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Control of Air Emissions from Superfund Sites

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Handbook

Control of Air Emissions from Superfund Sites

Center for Environmental Research Information
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Notice

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Cost Information

Except where noted, all costs quoted in the manual are in 1992 U.S. dollars. Cost values from prior years have been adjusted to 1992 U.S. dollars by assuming five percent per year compounded inflation.

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Acronyms and Abbreviations

A/C	Air-to-cloth (ratio)
acfh	Actual cubic feet per hour
acfm	Actual cubic feet per minute
acmh	Actual cubic meters per hour
APA	Air Pathway Analysis (or Assessment)
APC	Air pollution control
APCD	Air pollution control device
ARAR	Applicable or Relevant and Appropriate Requirements
BTEX	Benzene, toluene, ethylbenzene, and xylenes
Btu	British thermal units
BP	Boiling point
CAAA	Clean Air Act Amendments
CAS	Carbon adsorption system
CE	Control efficiency
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CERI	Center for Environmental Research Information
CFC	Chlorofluorocarbons
cfm	Cubic feet per minute
CHEMDAT	Emission model
CO	Carbon monoxide
CO_2	Carbon dioxide
CPE	Chlorinated polyethylene
CSPE	Chlorosulfonated polyethylene
CSTR	Continuously stirred tank reactor
DC	Direct cost
DE	Destruction efficiency
DRE	Destruction and removal efficiency
dscf	Dry standard cubic feet
DSI	Dry sorbent injection
EC	Equipment cost
ECO	Epichlorohydrin rubber
EPA	Environmental Protection Agency
EPDM	Ethylene propylene rubber
ESP	Electrostatic precipitator
FGD	Flue gas desulfurization
GAC	Granular activated carbon
G/L	Gas-to-liquid ratio
HAP	Hazardous air pollutant
HCl	Hydrochloric acid
HCN	Hydrogen cyanide
HDP	High-density polyethylene
HEPA	High efficiency particulate air
HF	Hydrogen fluoride
IC	Indirect cost
ICE	Internal combustion engine
IDLH	Immediately dangerous to life/health
IWS	Ionizing wet scrubber
LAND7	Emission model
LEL	Lower explosive limit
L/min	Liters per minute
LUST	Leaking underground storage tank
m	Meter
MACT	Maximum achievable control technology
MEI	Maximum exposed individual
mil	Millimeter
MMBtu	Millions of Btu's
MSW	Municipal solid waste (incinerator)
MWI	Municipal waste incinerator
NOx	Oxides of nitrogen
NPL	National Priority List (Superfund)
NTGS	National technical guidance series
OSC	On-scene coordinators
OSHA	Occupational Safety and Health Administration
PCB	Polychlorinated biphenyl
PCDD	Polychlorinated dibenzo dioxin
PCDF	Polychlorinated dibenzo difuran
PEL	Permissible exposure limit
PIC	Product of incomplete combustion
PM	Particulate matter
PM_{10}	Particulate matter under 10 microns in diameter
ppb	Parts per billion
ppbv	Parts per billion on a volume basis
ppm	Parts per million
ppmv	Parts per million volume
PVC	Polyvinyl chloride
RA	Remedial action
RC	Recovery credit
RCRA	Resource Conservation and Recovery Act
RD	Remedial design
RE	Removal efficiency
RI/FS	Remedial investigation/feasibility study
ROD	Record of decision

Acronyms and Abbreviations (continued)

RPM	Remedial project managers
SARA	Superfund Amendments and Reauthorization Act
SCA	Specific collection area (of an electrostatic precipitator)
scfm	Standard cubic feet per minute (25°C, 1 atm)
SD	Spray dryer
SDA	Spray dryer absorber
SIMS	Surface impoundment modeling system
SITE	Superfund innovative technology evaluation
SO_2	Sulfur dioxide
SOP	Standard operating procedure
SVE	Soil vapor extraction
SVOC	Semi-volatile organic compound
TCE	Trichloroethylene
TCI	Total capital investment
TEC	Total equipment cost
THC	Total hydrocarbons
TIC	Total installation cost
TSDF	Treatment storage and disposal facility
TSP	Total suspended particulate
UEL	Upper explosive limit
UV	Ultra-violet
VOC	Volatile organic compound

Metric Conversions

Non-metric	Multiplied by	Yields metric
MMBtu/hr	1054.35	MM J/hr
°F	0.555556 (°F-32)	°C
ft	0.3048	m
acfm	0.028317	acmm
dscfm	0.028317	dscmm
gal	3.78541	L
hp	746	J/sec
in	2.54	cm
lb	0.453592	kg
mil	0.0254	mm
mile	1609.344	m
ton	0.907185	metric ton (1,000 kg)
cu yd	0.76455	m^3

Chapter 1
Introduction

1.1 Background

The Superfund Amendments and Reauthorization Act (SARA) of 1986 mandates that all exposure pathways, including the air pathway, be considered for sites on the National Priority List (NPL). Therefore, the remedial project managers (RPMs) and on-scene coordinators (OSCs) have had to consider actual and potential air emissions from Superfund, i.e. NPL, sites and perform some level of air pathway assessments for their sites. To assist the RPMs and OSCs, Air/Superfund coordinators have been appointed in each EPA region to act as the liaison between the Air and Superfund offices. These Air/Superfund coordinators have a need for more explicit guidance for determining actual and potential air emissions. Superfund sites generally must meet applicable or relevant and appropriate requirements (ARARs) such as Section 112 of the Clean Air Act Amendments (CAAA) of 1990 that designates 189 toxic chemicals that must be controlled from any source that meets certain minimum, designated emission limits.

A major emphasis of the Air/Superfund coordination program has been to provide technical assistance to Superfund staff concerning air emissions problems at NPL sites. As more NPL sites move from the remedial investigation/feasibility (RI/FS) phase to the remedial design (RD) and remedial action (RA) phases, formal guidance is needed by RPMs and OSCs on air issues related to remediation. This need is exacerbated by new control requirements demanded by the CAAA, as well as the SARA requirements.

1.2 Technical Objectives

The overall objective of this program was to develop an easy-to-use tool for decision makers to evaluate air emission control devices for use with Superfund remediation actions and assist in the selection of cost-effective control options. The specific objectives of this project are to develop:

1) Concise descriptions of available control techniques, factors that affect their performance, the relative advantages and disadvantages of each technique, and interactive effects of control techniques when used in combination;

2) Information on the expected emission reduction (i.e. efficiency) for each control technique when used alone or in combination with another technique for both individual contaminants and mixtures of contaminants;

3) Information pertinent to the selection of optimum control techniques and strategies, including possible alterations to the remediation approach; and

4) Cost information, or estimated total costs, for applying a given control technique (or combination of techniques).

1.3 Approach

Information for this handbook was obtained via a literature search and a survey of vendors of control devices. No field or laboratory testing of control devices was performed.

1.4 Uses and Limitations of the Document

The intended audience for this handbook are engineers and scientists involved in preparing Remedial Design (RD) plans for Superfund sites. The handbook contains a summary of existing information and an overview of the topic of air emission controls is presented. The handbook contains background information to familiarize the user with the technical basis for each control technology. Specific guidance is provided to assist the user in limiting the choices of potential control technologies and in selecting a specific set of control technologies for a given application. References are included for users seeking more detailed guidance. The user must perform a detailed engineering evaluation of the control options, gather vendor information, and perform feasibility studies. The handbook is a screening tool and is not intended to provide detailed technical specifications for preparing bid packages.

Developing guidance for the processes used to remediate Superfund sites is a challenge, since many of the cleanup processes used at Superfund sites are emerging technologies and have short operating histories. For these technologies, data on which to base emission estimates and control needs are very limited. Furthermore, each Superfund site has a unique set of contaminants and site conditions. These site-specific factors may force modifications of the cleanup hardware or operating conditions which could affect air emissions. Obviously, the diverse nature of sites on the National Priorities List (i.e. Superfund) results in the guidance being more relevant to some sites than others. Site-specific factors must be taken into account when selecting emission control approaches, rather than relying solely on the generalized guidance contained in this document.

Chapter 2
Development of a Control Strategy

2.1 Introduction

Development of an air emissions control strategy and selection of specific control devices must be an integral part of the overall remediation process. Control options should be considered in tandem with remediation options and not considered independently after the final remediation approach has already been selected. The type of air emission controls used may affect the cost-effectiveness of a given remediation approach and vice versa. The ideal time to begin to consider control options (and remediation options) is when planning the Remedial Investigation/Feasibility Study (RI/FS).

A generic control strategy is given in Figure 2-1 that is applicable to most Superfund sites. The individual steps in the figure are discussed below. Additional guidance on these topics may be found in the National Technical Guidance Study (NTGS) manuals (see Appendix B) or by contacting the Air-Superfund Coordinator in the appropriate EPA Regional Office (see Appendix B).

2.2 Generic Strategy for Selecting an Air Emissions Control Approach

2.2.1 Select Most Promising Remediation Technologies

The two or three most promising remediation scenarios for the given site should be identified as early as possible in the RI/FS phase. An initial consideration of applicable air emission control approaches should also take place at the same time. This information can then be used to plan the RI/FS activities so that field data are collected that can be used to assess the need for air emission controls and the probable effectiveness of various control options for the specific site conditions. All types of potential air emissions should be considered: volatile organic compounds (VOCs), semi-volatile organic compounds (SVOCs), particulate matter (PM), and metals. All potential emission sources also should be considered; for example, any ex-situ treatment process likely will result in VOC (if present in the waste/soil) and PM emissions from materials handling activities (e.g., excavation, transport, waste feeding) and soil/waste storage, as well as emissions from the treatment process itself.

2.2.2 Estimate Uncontrolled Emissions From Remediation

The overall list of contaminants present at the site should be examined and target analytes selected based on their frequency of occurrence at the site, concentration levels in the waste/soil, representativeness of the overall contamination, and their associated risk. Worst-case and average emission rates should be estimated for each remediation scenario under consideration. The preferred estimation approach is pilot-scale FS data from the site, while modeling using site-specific inputs is also usually acceptable.

2.2.3 Estimate Downwind Ambient Air Concentrations

The maximum exposed individual (MEI) should be identified based on historical site meteorological data. Air dispersion modeling should be performed using an EPA-approved model and using the estimates of uncontrolled emissions as source terms to estimate maximum short-term and annual average concentrations at the MEI location.

2.2.4 Select Action Levels

Three types of action level "triggers" may be important. One, both short-term and long-term acceptable health-based risk levels at the MEI should always be considered. Since no universally accepted risk levels exist for short-term or long-term exposure for either carcinogens or non-carcinogens, the acceptable risk level must be determined on a case-by-case basis and approved by the EPA. Two, applicable or relevant and appropriate requirements (ARARs) (local, state, and Federal) may limit the acceptable emission rates from process stacks, e.g., PM emissions from incinerators. Three, odor thresholds at the MEI may be a consideration for some sites. While odors may not pose a health threat, they can create a sufficient nuisance to the local community that their control may override other considerations.

