 4.10-5.

The purchased equipment cost, PEC, is composed of equipment costs (EC) and the cost of instrumentation, sales tax, and freight. The equipment cost is the sum of the ESP structure cost obtained from Figure 4.10-2 or 4.10-3 and the auxiliary cost obtained from Section 4.12. Tables 4.10-6 and 4.10-7 are used to adjust the ESP cost obtained from Figure 4.10-2 or 4.10-3 to specific conditions.

1. ESP cost (from Figure 4.10-2 or 4.10-3) = $ __________
2. Cost factor from Table 4.10-6 = __________ (default = 1.0)
3. Cost factor from Table 4.10-7 = __________ (default = 1.0)

   Total ESP cost = (1) × (2) × (3)

   Total ESP cost = $ __________

4. Equipment cost (EC) = Total ESP cost + auxiliary equipment cost

   Equipment cost (EC) = $ __________

5. Purchased equipment cost, PEC = 1.18 × EC (see Table 4.10-5)

   Purchased equipment cost, PEC = $ __________

The factors given in Table 4.10-5 are used to estimate the total capital cost (TCC) of an ESP system.

TCC = 2.24 PEC + SP + Bldg.

TCC = $ __________

4.10.5.2 Annual Costs for ESP

The annual costs of an ESP system consist of direct and indirect annual costs.

Direct Costs

The direct costs include electricity, operating labor, maintenance costs, plus, if applicable, water costs, wastewater treatment costs, and SO_3 conditioning costs.

The annual electricity cost is the product of the annual electricity usage and the electricity cost factor given in Table 4.10-9. The annual electricity usage is estimated using Equation 4.10-2.

$$F_p = 1.81 \times 10^{-4} (Q_{ea}) (P) (HRS) \qquad 4.10\text{-}2$$

where:

F_p = annual electricity usage, kWh/yr

$Q_{e,a}$ = emission stream flowrate, acfm

P = pressure drop, in. H_2O (default = 5 in. H_2O)

HRS = annual operating hours, hr/yr

F_p = __________ kWh/yr

For wet ESPs the pump power (P_p) is estimated using Equation 4.10-3.

$$P_p = 0.746\,(Q_L)(Z)(S_g)(HRS)/(3960n) \qquad 4.10\text{-}3$$

where:

P_p = Pump power requirements, kWh/yr

Q_L = Liquid flow rate, gal/min

Z = fluid head, ft

S_g = specific gravity of fluid relative to water at 77°F, 1 atm

HRS = annual operating hours, hr/yr

n = combined pump-motor efficiency, fraction

P_p = __________ kWh/yr

This power requirement is multiplied by the electricity cost factor to obtain annual pump power costs.

For TR sets and motor driven or electromagnetic rapper systems the power requirement (OP) is estimated using Equation 4.10-4.

$$OP = 1.94 \times 10^{-3}\,(A_p)\,(HRS) \qquad 4.10\text{-}4$$

where:

OP = annual ESP operating power, kWh/yr

A_p = collection plate area, ft^2

HRS = annual operating hours, hr/yr

OP = __________ kWh/hr

This power requirement is multiplied by the electricity cost factor to obtain annual costs.

For two stage ESPs, power requirements (P_{TS}) are assumed to equal 40 W/kacfm.

$P_{TS} = 40\ (Q_{e,a} \times 0.06)\ (HRS)/1,000$

$P_{TS} =$ ___________ kWh/yr

This value for P_{TS} is multiplied by the electricity cost factor given in Table 4.10-8 to obtain annual costs.

For wet ESPs, the consumption of water (W_{CT}) is estimated at 5 gal/min kacfm for single stage ESPs, and 16 gal/min kacfm for two stage ESPs.

Single Stage ESPs:

$W_{CT} = 5\ (Q_{e,a} \times 0.06)\ (HRS)$

$W_{CT} =$ ___________ gal/yr

Two Stage ESPs:

$W_{CT} = 16\ (Q_{e,a} \times 0.06)\ (HRS)$

$W_{CT} =$ ___________ gal/yr

The value obtained for W_{CT} is multiplied by the cost factor given in Table 4.10-8 to obtain annual costs.