2.2.5 Compare Emission Rates/Downwind Concentrations to Action Levels

The emission rate estimates from any stacks or vents and the downwind ambient air concentrations at the MEI should be compared to the action levels and any exceedances noted. Exceedances indicate the need for emission controls. If no exceedances are noted, then air emission controls may not be needed. It

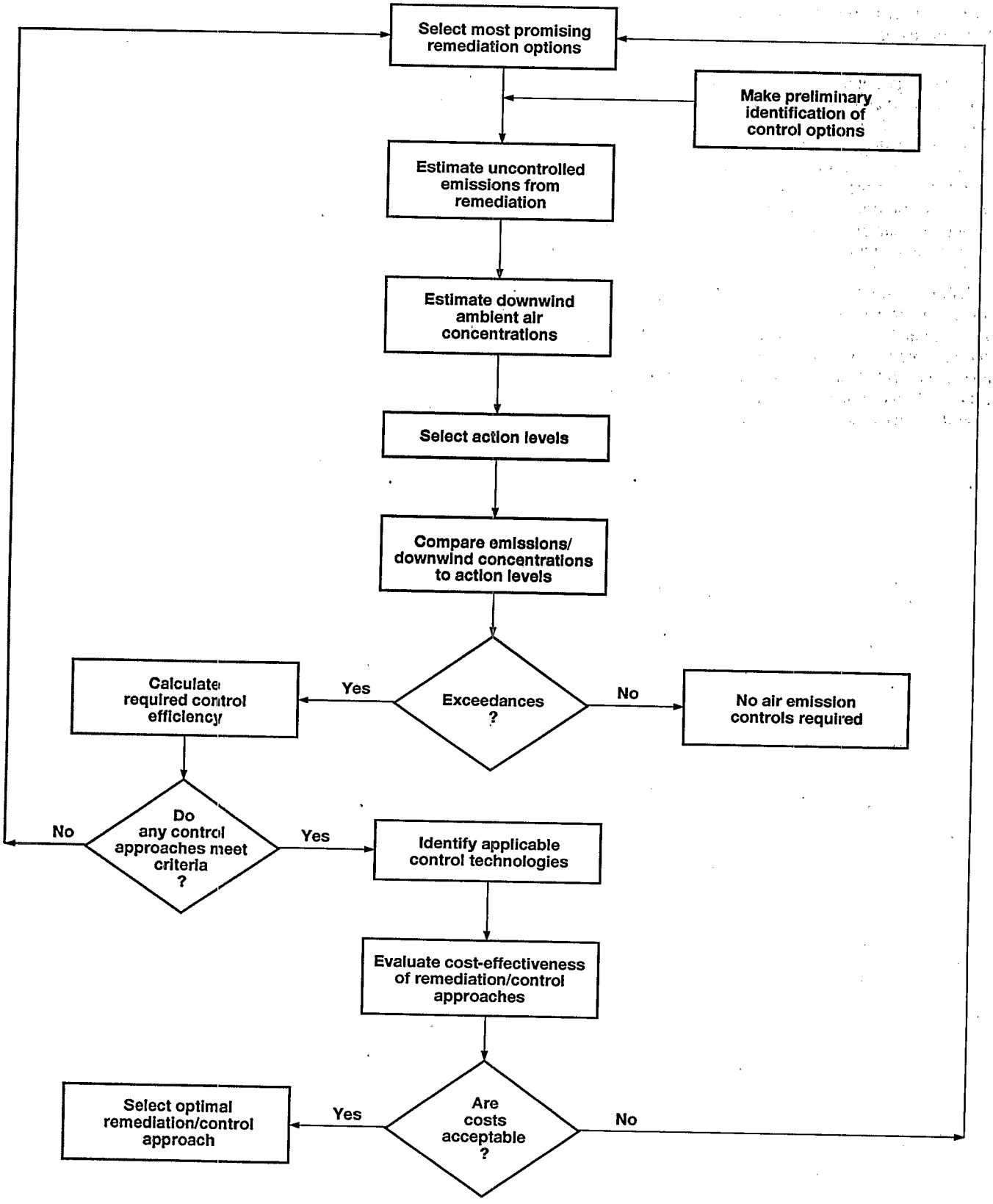


Figure 2-1. Generic strategy for selecting an air emissions control approach.

is recommended, however, that the uncertainties associated with the estimates be taken into account.

The average control efficiencies required to meet the action level should be calculated. The overall control efficiency that is required should be compared to that for the maximum achievable control technology to determine the technical feasibility of meeting the required control efficiency. If no acceptable controls exist, then the remediation scenarios should be reconsidered or some type of pretreatment added. For example, soil vapor extraction could be used as a pretreatment prior to excavation if air emissions of benzene or other VOCs pose a potential problem.

Identify Applicable Control Technologies. The two or three most promising control options for each class of contaminants for each remediation technology should be selected using the information contained in this manual and other references along with input from engineers with remediation design experience and from vendors of remediation and control equipment. Selection criteria are discussed in Section 3.

2.2.6 Evaluate Cost-Effectiveness of Remediation/ Control Approaches

Estimate the size of control system or application rate that is required to meet the control efficiency goal for each remediation/ control approach. Collection of data for full-scale or pilot-scale remediation and control processes using the specific contaminated material of interest should be considered. Estimate the cost of controls and their impact on the overall cost for remediation. Estimate the cost-effectiveness of each control approach. Control options that have unacceptably high costs should be excluded from further consideration. If most or all the control costs are unacceptably high as a percentage of the total remediation cost, then the remediation scenarios should be reconsidered.

2.2.7 Select the Optimal Remediation/Control Approach

The cost-effectiveness of the air emission controls should be used as one input into the overall selection process of a remedial design.

Chapter 3
Overview of Control Device Selection Guidance

A summary of the information contained in this manual is given in this chapter along with tables and figures showing comparisons of the performance and cost of various control options. More detailed information about specific remediation technologies is given in Chapter 4, while detailed information about specific control technologies is given in Chapters 5, 6, and 7. The applicability of control options is discussed below followed by a discussion of the cost-effectiveness of various control options.

3.1 Applicability of Control Options

Each control technology has relative advantages and disadvantages and no single control option will always be the best choice for a given remediation technology. Selection criteria for control technologies include

- Demonstrated past use of the control technology for the specific application of interest;
- Ability to meet or exceed the required average capture and/or control efficiency;
- Compatibility with the physical and chemical properties of the waste gas stream;
- Reliability of control equipment and process;
- Capital cost of control equipment;
- Operating costs of system (including disposal of byproducts or regeneration costs); and
- Permitting requirements.

As previously stated, the information in this manual is intended to be used to screen potential control options and used in conjunction with detailed engineering evaluations, vendor data, and feasibility studies to select control technologies.

A large number of remediation technologies have been used or proposed for cleaning up Superfund and other hazardous waste sites. Table 3-1 is a list of the control technologies typically used at Superfund sites for the most common remediation technologies and other emission sources. Past usage is not an infallible selection guide, but deviations from typical usages generally require some justification. Lists of typical volatile, semi-volatile, and metallic compounds often encountered at Superfund sites are given in Appendix D.

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

The various VOC controls for point sources are listed in Table 3-2 along with the remediation technologies for which the controls are potentially applicable and the relative advantages and disadvantages of each control option. This same type of information is given in Table 3-3 for PM controls for point sources and in Table 3-4 for VOC/PM controls for area sources. Area source controls tend to be effective for both VOC and PM. The control technologies listed in Tables 3-2, 3-3, and 3-4 have all been demonstrated at full-scale (except for those identified as emerging technologies) although not necessarily at Superfund sites.

The applicability and effectiveness of control devices for point sources will depend on the physical and chemical properties of the waste gas stream. The typical required emission stream and contaminant characteristics for point source VOC controls and PM controls are given in Table 3-5 and 3-6, respectively. This same type of information for area source controls is given in Table 3-7.

3.2 Cost-Effectiveness of Control Options

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

Table 3-1. Typical Control Technologies Used for Selected Remediation Technologies and Pollutants

Emission Source[1]	VOCs/SVOCs	Metals and Particulate Matter	Acid Gases
Materials Handling			
Excavation	Operational Controls Foam Operational Controls Enclosure	Water Sprays	NA
Storage Piles			
Enclosure	Polymer Sheeting Enclosure	Cover Wind Screen	NA
Transport Vehicles	Cover Foam	Cover	NA
Roadways	NA	Gravel/Paving Water Sprays Water Sprays with Additives	NA
Thermal Desorption	Condensers Thermal Incineration[2] Carbon Adsorption	Cyclone Venturi Scrubber Fabric Filter HEPA Filter	Wet Scrubber Dry Scrubber
On-Site Incineration	NA	Cyclone Venturi Scrubber Ionizing Wet Scrubber Wet ESP Fabric Filter	Wet Scrubber Dry Scrubber
Soil Vapor Extraction	Carbon Adsorption Catalytic Incineration Thermal Incineration Internal Combustion Engine	NA	NA
Air Stripping of Water	Carbon Adsorption Catalytic Incineration	NA	NA
Solidification/Stabilization[3]	Carbon Adsorption	Venturi Scrubber Filter Water Sprays	Wet Scrubber (if needed)
Bioremediation[3]			
In-situ	Carbon Adsorption	NA	NA
Ex-situ	Carbon Adsorption	NA	NA
Soil Washing[3]	Carbon Adsorption	NA	NA
Soil Flushing[3]	Thermal Incineration	NA	NA
Solvent Extraction[3]			

NA = Not applicable
[1] Reduced operation or activity will also limit emissions in most cases.
[2] Fuel spill/leak sites.
[3] Controls not always used. Control system generally must include collection hood.

A reasonable maximum removal efficiency for various VOC controls for point sources is shown in Figure 3-1 as a function of the VOC content of the inlet gas stream. The typical ranges of cost-effectiveness for these same APCDs are depicted in Figure 3-2.

Less comparative data are available for particulate matter controls. These types of controls are used almost exclusively at Superfund sites with thermal treatment methods such as incineration and thermal desorption.

In general, selection of PM control devices for point sources will not be required since the vendors of thermal treatment equipment will have already selected control devices for use with their remediation equipment. Limited data for removal efficiencies for PM controls for point sources are given in Table 3-8. Comparative costs are shown in Figure 3-3.

The estimated efficiencies for various APCDs and combinations of APCDs for controlling emissions of toxic metals are shown in Table 3-9. Control efficiencies for various dioxins and

Table 3-2. VOC Controls for Point Sources

Control	Applicable Remediation Technologies	Advantages	Disadvantages
Carbon adsorption	SVE, air stripping, thermal destruction, bioremediation, thermal desorption, solidification/stabilization, soil washing, etc.	Effective for gas streams with variable flow rates. Effective for gas streams with variable VOC content. Effective for gas streams with low VOC content.	Bed fires may occur if oxygenated material is present and bed temperature rises due to heat of adsorption. Spent carbon must be either regenerated or discarded. Filters/mist eliminators may be needed for liquids or PM. Not effective for low molecular weight compounds. Less effective for high humidity gas streams.
Thermal oxidation (incineration)	All remediation technologies	Widely demonstrated technology. Effective for a variety of VOCs. No disposal concerns.	Potential generation of PICs, acid gases. Supplemental fuel required. Only effective for combustibles.
Catalytic Oxidation (Incineration)	SVE, air stripping	Requires operating lower temperatures than thermal oxidizers. No disposal concerns.	Catalyst easily fouled or degraded. High temperatures may cause burnout. Low heat content of waste gas steam will require extra fuel. Not effective for many chlorinated solvents.
Condensers	SVE, air stripping, biotreatment	Effective for very high VOC concentrations. Good for pretreatment of dilute streams prior to other controls.	Performance somewhat sensitive to process conditions (flow rate, temperature). High utility costs.
Internal combustion engines	SVE, air stripping.	Compact units can provide usable power. Well-developed technology.	Limited capacity (<1000 scfm). Supplemental fuel may be expensive. Easily fouled or corroded.
Membranes	SVE, air stripping	Reduces waste stream volume. Concentrates VOCs.	Pre-treatment only. Limited data available.
Operational controls	All remediation technologies	Improved removal efficiency for minimal cost.	Requires knowledgeable operator.
Soil filters/biotreatment	SVE, air stripping	Low cost Simplicity May degrade semi- or non-volatile organics. May trap some metals. Not susceptible to variations.	Not effective on all VOCs. May require large surface area, biologically sensitive to temperature and humidity High pressure drop.
Wet absorbers	Incineration, thermal destruction	Good for high temperature gas streams. Simple to operate. Effective for wide variety of VOCs.	Low RE for low VOC concentrations. Effluent may pose disposal problems. Susceptible to concentration, flowrate, and temperature changes, less efficient at low flow rates.
UV	SVE, air stripping	High removal efficiencies. No solvent or wastewater generated.	Complex system. Limited data available.

Table 3-3. Particulate Matter Control Devices for Point Sources

Control	Remediation	Advantages	Disadvantages
Baghouse (fabric filter)	Incineration Thermal desorption Stabilization/solidification Materials handling	Lower pressure drop than venturi for fine PM removal (i.e. 2-6" H_2O compared with > 40" H_2O for venturi). Simple to operate. Can collect electrically-resistive PM.	Cannot control a high temperature (>550° F) stream without a precooler. Cannot control highly humid stream. Special fabric requirements. Mechanical collectors required for large (>20 μm) particles.
ESP	Incineration Thermal desorption	Low operating cost. Low pressure drop (0.5" H_2O). Control very small (<0.1 μm) PM with high RE. Can collect corrosive or sticky mists. Wet ESPs can collect acid gases, PM.	High initial capital investment. Not readily adaptable to changing conditions, particle loading. Space requirements greater than for baghouse or venturi. Conditioning agents may be needed to control resistive particles.
Venturi scrubber	Incineration Thermal desorption Materials handling	Low initial investment. Little space required. Simple to operate, few moving parts. Can control sticky, flammable, or corrosive matter with few problems. Simultaneous collection of PM and gases. RE is independent of resistivity.	High operating cost due to pressure drop (>40" H_2O), especially for smaller PM. Has wastewater and cleaning/disposal costs.
Packed, Spray, or tray tower absorbers	Incineration Thermal desorption Materials handling	Can be very effective, as part of control train. Simple to operate, few moving parts. Can control sticky, flammable, or corrosive matter with few problems. Simultaneous collection of VOCs, larger PM, metals and gases. RE is independent of resistivity for Venturis, tower absorbers (wet ionizing).	Has wastewater and cleaning/disposal costs. Not effective for streams <1000 scfm.
Dry scrubber: DSI, SDA	Incineration Thermal desorption Materials handling	Not wet slurry. Effective for removal of PM, metals, and dioxins.	Contaminated lime must be disposed.
HEPA filter	Incineration Thermal desorption Materials handling	Extremely high PM removal rate. Simple to operate, few moving parts. Can control asbestos to very low levels.	High pressure drop. Subject to fouling corrosion. Used filters require proper disposal. Requires prefilter for heavily loaded streams.
Operational controls	All remediation technologies	Improved removal efficiency for minimal cost.	Requires knowledgeable operator.

Table 3-4. Applicable Controls for Area Sources

Control	Remediation	Advantages	Disadvantages
Covers (soil, organic solids, synthetic liners, paving, road carpet/gravel)	Materials handling Unpaved roads Inactive sites	Availability of equipment Simplicity Effectiveness Cost	Grader, other heavy equipment may be required Paving is expensive Soil covers increase volume of contaminated material
Foams	Inactive sites Storage piles Excavation	Effectiveness for both PM and VOC control Applicability to all media Ease of application	Relatively expensive May be ineffective on steep slopes Inapplicability in winds > 10 mph
Wind screens	Storage piles Inactive sites Excavation areas	Inexpensive Ease of installation Limitation of site access/view	Limited control area Fragility Limited height
Water sprays	Unpaved roads Storage piles Loading/dumping operations Excavation	Inexpensive Ease of application Availability of equipment	Frequent application required May create contaminated water Material handling problems Inappropriate at sites with no water access Not designed for VOC control
Water spray with additives	Materials handling Storage piles Inactive sites Unpaved roads	Less water required than for water sprays Ease of application Availability of equipment Less frequent application required than for water sprays	May create contaminated water, or be washed away by rain Creates material handling problems Inappropriate at sites with no water access May react with soil contaminants Relatively expensive May cause traffic problems in cool weather Some additives are corrosive to machinery/vehicles Not designed for VOC control
Operational controls Enclosures	All remediation technologies Materials handling Storage piles	Improved control efficiency for minimal cost Near 100% control of VOC/PM emissions	Requires knowledgeable operator High cost Difficult access Potentially hazardous working conditions
Collection hoods	Most remediation technologies	Converts area source to point source	Collects rather than controls emissions

Table 3-5. Typical Required Emission Stream and Contaminant Characteristics for Point Source VOC Controls

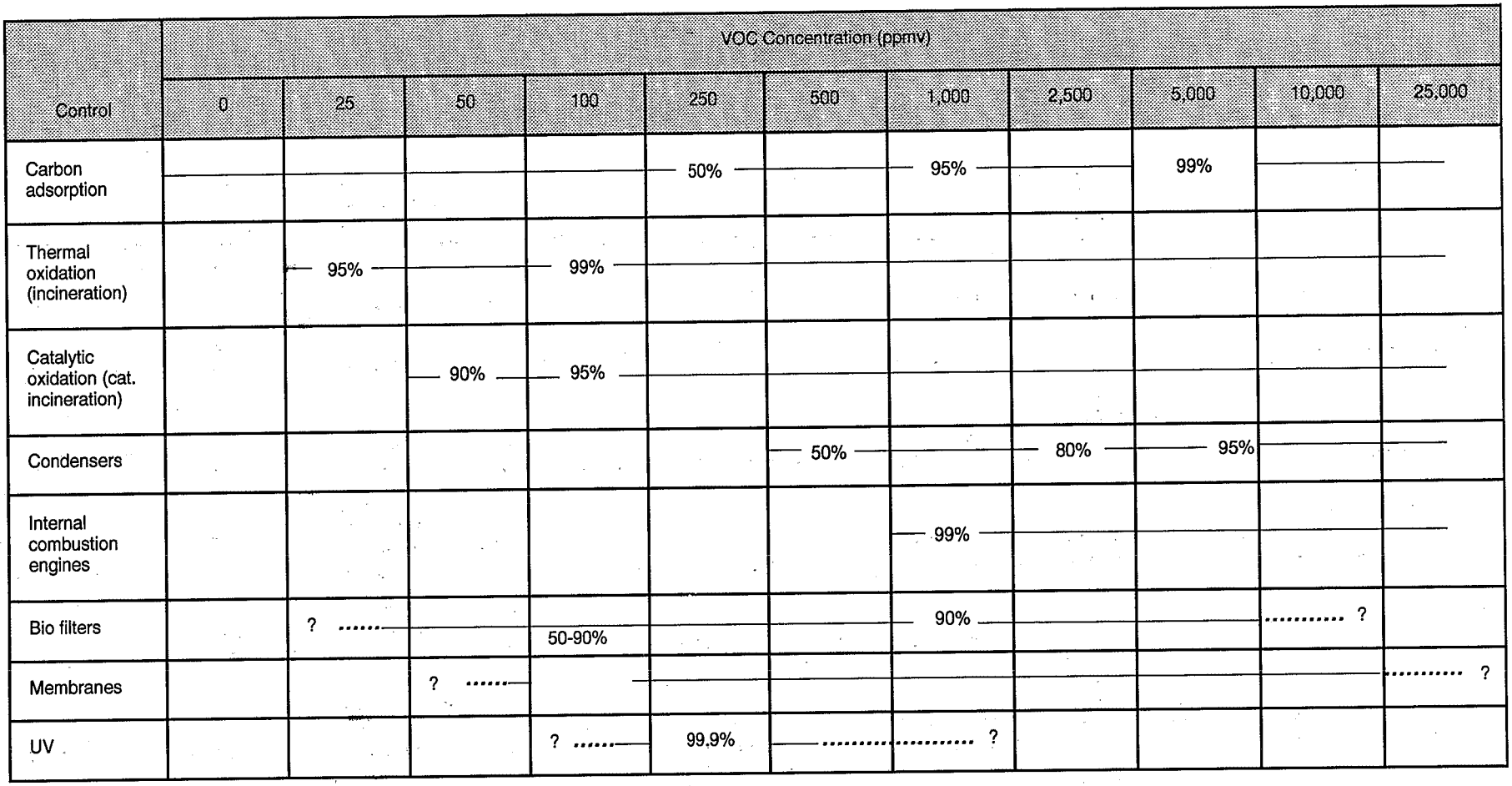
Control	Concentration (ppmv)	Flow rate (scfm)	Applicable organics	Inorganic/Corrosive contaminants	PM damage	Temperature (°C)	Humidity	Variable stream	Pressure drop (in. H_2O)
Carbon adsorption	<10,000	Regenerable: <500,000 Disposable: <1500	Most compounds with 50 < MW <200	Some inorganics and metals can be controlled	PM must be removed	<120 (most effective around 38)	<50%	Variable flow or conc. present no problem	25-125
Thermal Oxidation (Incineration)	< 25% LEL	Packaged: <50,000 Custom to 100,000 and above	Most organics acceptable. Formation of acid gases or PICs possible	Extra controls may be required for halogenated organics and sulfur	PM not a problem	Combustion at 760-870	High humidity streams may reduce Btu content	Small flowrates require supplementary fuel	4 (a 70% efficient heat exchanger may have a drop of 15")
Catalytic Oxidation (incineration)	<25% LEL >10 Btu/scf may overheat catalyst	Packaged: <50,000	Halogenated organics usually a problem	Corrosives, metals can degrade catalyst	PM can clog catalyst	260-593	Increasing humidity increases required supplementary heat	Variable flow requires dilution/ supplemental fuel. Might overheat catalyst	6 (a 70% efficient heat exchanger may have a drop of 15")
Condensers	>5,000	<2,000	BP > 38° C preferred	Corrosive gases a problem	PM not a problem	As close to dew point of HAPs as possible	Humid streams can ice over refrigeration unit	Changes in VOC content, conc., or temp. can reduce condensation	Minimal
Internal Combustion Engines	<25% LEL	< 1,000/unit (200 typical)	All combustible organics	Corrosive gases unacceptable; will not treat metals or other combustibles	PM may cause fouling	Must be less than combustion temp.	High humidity stream may reduce Btu content	Variable flowrate requires supplementary fuel; excessive loading dumps untreated hydrocarbons	Pressure increases across device (power is generated)
Soil Beds/ Biofilters	1,000 (pilot system)	600-90,000	Most organics acceptable	SO_2, NO_x, H_2S can be controlled	PM can plug soil pores	38: optimal (highly sensitive)	90% RH required to prevent drying out bed	Variable flow or conc. may impact microbe culture	2-3 (pilot system)
Emerging/ Misc.Controls (Membrane, UV)	Membrane: >300, UV: 100 in pilot studies)	Low	Some organics acceptable	Corrosive gases may degrade membrane	PM may be problem for membrane	Unknown effects	Unknown	Unknown	Varies

Table 3-6. Typical Required Emission Stream and Contaminant Characteristics for Point Source PM Controls

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

Table 3-7. Typical Required Emission Source and Contaminant Characteristics for Area Source VOC and PM Controls

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



Note: All values assume a well-designed, well-run system.

Figure 3-1. Removal efficiency vs. VOC loading for point source VOC controls.

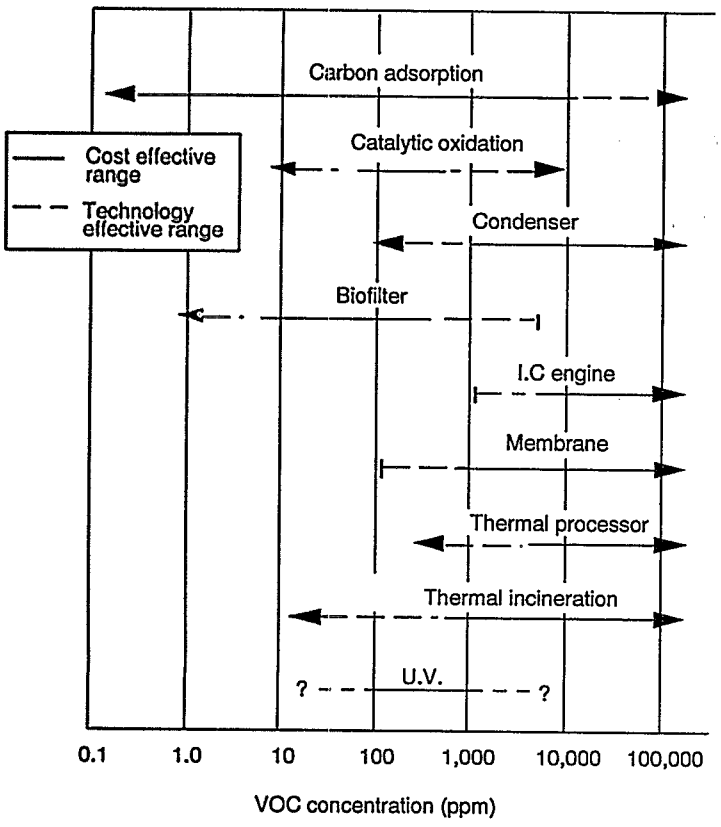
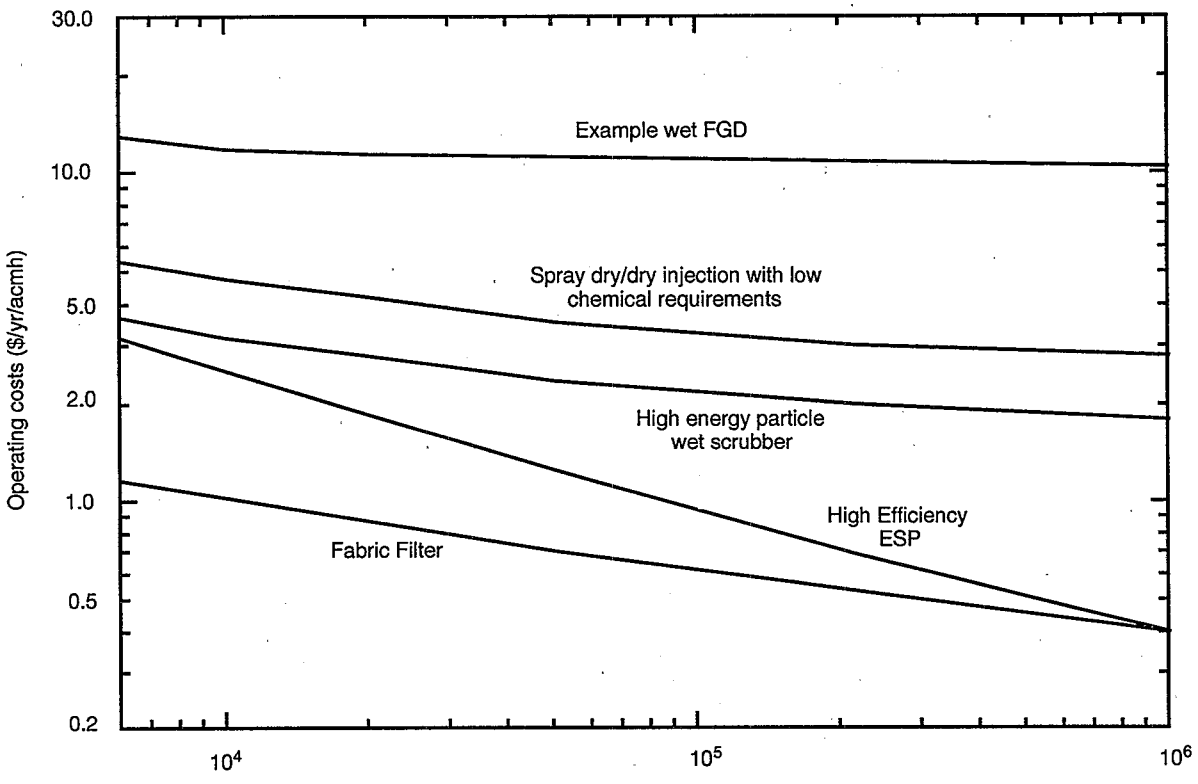