The cost of an SO_3 conditioning system for a large (2.6×10^6 acfm) ESP ranges from $\$1.61/10^6\ ft^3$ gas processed to $\$2.30/10^6\ ft^3$ gas processed. Taking the midpoint,

$\text{Cost}_{SO3} = \$1.96/10^6\ ft^3\ (Q_{e,a})(60)(HRS)$

$\text{Cost}_{SO3} = \$$ ___________

The operating labor cost is estimated using a labor requirement of 0.5 hr/shift and the wage rate given in Table 4.10-8. Supervisory costs are assumed equal to 15 percent of the operating labor cost.

Operating labor = [(0.5 hr/shift)/(8 hr/shift)](HRS)($12.96/hr)

Operating labor = $ ___________

Operating costs = 0.15 (Operating labor)

Operating costs = $ ___________

Maintenance costs (MC) are estimated from Equation 4.10-5.

$$MC = 0.01\ (PEC) + \text{Labor cost} \qquad 4.10\text{-}5$$

where:

PEC = purchased equipment cost, $

Labor cost = $4,125, if $A_p <$ 50,000 ft^2

Labor cost = $0.0825 A_p, if $A_p \geq$ 50,000 ft^2

MC = $ __________

Waste disposal costs are estimated at $200/ton hazardous waste. The equation below can be used to estimate this cost.

Waste disposal costs per year = (Particulate content in gr/ft^3)

(lb/7,000 gr)($Q_{e,a}$)(60)(HRS)($200)/2000

Waste disposal cost per year = $ __________

Total Direct Costs = $ __________

Indirect Costs

These costs are obtained from the factors provided in Table 4.10-8.

Overhead = $ __________

Administrative = $ __________

Property tax = $ __________

Insurance = $ __________

Capital recovery = $ __________

Total Indirect Costs = $ __________

TAC = Total Direct Costs + Total Indirect Costs

TAC = $ __________

Appendix C.11
Calculation Sheet for Venturi Scrubbers

4.11.1 Data Required

HAP emission stream characteristics:

1. Flow rate, $Q_{e,a}$ = __________ acfm
2. Temperature, T_e = __________ °F
3. Moisture content, M_e = __________ %
4. Required collection efficiency, CE = __________ %
5. Particle mean diameter, D_p = __________ µm
6. Particulate content = __________ grains/scf
7. HAP content = __________ % (mass)

In the case of a permit review, the following data should be supplied by the applicant:

1. Reported pressure drop across venturi, P_v = __________ in. H_2O
2. An applicable performance curve for the venturi scrubber
3. Reported collection efficiency, CE = __________ %

4.11.2 Pretreatment of Emission Stream

If the emission stream temperature is not from 50° to 100°F above the dew point, pretreatment is necessary (see Section 3.3.1 and Appendix B.1). Pretreatment will cause two of the pertinent emission stream characteristics to change; list the new values below.

1. Maximum flow rate at actual conditions, $Q_{e,a}$ = __________ acfm
2. Temperature, T_e = __________ °F

4.11.3 Venturi Scrubber Design Variables

4.11.3.1 Venturi Scrubber Pressure Drop

The pressure drop across the venturi (P_v) can be estimated through the use of a venturi scrubber performance curve (Figure 4.11-1) and known values for the required collection efficiency (CE) and the particle mean diameter (D_p).

P_v = __________ in. H_2O

If the estimated P_V is greater than 80 in H_2O, assume that the venturi scrubber cannot achieve the desired control efficiency.

4.11.3.2 Materials of Construction

Select the proper material of construction by contacting a vendor, or as a lesser alternative, by using Table 4.11-2.

Material of construction ____________________

4.11.4 Sizing of Venturi Scrubber

Some performance curves and cost curves are based on the saturated gas flow rate ($Q_{e,s}$). If $Q_{e,s}$ is needed, it can be calculated as follows:

$$Q_{e,s} = Q_{e,a} \times (T_{e,s} + 460)/(T_e + 460) + Q_W \qquad 4.11\text{-}1$$

where:

$Q_{e,s}$ = saturated emission stream flow rate, acfm

$T_{e,s}$ = temperature of the saturated emission stream, °F

Q_W = volume of water added, ft^3/min

Use Figure 4.11-2 to determine $T_{e,s}$; the moisture content of the emission stream (M_e) must be in units of lbs H_2O/lbs dry air.

Convert M_e (% vol) to units of lbs H_2O/lbs dry air, decimal fraction:

$(M_e/100) \times (18/29)$ = __________ lb H_2O/lb dry air

From Figure 4.11-2 and Section 4.11.4:

$T_{e,s}$ = __________ °F

$Q_W = (1-L_{w,a})(D_e)(Q_{e,a})(L_{w,s} - L_{w,a})(1/D_w)$

Q_W = __________ ft^3/min

$Q_{e,s}$ = __________ acfm

4.11.5 Evaluation of Permit Application

Using Table 4.11-3, compare the results of this section and the data supplied by the permit applicant. Compare the estimated P_V and the reported pressure drop across the venturi, as supplied by the permit applicant.

If the estimated and reported values differ, the differences may be due to the applicant's use of another performance chart, or a discrepancy between the required and reported collection efficiencies. Discuss the details of the design and operation of the system with the applicant. If there are no differences between the estimated and reported values for P_v, the design and operation of the system can be considered appropriate based on the assumptions employed in this handbook.

Table 4.11-3 Comparison of Calculated Values and Values Supplied by the Permit Applicant for Venturi Scrubbers

	Calculated Value	Reported Value
Particle Mean Diameter, D_p	. . .	. . .
Collection efficiency, CE	. . .	. . .
Pressure drop across venturi, P_v	. . .	. . .

4.11.6 Capital and Annual Costs of Venturi Scrubbers

4.11.6.1 Capital Costs of Venturi Scrubbers

The capital cost of a venturi scrubber system consists of the purchased equipment costs and the direct and indirect installation costs.

The purchased equipment cost (PEC) is composed of equipment costs and the cost of sales tax and freight. The equipment cost (EC) is the sum of the scrubber cost obtained from Table 4.11-4 and the auxiliary equipment cost (Aex), obtained from Section 4.12. Table 4.11-5 provides the factors necessary to estimate the PEC

1. Venturi scrubber cost, VSC (Table 4.11-4)

   VSC = $ __________ × 2.3 or 3.2 (if applicable)

   Note: If 304L stainless steel is used, multiple VSC by 2.3, or if 316L stainless steel is used, multiple VSC by 3.2, to obtain the corrected VSC.

2. Equipment cost, EC = VSC + Aex

   EC = $ __________

3. Purchased equipment cost, PEC = 1.08 EC

   PEC = $ __________

The factors given in Table 4.11-5 are used to estimate the total capital cost, TCC.

TCC = 1.91 PEC + SP + Bldg.

TCC = $ __________

4.11.6.2 Annual Costs for Venturi Scrubbers

The annual cost of a venturi scrubber system consists of direct and indirect annual costs.

Direct Costs

The direct costs include electricity, water, operating labor and maintenance costs.

The annual electricity consumption is estimated using Equation 4.11-2.

$$F_P = 1.81 \times 10^{-4} (Q_{e,a})(P)(HRS) \qquad 4.11\text{-}2$$

F_p = __________ kWh/yr

This value is multiplied by the cost of electricity to obtain annual electricity costs, AEC.

$AEC = 0.059 (F_p)$

AEC = $ __________

The water consumption for a venturi scrubber is estimated from Equation 4.11-3.

$$WR = 0.60 (Q_{e,a})(HRS) \qquad 4.11\text{-}3$$

WR = __________ gal/yr

Operating costs

Operating labor costs = [(2 hr/shift)/(8 hr/shift)](HRS)($12.96/hr)

Operating labor costs = $ __________

Supervisory costs = 0.15 (Operating labor costs)

Supervisory costs = $ __________

Maintenance costs

Maintenance labor costs = [(1 hr/shift)/(8 hr/shift)](HRS)($14.26/hr)

Maintenance labor costs = $ __________

Maintenance materials = 1.0 (Maintenance labor costs)

Maintenance materials = $ __________

Total Direct Costs = $ __________

Indirect Annual Costs

These costs are obtained from the factors provided in Table 4.11-7.