Figure 3-2. Relative cost-effectiveness for point source VOC controls.

Table 3-8. Ranges of % RE for Point Source PM Controls

	Fly Ash	PCDD/PCDF	Acid Gases	<10 µm	>10 µm	Metals
Baghouses	—	Entrained fraction removed	—	99+[1]	99+[1]	90-95[2]
Wet Scrubbers	—	—	95-99+	Low	—	40-50[2]
Venturi Scrubbers	—	—	99	80-95	80-95	Variable
Dry Scrubbers	—	90-99+	95-99+	99+	99+	95-99[2]
ESP	99+	98% with SDA	—	99[3]	99[3]	85-99[2]
Quench Chambers	—	—	50%	—	—	—
HEPA Filters	—	Entrained fraction removed	—	99.9+[4]	99.9+[4]	—

[1] Except for "sticky" particles.
[2] Lower removal efficiency for mercury.
[3] For resistive particles.
[4] With high pressure drop.



Source: Hesketh, 1991.

Figure 3-3. Typical APCD operating costs in 1988 dollars.

Table 3-9. Estimated APCD Efficiencies for Controlling Toxic Metals

Air pollution control device	Pollutant				
	Ba, Be	Ag	Cr	As,Sb,Cd,Pb,Tl	Hg[a]
WS[a]	50	50	50	40	30
VS-20[a]	90	90	90	20	20
VS-60[a]	98	98	98	40	40
ESP-1	95	95	95	80	0
ESP-2	97	97	97	85	0
ESP-4	99	99	99	90	0
WESP[a]	97	97	96	95	60
FF[a]: FF/WS[a]	95	95	95	90	50
PS[a]	95	95	95	95	80
SD/FF; SD/C/FF	99	99	99	95	90
DS/FF	98	98	98	98	50
ESP-1/WS; ESP-1/PS	96	96	96	90	80
ESP-4/WS; ESP-4/PS	99	99	99	95	85
VS-20/WS[a]	97	97	97	96	80
WS/IWS[a]	95	95	95	95	85
WESP/VS-20/IWSa	99	99	98	97	90
C/DS/ESP/FF; C/DS/C/ESP/FF	99	99	99	99	98
SD/C/ESP-1	99	99	98	95	85

[a] Flue gases are assumed to have been precooled (usually in a quench). If gases are not cooled adequately, mercury recoveries will diminish, as will cadmium and arsenic recoveries to a lesser extent.

APCD codes

C	=	Cyclone
WS	=	Wet scrubber including: sieve tray tower, packed tower, bubble cap tower
PS	=	Proprietary wet scrubber design (high efficiency PM and gas collection)
VS-20	=	Venturi scrubber, ca. 2-30in W.G. p
VS-60	=	Venturi scrubber, ca. > 60 in W.G. p
ESP-1	=	Electrostatic precipitator; 1 stage
ESP-2	=	Electrostatic precipitator; 2 stages
ESP-4	=	Electrostatic precipitator; 4 stages
WESP	=	Wet electrostatic precipitator
IWS	=	Ionizing wet scrubber
DS	=	Dry scrubber
FF	=	Fabric filter (baghouse)
SD	=	Spray dryer (wet/dry scrubber)

Source: Carroll, 1992.

furans are shown in Table 3-10. The effectiveness of various APCDs for acid gas control is shown in Table 3-11.

Area source controls also can be applied in theory to achieve any desired removal or control efficiency. Once again, a practical trade-off exists between removal or control efficiency and cost. The control efficiencies of area source controls will vary more widely than those for point source controls. This variability is true both from site to site and over time at a given site. Control efficiencies often may be as low as 50%. Comparative costs per given area for various area source controls as typically applied are shown in Table 3-12.

Table 3-10. Spray Dryer Control of Selected Organic Pollutants for Hazardous Waste Incinerators

	Control system (% removal)		
Compound	SD + ESP	SD + FF @ high temperature	SD + FF @ low temperature
Dioxins			
tetra CDD	48	<52	>97
penta CDD	51	75	>99.6
hexa CDD	73	93	>99.5
hepta CDD	83	82	>99.6
octa CDD	89	NA	>99.8
Furans			
tetra CDF	65	98	>99.4
penta CDF	64	88	>99.6
hexa CDF	82	86	>99.7
hepta CDF	83	92	>99.8
octa CDF	85	NA	>99.8

Source: U.S. EPA, 1987.

Table 3-11. Effectiveness of Acid Gas Controls (% Removal) for Hazardous Waste Incinerators

		Pollutant		
Control system	Temperature[1] °C	HCl	HF	SO_2
Dry injection + fabric filter (FF)	160-180	80	98	50
Dry injection + fluid-bed reactor + ESP	230	90	99	60
Spray dryer + ESP	—	95+	99	50-70
(recycle)	140-160	(95+)	(99)	(70-90)
Spray dryer + fabric filter	—	95+	99	70-90
(recycle)	140-160	(95+)	(99)	(80-95)
Spray dryer + dry injection + ESP of FF	200	95+	99	90+
Wet scrubber	40-50	95+	99	90+
Spray dryer + wet scrubber(s) + ESP or FF	40-50	95+	99	90+

[1] The temperature at the exit of the control device.

Source: U.S. EPA, 1987.

Table 3-12. Costs of Area Source Controls

Control		Material cost ($/m²) except as noted)	Comments
Clay		$4.15	Covers, mat, and membrane
Soil		1.33	Assume 6" deep; does not include soil transport
Wood chips, plastic net		0.50	Chip cost vary with site
Synthetic cover		4.40	Assume 45 ml thickness
Short-term foam		0.04	Assume 2.5" thick, $0.7/m³ foam
Long-term foam		0.13	Assume 1.5" thick, $3.3/m³ foam
Wind screen		40./m	Per linear meter
Water spray		$0.001 (varies)	Assuming municipal water cost of $1/1,000L. Water requires constant re-application. Water truck rental: $500/wk.
Additives	Surfactant	0.65	Costs vary with chemical used
	Hygroscopic salt	2.58	
	Bitu./Adhes.	0.02	

Source: Adapted from information in Chapter 7.

3.3 References

Carroll, J.P. Screening Procedures for Estimating the Air Impacts of Incineration at Superfund Sites. EPA-450/1-92-003. Research Triangle Park, NC. February 1992.

Hesketh, H.E. Air Pollution Control - Traditional and Hazardous Pollutants. Technomic Publishing Co., Lancaster, PA. 1991.

U.S. EPA. Waste Incineration and Emission Control Technologies. EPA/600/D-87/147-5 (NTIS PB87-208336). July 1987.

Chapter 4
Air Emissions-Related Information for Various Remediation Technologies

This chapter contains background information pertaining to air emissions and their control for various remediation technologies. References to general sources of information on process design, emissions estimation, and costs are provided at the end of the chapter. The majority of the text is taken directly from a recent EPA publication on air emissions from the treatment of contaminated soil that summarizes existing information on air emissions, controls, and cost for various remediation technologies (Eklund, et al., 1992c). A second source of information is a recent EPA publication giving emission factors for remediation technologies (Thompson, et al., 1991).

For each remediation technology, a typical remediation scenario for Superfund sites is given followed by a discussion of potential air emissions. References are given for emission estimation procedures, and applicable control technologies are identified.

4.1 Materials Handling

Materials handling covers such activities as excavation, dumping, grading, short-term storage, and sizing and feeding soil or waste into treatment processes. Information on equipment and operating practices is available in Church, 1981 and U.S. EPA, 1991a. The discussion below primarily addresses excavation.

4.1.1 Typical Remediation Scenario for Superfund Sites

Excavation and removal of soils contaminated with fuels is a common practice at Superfund sites. Excavation and removal may be the selected remediation approach or it may be a necessary step in a remediation approach involving treatment. If removal is the preferred approach, the excavated soil typically is transported off-site for subsequent disposal at a landfill. If the soil contains large amounts of fuel or highly toxic contaminants, the soil may need to be treated off-site prior to final disposal. Excavation activities are also typically part of on-site treatment processes such as incineration, thermal desorption, batch biotreatment, land treatment, and certain chemical and physical treatment methods. The soil is excavated and transported to the process unit and the treated soil typically is put back into place on the site.

The rate of materials handling operations at Superfund sites tend to be controlled by factors such as safety concerns, storage capacity or treatment capacity, rather than being limited by the operational capacities of the equipment that is used. For these reasons, actual materials handling rates tend to be far below typical handling rates at construction sites (Church, 1981). Typical scenarios for excavation at Superfund sites are given in Table 4-1.

Table 4-1. Example Scenarios for Excavation of Contaminated Soil

		Scenario		
Parameter	Units	Small	Medium	Large
Soil moved per scoop	m^3	1	2	4
No. scoops per hour	#/hr	50	75	60
Total volume of soil moved	m^3/hr	50	150	240
Excavation pit:				
dimensions:	m	10x5x1	10x15x1	10x12x2
area	m^2	50	150	120
Storage pile:				
dimensions:	m	5x5x2	5x10x3	8x10x3
area	m^2	65	140	188

Source: Eklund, et al., 1991a.

Since digging soil and immediately transferring it directly to transport vehicles or treatment systems is rarely feasible or efficient, soil will be handled several times. In most cases, soil will be excavated and placed into a temporary holding area and then handled one to two more times on-site. Elevated levels of VOC and PM emissions are possible each time the soil is handled.

4.1.2 Potential Air Emissions

The exchange of contaminant-laden soil-pore gas with the atmosphere when soil is disturbed and diffusion of contaminants through the soil both contribute to VOC emissions from excavation. Multiple potential emission points exist for each of the various soils handling operations. For excavation, the main emission points of concern are emissions from:

- Exposed waste in the excavation pit;
- Material as it is dumped from the excavation bucket; and
- Waste/soil in short-term storage piles.

In addition, emissions of VOC, particulate matter, nitrogen oxides, etc. will also occur from the engines of the earth-moving equipment. While these emissions will not require any additional control devices (beyond those provided by the manufacturer), the

equipment emissions should be considered when evaluating any air monitoring data.

The magnitude of VOC emissions depends on a number of factors, including the type of compounds present in the waste, the concentration and distribution of the compounds, and the porosity and moisture content of the soil. The key operational parameters are the duration and vigorousness of the handling, and the size of equipment used. The longer or more energetic the moving and handling, the greater likelihood that organic compounds will be volatilized. The equipment size influences volatilization by affecting the mean distance a volatilized molecule has to travel to reach the air/solid interface at the surface of the soil. In general, the larger the volumes of material being handled per unit operation, the lower the percentage of VOCs that are stripped from the soil. Control technologies for large area sources such as excavation are relatively difficult to apply and are often much less effective than controls for point sources.

Particulate matter (PM) emissions will depend primarily on the particle size distribution of the soil, its moisture content, the wind speed, and the operating practices that are followed. The longer or more energetic the moving and handling, the greater likelihood that PM emissions will occur.

The success of excavation and removal for a given application depends on numerous factors with the three key criteria being: 1) the nature of the contamination; 2) the operating practices followed; and 3) the proximity of sensitive receptors. Each of these criteria is described below.

The magnitude of emissions from soils handling operations will vary with the operating conditions. Add-on control technologies are available for minimizing VOC and PM emissions, but they are relatively ineffective and costly to implement. Control of emissions can also be achieved by controlling the operating conditions within preset parameters. The rate of excavation and dumping, the drop height, the amount of exposed surface area, the length of time that the soil is exposed, the shape of the storage piles, and the dryness of the surface soil layers will all influence the levels of VOC and PM emissions. Large reductions in emissions can be achieved by identifying and operating within acceptable ranges of operating conditions.

Since some release of volatile contaminants is inevitable during excavation and removal unless extreme measures are taken (e.g., enclose the remediation within a dome), the proximity of downwind receptors (i.e., people) will influence whether excavation is an acceptable option. Excavation of contaminated areas that abut residential areas, schoolyards, etc. may require more extensive controls, relocation of the affected population, or remediation only during certain periods (e.g., summertime for school sites).

4.1.3 Emission Estimation Procedures

Relatively limited VOC emissions or emission rate data for excavation are available. The process of measuring emission rates from dynamic processes, such as excavation, is difficult and costly, and has rarely been attempted. The factors that govern emissions from materials handling are very complex. During excavation, for example, the physical properties of the soil that control the vapor transport rate (e.g., air-filled porosity) are changing with time and the concentration of contaminants may be rapidly decreasing.

Predictive equations for estimating emissions from excavation and dumping are under development (Eklund, et al., 1992a). These models are based on estimating emissions from diffusion through the soil and from the loss of saturated pore-space gas to the atmosphere. The predictive equations require assumptions about the size of each scoop of soil, the dimensions of the soil scoops and the excavation pit, and the shape of the soil after it is dumped. Further assumptions are required about the air and soil temperatures and the length of time that dumped soil is exposed before it is covered with more soil or with an emissions barrier. The equations generally predict high levels of emissions. For dry, porous soils containing low ppb levels of contaminants, most or all of the more volatile VOCs are assumed to be lost to the atmosphere during soils handling. For sites with moist soils and ppm levels of contaminants, however, only 5 to 10% of the VOCs are assumed to be emitted to the atmosphere during each handling step. More field measurement data are needed to validate these assumptions.

Soils handling operations such as excavation substantially increase VOC emission rates from contaminated soil over baseline rates (Eklund, et al., 1989). The increase in emissions is typically a factor of ten or more, and the increased emission rate decays exponentially back to near the baseline rate over short time periods (e.g., 4 days). A database of baseline emission rate measurement data (Eklund, et al., 1991a) is available. Other estimation procedures and field data are summarized in Eklund et al., 1992c.

Particulate matter emissions can be estimated using the empirical equations in Cowherd, et al., 1988. Emissions for topsoil removal, earth moving, and truck haulage are reported to range from about 1 to 6 kilograms of particulate matter per vehicle per kilometer traveled.

4.1.4 Identification of Applicable Control Technologies

A number of methods are available for controlling VOC and particulate matter emissions from soils. In general, any method designed primarily for particulate control will also reduce VOC emissions and vice versa. Compared to point source controls, VOC emission controls for excavation and other area sources are difficult to implement and only moderately effective. Controls such as water sprays or foams will alter the percent moisture, bulk density, and average heating value of the soil and may affect treatment and disposal options.

VOC emission controls for soil area sources are discussed in Section 7 and include:

- Covers and physical barriers;
- Temporary and long-term foam covers;
- Water sprays;
- Water sprays with additives;

- Operational controls;
- Complete enclosures;
- Wind screens; and
- Collection hoods.

4.2 Thermal Desorption Treatment

Mobile process units designed for soil remediation and the use of asphalt kilns for soil remediation are discussed in this section. The best currently available source of information is an engineering bulletin prepared by the U.S. EPA (U.S. EPA, 1990a). Design and operating information for thermal desorption systems are given in an EPA Guidance Document being prepared (Troxler, et al., 1992). Air emissions and cost data have been summarized (Eklund, et al., 1992c).

4.2.1 Typical Remediation Scenario for Superfund Sites

In the thermal desorption process, volatile and semi-volatile contaminants are removed from soils, sediments, slurries, and filter cakes. This process typically operates at temperatures of 200°-1000°F but often is referred to as low temperature thermal desorption to differentiate it from incineration. At these lower temperatures, thermal desorption promotes physical separation of the components rather than combustion. Contaminated soil is removed from the ground and transferred to treatment units, making this an *ex situ* process. Direct or indirect heat exchange vaporizes the volatile compounds producing an off-gas that typically is treated before being vented to the atmosphere. After it is excavated, the waste material is screened to remove objects greater than 1.5" in diameter (de Percin, 1991a). In general, three desorber designs are used: an indirectly fired rotary dryer, internally heated screw augers, or a fluidized bed (de Percin, 1991b). The treatment systems include both mobile process units designed specifically for treating soil and asphalt kilns, which can be adapted to treat soils. Typical characteristics of the processes and off-gas streams for mobile units and rotary drum units at asphalt plants are summarized in Table 4-2.

Because thermal desorbers, in some cases, may operate near or above 1000°F, some pyrolysis and oxidation may occur in addition to the vaporization of water and organic compounds. Collection and control equipment such as afterburners, fabric filters, activated carbon, or condensers prevent the release of the contaminants to the atmosphere. Thermal desorbers can create up to seven process residual streams: treated soil, oversized media rejects, condensed contaminants, water, particulate control dust, clean off-gas, and spent carbon (de Percin, 1991b).

4.2.2 Potential Air Emissions

Thermal desorbers effectively treat soils, sludges and filter cakes and remove volatile and semi-volatile organic compounds from the material. Some higher boiling point substances such as polychlorinated biphenyls (PCBs) and dioxins also may be removed and thus be present in the off-gas. Inorganic compounds are not easily removed with this process, although some relatively volatile metals such as mercury may be volatilized. Temperatures reached in thermal desorbers generally do not oxidize metals (de Percin, 1991a). VOC removal is enhanced if the soil contains 10-15 percent moisture prior to treatment since water vapor carries out some VOCs.

Point sources of air emissions from thermal desorption vary widely with each process. The stack of an afterburner vents combustion products, as does a fuel-fired heating system if the combustion gases are not fed into the desorber. The fuel-fired heating system typically operates with propane, natural gas or fuel oil. If emissions controls consist of a baghouse, scrubber, and vapor phase carbon adsorber, the stack will vent small concentrations of the original contaminants, as well as products of any chemical reactions that might occur. Relative to incineration, the volume of off-gas from the treatment chamber may be smaller, there is less likelihood of creating dioxins and other oxidations products, and metals are less likely to partition to the gas-phase (de Percin, 1991a).

Fugitive emissions from area sources may contribute significantly to the total air emissions from a remediation site. Probably the largest source is excavation of the contaminated soil. Other sources may include the classifier, feed conveyor, and the feed hopper. Fugitive emissions from the components of the thermal desorption system and controls are possible as well. Emissions may also emanate from the waste streams such as exhaust gases from the heating system, treated soil, particulate control dust, untreated oil from the oil/water separator, spent carbon from liquid or vapor phase carbon adsorber, treated water, and scrubber sludge.

4.2.3 Emission Estimation Procedures

The volatile and semi-volatile contaminants under remediation are the species emitted if no destruction or other chemical treatment has taken place. The sources emitting these VOC's may include excavation, soil handling, classifier, oversize objects rejected by the classifier, feed conveyor, feed hopper, control stack, and fugitive emissions from the entire thermal desorption system and from waste streams. Combustion products are emitted when a destructive control such as an afterburner is used and also when the heating system is fuel-fired. In some cases, pyrolysis occurs to a certain degree in the dryer so products from these reactions may also be emitted. If scrubbers are used to treat VOC's or combustion gases, then an additional category of species is emitted.

Theoretical models based on fundamental principles have been proposed for predicting the evolution of volatile compounds from soil in the thermal desorption process, but these models are not practical for use as a predictive tool (Lighty, et al., 1990). In practice, an assessment of the applicability of thermal desorption for a given site will not be based on modeling calculations, but will be based on the types of contaminants present in the soil, the physical properties of the soil, and the results of any bench-, pilot- or full-scale test runs. In most cases, the process conditions such as temperature and residence time in the desorber can be modified to yield the desired removal efficiency, though heavier weight compounds such as those in No. 6 fuel oil may present problems for systems with relatively low operating temperatures. The cost to operate at these process conditions, however, will dictate whether thermal desorption is competitive with other remediation options.

A mass balance equation to estimate an emission rate for a volatile compound leaving the desorber using removal efficiencies obtained from test runs is given in Eklund, et al., 1992c. This

Table 4-2. Comparison of Features of Thermal Desorption and Off-Gas Treatment Systems

	Rotary dryer	Asphalt plant aggregate dryer	Thermal screw	Conveyor furnace
Estimated number of systems	40-60	100-150	18-22	1
Estimated number of contractors	20-30	No estimate	9	—
Mobility	Fixed and mobile	Fixed	Mobile	Mobile
Typical site size (tons)	500-25,000	0-10,000	500-5,000	500-5,000
Soil throughput (tons/hr)	10-50	25-100	3-15	5-10
Maximum soil feed size (inches)	2-3	2-3	1-2	1-2
Heat transfer method	Direct	Direct	Indirect	Direct
Soil mixing method	Shell rotation and lifters	Shell rotation and lifters	Auger	Soil agitaters
Discharge soil temperature (°F)	300-600 [a] 600-1,200 [b]	300-600	300-500 [c] 600-900 [d] 1,000-1,600 [e]	300-800
Soil residence time (minutes)	3-7	3-7	30-70	3-10
Thermal desorber exhaust gas temperature (°F)	500-850 [a] 800-1,000 [b]	500-850	300	1,000-1,2000
Gas/solids flow	Co-current or counter-current	Co-current or counter-current	N/A	Counter-current
Atmosphere	Oxidative	Oxidative	Inert	Oxidative
Afterburner temperature (°F)	1,400-1,800	1,400-1,800 [f]	Generally not used	1,400-1,800
Maximum thermal duty (MM Btu/hr) [g]	15-85	50-125	7-10	10
Heatup time from cold condition (hrs)	0.5-1.0	0.5-1.0	Not reported	0.5-1.0
Cool down time from hot condition (hrs)	1.0-2.0	1.0-2.0	Not reported	Not reported
Total petroleum hydrocarbons				
Initial concentration (mg/kg)	800-35,000	Not reported	60-50,000	5,000
Final concentration (mg/kg)	<10-300	Not reported	ND-5,5000	<10.0
Removal efficiency (%)	95.0-99.9	Not reported	64-99	>99.9

[a] Carbon steel materials of construction
[b] Alloy materials of construction
[c] Hot oil heat transfer system
[d] Molten salt heat transfer system
[e] Electrically heated system
[f] Not used on all systems
[g] Total duty of thermal desorber plus afterburner

Source: Eklund, et al., 1992c.

equation does not include emissions from excavation or other handling of contaminated soil nor does it include fugitive emissions from the desorber system or from liquid and solid phase waste streams. Neither are combustion gases emitted from the heating system and exhaust gases from afterburners included in this estimation method. However, tabulated emissions data for a number of thermal desorption systems are included. Most of the studies cited include data about contaminant concentrations in the soil directly before and after treatment, data which can yield information about point source air emissions from the desorption process itself. These studies do not include the change in concentration before and after excavation due to volatilization. Similarly, little data are available on fugitive emissions from the parts of the process that do not include the desorption chamber and from the other waste streams.

4.2.4 Identification of Applicable Control Technologies

The control of volatile organic emissions is crucial to the overall success of thermal desorption remediation of contaminated soils. Because the process uses physical separation driven by heat, the vaporized contaminants would simply be transferred from one medium (soil) to another (air) if no emission controls were employed. The types of controls include both destruction and separation technologies. Typically two to six controls in series are chosen to suit the specific VOC contaminants present and the other pollutants of concern. Liquid phase and solid waste streams are usually treated on site or stored for subsequent off-site treatment.