Overhead = $ __________

Administrative = $ __________

Property tax = $ __________

Insurance = $ __________

Capital recovery = $ __________

Total Indirect Costs = $ __________

Total Annual Costs = Total Direct Costs + Total Indirect Costs

Total Annual Costs = $ __________

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Appendix C.12
Calculation Sheet for Auxiliary Equipment

Auxiliary equipment is defined to include fans, ductwork, stacks, dampers, and cyclones (if necessary).

C.12.1 Fan Purchase Cost

Equation 4.12-1 provides the cost of a fan system including a motor and starter.

$$P_{fan} = 42.3\ d_{fan}^{\ 1.20} \qquad 4.12\text{-}1$$

P_{fan} = \$ __________

Equation 4.12-2 provides the cost of a FRP fan system without motor or starter.

$$P_{fan} = 53.7\ d_{fan}^{\ 1.38} \qquad 4.12\text{-}2$$

P_{fan} = \$ __________

Equation 4.12-3 gives the cost of a carbon steel fan without motor or starter. Consult Table 4.12-2 for values of a and b.

$$P_{fan} = a\ d_{fan}^{\ b_f} \qquad 4.12\text{-}3$$

P_{fan} = \$ __________

Equation 4.12-4 provides the cost of a motor and starter for a required motor horsepower between 1 and 7.5 hp. This cost is added to the cost obtained from Equation 4.12-2 or 4.12-3.

$$P_{motor} = 235\ hp^{0.256} \qquad 4.12\text{-}4$$

P_{motor} = \$ __________

For a horsepower requirement between 7.5 and 150 hp, use Equation 4.12-5. This cost is added to the cost obtained from Equation 4.12-2 or 4.2-3.

$$P_{motor} = 94.7\ hp^{0.821} \qquad 4.12\text{-}5$$

P_{motor} = \$ __________

P_{fan} = \$ __________

C.12.2 Ductwork Purchase Costs

The cost of ductwork is calculated assuming a duct velocity (U_{duct}) of 2000 ft/min. Use Equation 4.12-6 to obtain the duct diameter requirement.

$d_{duct} = 12\ [(4/\pi)(Q_{e,a}\ /U_{duct})]^{0.5} = 0.3028\ (Q_{e,a})^{0.5}$ 4.12-6

d_{duct} = __________ in

Once this value is obtained, use Equation 4.12-7 for PVC ductwork with a diameter between 6 and 24 inches. Consult Section 4.12.2 for values of a_d and b_d or Equation 4.12-8 for the cost of FRP ductwork with a diameter between 2 and 5 feet.

$P_{PVCD} = a_d\ d_{duct}{}^{b_d}$ 4.12-7

P_{PVCD} = __________ \$/ft length

$P_{FRPD} = 24\ D_{duct}$ 4.12-8

P_{FRPD} = __________ \$/ft length

C.12.3 Stack Purchase Cost

For small FRP stacks, estimate the stack cost as 150 percent of the corresponding duct cost obtained in Section 4.12.2

Stack Cost = 1.5 (P_{FRPD})

Stack Cost = __________ \$/ft length

For taller stacks (i.e., between 200 and 600 feet) use Equation 4.12-9 to estimate the stack cost. Obtain parameters a and b from Table 4.12-3.

$P_{stack} = a\ H_{stack}{}^{b}$ 4.12-9

P_{stack} = \$ __________

C.12.4 Damper Purchase Cost

Use Equation 4.12-10 to obtain the cost of backflow dampers or 4.12.-11 to obtain the cost of two-way diverter valves.

$P_{damp} = 7.46\ d_{duct}{}^{0.944}$ 4.12-10

P_{damp} = \$ __________

$P_{divert} = 4.84\ d_{duct}{}^{1.50}$ 4.12-11

P_{divert} = \$ __________

C.12.5 Cyclone Purchase Cost

Cyclones may be necessary for particulate emission streams if the streams contain large particles. Equation 4.12-12 is used to obtain the cyclone cost while Equation 4.12-14 provides the cost of a rotary air lock. The sum of these two costs yields the cyclone purchase cost.

$$P_{cyc} = 6{,}520\ A_{cyc}^{\ 0.9031} \qquad 4.12\text{-}12$$

P_{cyc} = $ __________

$$P_{ral} = 2{,}730\ A_{cyc}^{\ 0.0965} \qquad 4.12\text{-}14$$

P_{ral} = $ __________

$P_{cyc} + P_{ral}$ = $ __________