Asphalt kilns will have similar air emission control devices as for mobile thermal desorption units, except that no VOC controls typically are employed and the air flowrates are higher requiring some differences in design parameters.

Off-gases from the desorber typically pass first through a particulate control device. Particles that become entrained in the off-gas stream may be removed with:

- Cyclones;
- Venturi scrubbers; or
- Fabric filters.

Collected particulates usually are returned to the incoming waste stream and retreated with the soil.

VOC control devices include:

- Condensers;
- Fume incinerators; and
- Carbon adsorption.

Condensers serve to remove VOCs while fume incinerators (i.e., afterburners) destroy the VOCs. Carbon adsorption is sometimes added to either of these primary VOC control methods as a final polishing step. Exhaust gases from destruction controls may be treated in an acid gas scrubber. Gases are first cooled to saturation temperature then passed through a packed-bed absorber or spray tower where acidic gases are neutralized with caustic (sodium hydroxide) solution or dissolved into water.

Other emissions control techniques include rerouting combustion off-gases to a dryer, using treated water for dust control, and passing an inert gas such as nitrogen through the desorber as explosion prevention. Ultraviolet rays have been used to destroy dioxin in the condensate from the thermal desorption of contaminated soils (Helsel and Thomas, 1987).

4.3 On-Site Incineration

4.3.1 Typical Remediation Scenario for Superfund Sites

A broad range of technologies fall into the category of thermal incineration. The most common incineration technologies include liquid injection, rotary kiln, and multiple hearth. The most common design for the remediation of contaminated soils, however, are rotary kilns. Remediation by on-site thermal destruction using a transportable incinerator is discussed in this section. Shipment of contaminated soils and wastes to a larger, permanent off-site unit may also be an option for a given site, but system design and selection of control options is not generally a consideration. Although incineration is a well-established technology, the evolution of mobile or transportable incinerators is a relatively new development. The literature on incineration is very extensive. The best sources of information on air emissions from incineration are two recent reviews (Oppelt, 1987) and (Eklund, et al., 1989).

In broad terms, thermal destruction of hazardous waste is an engineered process in which controlled combustion is used to reduce the volume of an organic waste material and render it environmentally safe. Incineration is a flexible process capable of being used for many waste types including solids, gases, liquids, and sludges.

A typical system includes the waste feed system, primary and (in most cases) secondary combustion chambers, and exhaust gas conditioning system. The largest part of the waste destruction usually takes place in the primary combustion chamber. As mentioned earlier, for contaminated soils this chamber is usually a rotating kiln. Gases formed in the primary combustion chamber

Table 4-3a. Properties of Off-Gas from Combustion Chamber from On-Site Incineration Systems

Parameter	Units	Value
Air flowrate	ACFM	30-50,000
Temperature	°F	1,400-1,800
Oxygen content	%	3
Pressure drop	In. H_2O	10-15

Table 4-3b. Hazardous Waste Incinerator Emissions Estimates

	EPA* conservative estimated efficiencies	Typical actual control efficiencies	Typical range of emissions rates
Particulate matter	99+%	99.9+%	0.005-0.02 gr/dscf
Hydrogen chloride (HCl)	—	99+	10-50mg/NM ^{3}
Sulfur dioxide (SO_2)	—	95+	30-60
Sulfuric Acid (H_2SO_4)	—	99+	2.6
Arsenic	95	99.9+	1-5 µg/Nm ^{3}
Beryllium	99	99.9	<0.01-0.1
Cadmium	95	99.7	0.1-5
Chromium	99	99.5	2-10
Antimony	95	99.5	20-50
Barium	99	99.9	10-25
Lead	95	99.8	10-100
Mercury	85-90	40-90+	10-200
Silver	99	99.9+	1-10
Thallium	95	99+	10-100
PCDD/PCDF**	—	90-99+	1-5 ng/NM ^{3}

* Based on spray dryer fabric filter system or 4-field electrostatic precipitator followed by a wet scrubber.
** Total all cogeners

Source: Donnelly, 1991.

are then routed to a secondary combustion chamber, or afterburner, where any unburned hydrocarbons or products of incomplete combustion can be oxidized. Typical off-gas properties for on-site incineration systems are summarized in Table 4-3.

4.3.2 Potential Air Emissions

The air emissions associated with full-scale thermal destruction are primarily stack emissions of combustion gas. However, some additional evaporative emissions may occur from equipment leaks and waste handling. Full-scale, off-site incineration units may vent all emissions from waste handling and transfer activities to the combustion chamber as make-up air. The air emissions for on-site incinerators are similar to off-site units, except that on-site waste handling activities have a greater likelihood of being uncontrolled. Stack heights for transportable units may be in the range of 40-100 ft. (Good engineering practice stack height will not apply unless large structures are present.)

The fugitive emissions sources associated with thermal treatment likely will be ground-level.

Emissions from incinerators include: undestroyed organics, metals, particulate matter, nitrogen oxides (NO_x), carbon monoxide (CO), acid gases, and products of incomplete combustion (PICs). The cause of each of these pollutants and typical levels of emissions are discussed in Eklund, et al., 1992c. Fugitive emissions associated with excavation, storage, and handling of the feed material also must be considered when assessing potential air impacts from incineration.

The wide variety in design and operation of incinerators makes it difficult to predict air emissions. However, extensive research has been done to determine the range of unburned hydrocarbon and PIC emissions that can be expected from full-scale incinerators. In general, incinerators treating wastes must achieve a required destruction and removal efficiency of at least 99.99% for RCRA wastes and 99.9999% for PCB- or dioxin wastes. The remaining 0.01% or 0.0001% of the waste can be assumed to pass through the system uncombusted (Eklund, et al., 1989). However, in addition to unburned hydrocarbons there may be some additional reactions in the combustion process that may produce a number of simpler organic compounds, called PICs. PICs may include dioxin, formaldehyde, and benzo(a)pyrene and other polynuclear aromatic hydrocarbons. Possible causes of PIC emissions include low temperatures due to quenching, residence time short circuits due to nonplug flow and/or unswept recesses, and locally high waste/oxygen concentration ratios due to poor microscale mixing.

The metals introduced to the incinerator via the waste feed stream are not destroyed. Depending on their boiling point, they can either be volatilized or remain as solids. Volatilized metals will exit the stack as a gas, condense or adsorb onto particles in the stack gas stream, or be captured in the wet scrubber. Metals associated with particulate matter (PM) will be captured in the PM control device. Non-volatilized metals can be fluidized and swept up into the combustion gas or leave the incinerator in the bottom ash.

The waste feed, auxiliary fuel, and combustion air can all serve as sources for particulate emissions from an incineration system. Particulate emissions may result from inorganic salts and metals which either pass through the system as solids or vaporize in the combustion chamber and recondense as solid particles in the stack gas. High molecular weight hydrocarbons may also contribute to particulate emissions through several possible mechanisms. RCRA requirements for particulate emissions call for a limit of 0.08 grains/dscf corrected to 7% O_2 (U.S. EPA, 1990b).

Achieving high levels of destruction of organic wastes is directly related to combustion chamber temperature: the higher the temperature, the greater the DRE of organics (for a given combustion gas residence time and degree of turbulence). Unfortunately, the fixation of nitrogen and oxygen to form NO_x also increases with combustion temperatures above 1600°F. NO_x emissions caused by this mechanism are referred to as thermal NO_x. Also if bound nitrogen atoms are present in the waste (e.g., amines), additional NO_x emissions, called fuel NO_x, will be formed. In such cases, two stage combustion or emissions controls may be needed. Carbon monoxide emissions are generally low (<25 ppmv) in incinerators due to the high operating temperatures and excess oxygen maintained in the process.

Hazardous waste incineration also will produce acid gases. These include oxides of sulfur (SO_x), and halogen acids (HCl, HF, and HBr).

4.3.3 *Emission Estimation Procedures*

Simple mass balance equations for estimating incineration emissions with an assumed DRE have been published (Eklund, et al., 1989 and IT, 1992). The equations cover VOCs, PM, metals, and acid gases. Both of these documents summarize typical operating rates, control efficiencies, etc.

Models have been reported for direct fired, high temperature rotary kiln systems that predict the temperature of the solid bed and kiln exit gas as a function of measurable physical parameters such as kiln rotational speed, burner firing rate, soil feed rate, etc. (Troxler, et al., 1992). These models theoretically could be combined with thermal stability data and oxygen content of the kiln gas data to predict the destruction efficiency of incinerators.

Emissions of PICs, both the amount and the type, will vary greatly from unit to unit depending on design and waste feed. Data are unavailable to generate emission factors.

The production of acid gases (HCl, SO_2, HBr, and HF) is determined by the respective chlorine, sulfur, bromine, and fluorine contents in the waste and fuel feed streams. The concentrations of these elements range widely amongst different wastes; consequently, the resulting acid gas emissions also will show wide variability.

NO_x is usually only a concern for wastes with high nitrogen content. Typical NO_x emissions for an incinerator may be on the order of 100-200 ppmv (dry basis), or expressed on a fuel basis, 0.12-0.33 lbs per MMBtu (Eklund, et al., 1992c). CO emissions from incinerators also are not considered a major problem since most systems are designed to be fired with excess air (i.e. oxygen rich) to ensure complete combustion of organic material to carbon dioxide. Vendors typically guarantee CO emissions less than 100 ppmv (dry basis) and actual measured CO levels are often lower.

4.3.4 *Identification of Applicable Control Technologies*

Unlike other soil remediation technologies, incineration, which converts organics into carbon dioxide and water, does not require additional add-on VOC controls. However, additional controls are usually required to reduce emissions of acid gases, particulate matter (PM), and metals. After the combustion gases leave the incinerator, they may be routed through a variety of air pollution control devices including gas conditioning, particulate removal, and acid gas removal units. Gas conditioning is accomplished with equipment such as waste heat boilers or quench units.

Typical particulate matter removal devices include:

- Venturi scrubbers;
- Wet electrostatic precipitators;

- Ionizing wet scrubbers; and
- Fabric filters.

Acid gas removal units include:

- Packed, spray, or tray tower absorbers;
- Ionizing wet scrubbers;
- Wet electrostatic precipitators; and
- Spray dryer adsorbers.

The absorbers generally will use a caustic solution. Units used to treat soil contaminated with halogenated solvents generally will be required to meet RCRA requirements governing HCl emissions.

4.4 Soil Vapor Extraction

A number of reports and articles have been published recently that provide useful information regarding soil vapor extraction (SVE) systems. The best single source of information on SVE design and operation is a recent EPA report (Pedersen and Curtis, 1991). Another key reference is a recent overview paper (Johnson, et al., 1990). Air emissions from SVE systems are addressed in Eklund, et al., 1992b and Eklund, et al., 1992c.

4.4.1 Typical Remediation Scenario for Superfund Sites

Soil vapor extraction is one method used for the treatment of soil contaminated with volatile hydrocarbons. The process sometimes is referred to as soil venting, vacuum extraction, aeration, or in-situ volatilization. In general terms, soil vapor extraction removes volatile organic constituents from contaminated soil by creating sufficient subsurface air flow to strip contaminants from the vadose (unsaturated) zone by volatilization. As the contaminant vapors are removed, they may be vented directly to the atmosphere or controlled in a number of ways. Among the relative advantages of SVE over other remediation approaches are that no materials handling operations are necessary and the air emissions are released from a point source and thus can be controlled readily.

Soil vapor extraction has been used widely to remediate sites contaminated with gasoline or chlorinated solvents (e.g., TCE). It is also used sometimes to minimize migration of vapors into structures or residential areas during other types of remediation. By its nature, SVE is an on-site, in-situ treatment method. SVE often is used in conjunction with or following other remedial measures such as excavation of subsurface waste bodies, removal (pumping) of any hydrocarbon lens that is present, or air stripping of contaminated ground water.

Typical SVE systems include extraction wells, monitoring wells, air inlet wells, vacuum pumps, vapor treatment devices, vapor/liquid separators and liquid phase treatment devices (if contaminated water is extracted in the process). Example scenarios for SVE systems at Superfund sites are given in Table 4-4. An option sometimes employed is to introduce the air at the air inlet well into the saturated zone (i.e. groundwater table). This technique, referred to as air sparging, acts to strip some of the volatile and semi-volatile compounds from the ground water.

Table 4-4. Example Scenarios for SVE Based on Size of System

Parameter	Units	Scenario: Very Small	Small	Medium	Large
Exhaust gas flowrate	m^3/min	1.4	14	85	425
	cfm	50	500	3,000	15,000
Exhaust gas velocity	m/sec.	3.0	7.4	12.5	14.2 [a]
Exit gas temp.					
-No controls	°C	50	50	50	50
-Carbon	°C	25	25	25	25
-Catalytic oxidation	°C	320	320	320	320
Stack height	m	3.0	4.6	7.6	9.1
Stack diameter	m	0.10	0.20	0.38	0.46

[a] Assume three adjacent stacks each handling 5,000 cfm. The flow is split to lower the velocity of the exiting gas to typical design levels to minimize corrosion of the stack.

Source: Eklund, et al., 1992b.

Another option is to heat the air entering the inlet wells to enhance the volatilization of less volatile, higher molecular weight contaminants, such as diesel fuel.

Steam-assisted SVE is another option that has been used for improving the removal efficiency of VOCs and SVOCs. The steam can be injected via inlet wells. A mobile treatment system also has been demonstrated that treats blocks of soil (7 x 4 ft. x up to 20 ft. deep) at a rate of about 3 m^3/hr (U.S. EPA, 1991b). Augers are used to stir the soil as steam is injected. The treated area is covered by a shroud (ducted hood) and all vapors are extracted and sent to control devices (see Section 4.4.3).

4.4.2 Potential Air Emissions

The contaminants removed from the soil by SVE systems and hence present in the off-gas generally have vapor pressures greater than 1.0 mm Hg at 20°F. The tendency of the organic contaminants to partition into water or to be adsorbed onto soil particles also affects the off-gas composition, as do the compounds' water solubility, Henry's Law constant, and soil sorption coefficient. The soil temperature affects each of these variables and hence the rate of vapor diffusion and transport. The concentration of contaminants that are initially present will also affect their relative partitioning between vapor and liquid phases, and the amount that is solubilized or adsorbed. The time that the contamination has been present is also an important factor, as mixtures of contaminants will generally become depleted of their more volatile components over time through volatilization. This process, referred to as weathering, will tend to cause SVE to become progressively less applicable as the site ages. It also affects the operation of the SVE system, as the more volatile components are typically removed first and the composition of the vapors collected and treated varies over time.

VOC loading rates in the off-gas can be 500-600 kg/day or higher. The air emissions associated with soil vapor extraction systems come primarily from the stack. Stack heights are typically 12-30 feet and usually only one stack is used. Additional releases of volatile organics may occur from the treatment of any contaminated water that is extracted. Fugitive emissions are considered negligible due to the negative pressure throughout most of the system.

Emissions include untreated volatile organics from the extraction process. Removal and emissions of semi-volatile organic compounds will occur also, though with less efficiency than for VOCs. Lesser amounts of air emissions associated with the control system may occur also. Due to the variety of technologies used, stack emissions may include products of incomplete combustion, nitrogen oxides, particulate matter, carbon monoxide, acid gases and any other possible products of these technologies. Of primary concern, however, are the volatile organics emitted from the point sources. Percent levels of carbon dioxide in the off-gas may occur and would suggest that in-situ biodegradation is occurring in conjunction with the SVE. The ambient air drawn through the soil would raise the oxygen content of the soil-gas and thus promote biodegradation.

The emission rate of VOC compounds over time from continuously operated SVE systems tends to show an exponential-type decay curve. If the system is stopped and then restarted, however, the VOC emission rate returns to near the original rate unless the remediation is nearing completion. Apparently, shutting off the vacuum allows the soil-gas equilibrium to become re-established. Due to this behavior, the most efficient method of operation is to run the SVE system only for a part of each day or week, i.e. operate in a "pulsed" mode.

4.4.3 Emission Estimation Procedures

The factors that govern vapor transport in the subsurface are very complex and no practical, accurate theoretical models for predicting emissions or recovery rates for SVE systems exist. During operation of SVE systems, the vacuum that is applied to the soil and the resulting pressure gradient is the dominant factor in determining the flowrate of vapors. Subsurface vapor flow equations based on Darcy's Law have been published that predict the flowrate of vented gas, but these equations are not useful as a predictive tool due to the large variability in air permeability among and within sites (Johnson, et al., 1990). In practice, field tests typically are performed to evaluate the potential effectiveness of SVE for a given site. The field tests may be either a pilot-scale demonstration of SVE or tests of the air permeability. This information is used to determine the number of wells required to remediate the site and the spacing of the wells, and also may yield information about the off-gas stream to be treated.

A simple screening model is available based on historical vapor extraction rates at sites where SVE systems have been used (Eklund, et al., 1992b). The guidance given in the screening model document encourages the user to provide site-specific extraction rate and vapor concentration data, but conservative default values also are provided.

4.4.4 Identification of Applicable Control Technologies

As the vapors are removed from the soil they are either discharged to the atmosphere or treated to reduce air emissions. If the hydrocarbon content is high enough, direct combustion is theoretically possible. However, because concentrations typically drop significantly during removal, natural gas or some other fuel will be needed to maintain combustion. Also, for safety reasons, dilution air typically is added to maintain the VOC concentration below the lower explosive limit (LEL). In some cases, the wells may be shut down for a period of time to allow subsurface vapor pressures to re-equilibrate, thus yielding concentrations sufficient to sustain a flame. For lower levels of hydrocarbons, catalytic oxidation may be effective. Carbon adsorption systems are used often but they may be costly to implement and generally are not acceptable for high-humidity gas streams.

A recent survey indicates that the exhaust from about 50% of SVE systems is vented directly to the atmosphere with no controls (PES, 1989). The trend, however, is for VOC controls to be required. For those systems with controls, the most viable options are:

1) Activated carbon adsorption;
2) Catalytic oxidation;
3) Thermal incineration;
4) Internal combustion engine; and
5) Miscellaneous control approaches.

The first three treatment options are the most commonly used for large SVE systems such as those used at Superfund sites or refineries. Internal combustion engines (ICE) are a common choice for control of emissions for small systems such as those used at small Leaking Underground Storage Tank (LUST) sites. Theoretically, removal efficiencies of 95-99% for VOCs should be achievable with any of these control options, though actual control efficiencies in the field may be closer to 90%. Control efficiencies for minor components of the off-gas stream may be lower.

The miscellaneous control devices that potentially may be applicable for controlling VOC emissions from SVE systems include:

- Condensers;
- Packed bed thermal processors; and
- Biofilters.

Condensers using chilled water or other refrigerants can remove anywhere from 50 to 90% of VOCs from concentrated streams (>5000 ppmv VOCs). Biotreatment requires time to establish an active culture of microbes and careful control of soil moisture, temperature, and air flow patterns to maintain the efficiency of the microbial action.

The mobile treatment system using steam-assisted SVE has a gas treatment system that consists of (U.S. EPA, 1991b):

- Scrubber;
- Cyclone separator;
- Cooling system;
- Carbon adsorption system; and
- Compressors.

Particulate matter entrained in the process air stream is removed in the scrubber. The air is then sent to the cyclone separator where water droplets are removed. Heat exchangers are then used to cool the gas and remove more water and organic compounds. The process air stream from the cooling system is passed through activated carbon to remove VOCs. The cleaned air stream is then sent to a compressor where it is heated and routed back to the treatment shroud. Air emissions from the system are minimal in terms of both volume and mass loading.

4.5 Air Stripping of Contaminated Water

4.5.1 Typical Remediation Scenario for Superfund Sites

Air strippers are used widely to remove chlorinated solvents and other VOCs from contaminated ground water. Air stripping is a mass transfer process in which volatile contaminants in water are evaporated (stripped) into air. The contaminated water is introduced at the top of a packed-tower through spray nozzles and allowed to slowly flow down through the column or tower. The packing media acts to retard the water flow and increase the effective surface area of the system. Air is introduced countercurrent to the direction of water flow. The saturated air containing the volatiles is emitted from the top of the column or routed to a control device. The treatment system may also contain wells, separators, and vessels for treating inorganic contaminants. Example scenarios for air stripping systems at Superfund sites are given in Table 4-5.

4.5.2 Potential Air Emissions

The primary source of emissions from air stripping is the stripper exhaust, and VOCs are the major pollutants of concern.

Table 4-5. Example Scenarios for Air Stripping

Parameter	Units	Typical Value Small	Medium	Large
Total influent liquid flowrate	L/min	570	2,840	5,700
	gpm	150	750	1,500
Column height	m	7.6	9	14
Column diameter	m	1.2	3.6	3.6
Exhaust gas flowrate	m^3/min	29	140	285
	cfm	1,020	5,000	10,000
Stack height	m	8.5	10	15
Stack diameter	m	0.31	0.61	0.91
Structure dimensions	m	7.6x1.2x1.2	9.0x3.6x3.6	13.0x3.6x3.6
Exit gas velocity	m/sec	6.4	8.0	7.3
Exit gas temperature	°C	20	20	20
Ambient temperature	°C	20	20	20
Gas/liquid ratio (G/L)	(vol/vol)	50	50	50
Stripping efficiency	%	99+	99+	99+

Source: Eklund, et al., 1991b.

For systems without control devices, the exhaust is vented through a short stack, typically a (3-6 ft) pipe, at the top of the column. For systems with control devices, the airflow from the column usually is vented down to the control device at ground level. A short stack (15-20 ft) is used after the control device.

In addition to the exhaust stack, other emission sources may exist. Any place upstream of the air stripping tower where water is in direct contact with the atmosphere, such as separators, holding tanks, treatment tanks, or conduits, is an emission source. Fugitive losses from pumps, valves, and flanges usually are not significant due to the dilute nature of the water contamination.

The important parameters affecting the emission rate for a given compound from an air stripping unit include: the concentration of the contaminant in the influent to the stripper, the influent flowrate, the stripping efficiency of the tower, and the effectiveness of any control technologies that are in place. The stripping efficiency will depend on a number of factors including: the compound's Henry's Law constant, the type of packing material in the tower, and the gas to liquid contact ratio within the tower.

4.5.3 Emission Estimation Procedures

For a given liquid treatment rate, the magnitude of the uncontrolled air emissions from an air stripper are governed by the effectiveness of the liquid-to-air mass transfer in the stripper. A stripping efficiency of 100% for volatile organic compounds is a reasonable, conservative assumption. A number of equations and associated computer models are available to aid the system designer in selecting the appropriate tower height, gas to liquid ratio, packing material, etc. to optimize the mass transfer and meet the performance goal in a cost effective manner (e.g., U.S. EPA, 1990c).

A simple screening model is also available that estimates VOC emissions using a mass balance approach, influent mass loadings, and the Henry's Law constants for the contaminants present (Eklund, et al., 1991b).

4.5.4 Identification of Applicable Control Technologies

The use of a control device can reduce emissions by one to two orders of magnitude (i.e. 90-99% control). VOC control from air strippers is possible by:

- Carbon adsorption; or
- Catalytic oxidation.

Thermal oxidation also could be used with air strippers if the VOC concentration was sufficiently high, but no such use has been found in the literature. In addition to these three VOC control methods, flares have been used at some landfills for the control of emissions from air strippers (Vancit, et al., 1987). Emissions of PM, SVOC, and metals are all negligible, so no air emission controls for these compounds are needed.

4.6 Solidification/Stabilization

General information about solidification and stabilization is contained in Cullinane, et al., 1986. Extremely limited data exists

about air emissions from these types of processes. The discussion in this section was taken largely from Thompson, et al., 1991.

4.6.1 *Typical Remediation Scenario for Superfund Sites*

Stabilization and solidification technologies are gaining increased use as Superfund site remediation methods. The goal of these processes is to immobilize the toxic and hazardous constituents in the waste, usually contaminated soil or sludge. This can be accomplished by several means:

1) Changing the constituents into an immobile (insoluble) form;

2) Binding them in an immobile, insoluble matrix; or

3) Binding them in a matrix which minimizes the material surface exposed to solvents (groundwater) which could leach the hazardous constituents.

Several types of stabilization and solidification technologies exist as alternatives for remedial action. A few of these processes involve in-situ treatment; however, most generally require excavation and other soil handling activities. Nearly all the commercially available stabilization and solidification technologies are proprietary.

Solidification and stabilization processes usually are batch operations, but may be continuous and all follow the same basic steps. Wastes are first loaded into the mix bin (wastes are sometimes dried before addition to the bin), and other materials for the solidification or stabilization are added. The contents of the bin then are mixed thoroughly. After a sufficient residence time, the treated waste is removed from the bin. Treatment rates are 25-100 tons/hr for in-situ processes and up to 130 tons/hr for ex-situ processes (U.S. EPA, 1990d and U.S. EPA, 1989a). The material usually is formed into blocks and allowed to cure for up to several days. The blocks then can be placed in lined excavations on-site. **Note:** This description does not apply to in-situ treatment methods, which use a variety of techniques (from applied high voltage to injection of stabilizing agents) to immobilize the contaminated waste in-place without excavation or soils handling.

Typical raw materials used in stabilization processes include fly ash, portland cement, cement kiln dust, lime kiln dust, or hydrated lime. Other additives that may be used to solidify or encapsulate wastes include asphalt, paraffin, polyethylene, or polypropylene.

4.6.2 *Potential Air Emissions*

The primary source of air emissions from stabilization and solidification processes is volatilization of organic contaminants in the waste. Up to 90% of the VOCs are lost during mixing and curing (Weitzman, et al., 1989). Volatilization can occur during waste handling activities such as soil excavation and transport or during the process of mixing the binding agents with the waste. Also, some evaporative emissions will occur from waste even after stabilization, especially during the curing period immediately after the blocks are formed. As shown in lab studies the largest fraction of volatile loss occurs during the mixing phase because heat may be required to assist mixing or is generated by exothermic stabilization reactions (Weitzman, et al. 1989).

Particulate matter emissions from a full-scale system were found to be about 2.5 lb/hr (Ponder and Schmitt, 1991).

4.6.3 *Emission Estimation Procedures*

In general, VOC emissions from stabilization and solidification processes will depend on the type and concentration of the VOCs in the waste, the duration and thoroughness of the mixing, the amount of heat generated in the process, and the average batch size processed. The longer or more energetic the mixing and processing, the greater likelihood that organic compounds will volatilize. The volatile losses also will increase as the temperature of the waste/binder mixture increases. Binding agents with high lime contents generally cause highly exothermic reactions. The batch size influences volatilization by affecting the mean distance a volatilized molecule has to travel to reach the air/solid interface at the surface of the stabilized waste. The larger the block of material, the lower the rate of volatilization.

In addition to volatile emissions, stabilization and solidification processes will generate fugitive dust emissions. Possible sources of fugitive dust emissions include storage of raw materials, preparation of the binding agents, transfer of wastes into the mixing bin, removal of the treated material from the mixing bin, and replacement of the material at the site after processing.

Little information exists about the fate of volatile contaminants in wastes treated by stabilization and solidification methods. A literature search found no available field data on air emissions at Superfund sites using this type of remediation technology. Based on laboratory studies, however, about 40-80% of the volatile contaminants in the treated waste is estimated to eventually evaporate (Weitzman, et al., 1989). Most of the loss occurs within 60 minutes of mixing the waste with binding agents. Thompson, et al., 1991 give a simple mass balance equation for estimating emissions.

Particulate matter emissions for stabilization and solidification processes can be estimated using emission factors for soil handling (see Section 4.1).

4.6.4 *Identification of Applicable Control Technologies*

Emission controls for excavation, storage, and feeding of the waste to the process unit were covered in Section 4.1.4. In general, solidification/stabilization is not the remedy of choice for wastes with high levels of VOCs and therefore VOC emissions are not usually a major concern. The only reference in the literature to emission controls from solidification/stabilization is a solidification system processing 12 tons/hr enclosed in a building (Ponder and Schmitt, 1991). Approximately 40,000 ft^3/min of air from the building was routed to PM and VOC control devices. Emissions were controlled by introducing the gas stream to a venturi scrubber, followed by a mist eliminator, an air preheater, a disposable prefilter, and finally two parallel carbon adsorption systems.

For in-situ processes, several options or combination of options could be appropriate for controlling VOC or PM emissions:

- Collection hood;
- Wind screens;
- Temporary foams;
- Water sprays;
- Water sprays with additives;
- Enclosures; and
- Operational controls.

4.7 Bioremediation

4.7.1 Typical Remediation Scenario for Superfund Sites

Bioremediation at Superfund sites may be either in-situ or ex-situ. Ex-situ biodegradation generally refers to treatment processes where an aqueous slurry is created by combining soil or sludge with water and then biodegraded in a self-contained reactor or in a lined lagoon. This is an emerging technology and often is referred to as slurry biodegradation. Ideally, the waste is decomposed into carbon dioxide and water. Background information is available in U.S. EPA, 1990e and Thompson, et al., 1991.

In-situ treatment employs the natural microbiological activity of soil to decompose organic constituents. Systems that try to enhance this natural biological activity typically use injection wells to provide an oxygen source (such as air, pure oxygen, or hydrogen peroxide) to stimulate aerobic degradation or add nutrients to support the growth of waste-consuming microorganisms. In some cases, microorganisms may be added to the soil that have the ability to metabolize specific contaminants of interest.

In-situ bioremediation at Superfund sites also may involve sequential isolation and treatment of waste areas using processes that closely resemble ex-situ processes except that it may not be necessary to excavate, pump, or otherwise transfer the waste material prior to treatment. Ex-situ processes are more developed and demonstrated than in-situ processes at this time.

Two main objectives behind using slurry biodegradation are: to destroy the organic contaminants in the soil or sludge, and, equally important, to reduce the volume of contaminated material. Slurry biodegradation can be the sole treatment technology in a complete cleanup system, or it can be used in conjunction with other biological, chemical and physical treatment methods.

Systems have a number of components, all of which could be emission sources: mix tank, bioreactor system (continuously stirred tank reactor or CSTR), or lined lagoon. Since aerobic treatment is the most common mode of operation for slurry biodegradation, aeration must be provided to the bioreactors by either floating or submerged aerators or by compressors or spargers. Other typical system components are a separation/dewatering system, a clarifier for gravity separation, and wastewater storage tanks.

Biodegradation is actually only one of several competing mechanisms in biotreatment. For ex-situ processes, the contaminants may also be volatilized, undergo chemical degradation, or be adsorbed onto the soil particles. For in-situ processes, these same pathways exist along with leaching. The overall contaminant removal achieved by biotreatment processes represents the combined effect of all of these mechanisms. Volatilization may account for the disappearance of the majority of VOCs being treated.

4.7.2 Potential Air Emissions

Typical emissions from biotreatment process are evaporative losses of volatile and semi-volatile organic compounds. If the soil is handled or mixed, though, some emissions of particulate matter may occur. Combustion emissions from the process equipment are also possible.

The air emissions from slurry biodegradation processes can either be area or point sources. For processes using open lagoons, emissions come from the exposed surface of the lagoon. On the other hand in systems using above-ground self-contained reactors, the primary source of emissions is usually a process vent.

In bioslurry processes the emissions of concern are usually VOCs. The soils handling steps required to deliver the contaminated soil to the treatment unit may also emit significant amounts of VOCs and PM. Emissions from soils handling are addressed elsewhere in this document.

In open lagoons, the primary environmental factors, in addition to the biodegradability and volatility of the waste, which influence air emissions are process temperature and wind speed. Emissions tend to increase with an increase in surface turbulence due to wind or mechanical agitation. Temperature affects emissions through its influence on microbial growth. At temperatures outside the band for optimal microbial activity, volatilization will increase. Emissions from self-contained reactors are also determined by reactor design parameters such as the amount of air or oxygen used to aerate the slurry. Higher gas flow will strip more volatiles out of solution and increase air emissions.

Little information exists on volatile losses from slurry biodegradation processes. Slurry processes have only recently become commercially available and field experience to date is limited. However, data on air emissions from wastewaster biotreatment processes are available. The percentage of each contaminant that is volatilized will vary greatly depending on the physical properties of the contaminant and the design of the treatment system. Based on field studies of an aerated impoundment treating contaminated *water*, as much as 20% of each compound may be volatilized depending on its volatility and biodegradability (Eklund, et al., 1988). Percentage emissions for soil and waste treatment would be expected to be higher.

4.7.3 Emission Estimation Procedures

Although no models have been developed explicitly for estimating VOC or PM emissions for bioremediation processes treating contaminated soils or waste, several public-domain PC models are available for estimating air emissions from a variety of other biotreatment options, principally surface impoundments. The two most commonly used models are CHEMDAT-7 (U.S. EPA, 1989b) and the Surface Impoundment Modeling System (SIMS). Both CHEMDAT-7 and SIMS are based on mass transfer and biodegradation models developed by EPA.

While not appropriate for Superfund sites, land treatment is a bioremediation process that is somewhat analogous to the types of remediation performed at Superfund sites. A PC-based model, LAND7 (U.S. EPA, 1989b), is recommended by the EPA to predict the emission rates resulting from the land treatment of wastes. Sensitivity studies done using these models show that under typical conditions they predict that 35-80% of the applied volatiles will be emitted to the air and the remainder degraded (Coover, 1989).

4.7.4 Identification of Applicable Control Technologies

When the air emissions from slurry biodegradation processes are released through a process vent, standard VOC air pollution control technologies can be applied. Common alternatives for controlling VOC vent emissions include:

- Carbon adsorption;
- Thermal incineration or oxidation; and
- Catalytic oxidation.

For the relatively low VOC levels and low gas flows from bioreactors, carbon-based VOC emission controls are generally the best choice. Since the vent stream will likely contain only dilute amounts of VOCs, relatively large amounts of auxiliary fuel must be fired in either thermal or catalytic oxidizers.

When the air emissions from slurry biodegradation processes are area air emission sources, applying air pollution control technologies is more difficult. The best approach is generally to use a vapor collection hood to capture any VOC emissions and then route those emissions to a standard control device. Other area source control approaches (e.g., foams, covers) generally are not applicable to in-situ bioremediation since the controls are designed to inhibit the transfer of gases between the soil and the atmosphere. While these approaches reduce VOC emissions, they will also limit the replenishment of oxygen to the soil and may cause anaerobic conditions to develop.

4.8 Separation Techniques

4.8.1 Typical Remediation Scenario for Superfund Sites

Three remediation technologies are described below: soil washing, solvent extraction, and soil flushing. These are all primarily separation processes and further treatment of the collected contaminants typically will be required. They have not been used widely at Superfund sites. Soil washing is an *ex situ* process in which contaminated soil is excavated and fed through a water-based washing process. It operates on the principle that contaminants can be dissolved or suspended in an aqueous solution or removed by separating clay and silt particles and the associated adhered contaminants from the bulk soil. The aqueous solution containing contaminants may be treated by conventional wastewater treatment methods (U.S. EPA, 1990f).

Most organic and inorganic contaminants bind chemically or physically to clay or silt soil particles, which in turn adhere to larger sand and gravel particles primarily by compaction and adhesion. Particle size separation by washing enables the contaminated clay and silt particles (and the bound contaminants) to be concentrated. Separating the sand and gravel from the small contaminated soil particles significantly reduces the volume of contaminated soil, making further treatment or disposal much easier. The larger particles may be returned to the site (U.S. EPA, 1990g).

Removal efficiencies range from 90-99 percent for volatile organic compounds and 40-90 percent for semi-volatile compounds, so the wastewater streams may contain high levels of organic compounds and be an emission source.

Excavation and removal of debris and large objects precedes the soil washing process. Sometimes water is added to the soil to form a slurry that can be pumped. After the soil is prepared for soil washing, it is mixed with washwater and sometimes with extraction agents. At this point, several separation processes occur. Soil washing generates four waste streams:

1) Contaminated solids separated from the washwater;
2) Wastewater;
3) Wastewater treatment sludges and residual solids; and
4) Air emissions.

Solvent extraction differs from soil washing in that it employs organic solvents rather than aqueous solutions to extract contaminants from the soil. The remediation process begins with excavating the contaminated soil and feeding it through a screen to remove large objects. In some cases, solvent or water is added to the waste in order to pump it to the extraction unit. In the extractor, solvent (e.g., liquefied propane and butane) is added and mixed with the waste to promote dissolving of the contaminants into the solvent. Up to five waste streams may result from the solvent extraction process:

1) Concentrated contaminants;
2) Solids;
3) Wastewater;
4) Oversized rejects; and
5) Air emissions.

Typically, solvent extraction units are designed to produce negligible air emissions, but significant levels of emissions may occur during waste preparation (U.S. EPA, 1990g).

Soil flushing differs from soil washing and solvent extraction in that it is an *in situ* process in which the solvent is sprayed over the contaminated area, percolates through the soil and dissolves the contaminants. Elutriate is collected in a series of wells and drains.

4.8.2 Potential Air Emissions

In addition to the contaminants that may volatilize, the solvents themselves may be cause for concern. Products of aerobic and anaerobic decomposition are also possible. No field data for emissions from any of these processes has been identified.

In the soil washing process the greatest potential for emissions of volatile contaminants occurs in the excavation, feed preparation, and extraction process. Collected emissions from these

processes typically are treated by carbon adsorption or incineration (U.S. EPA, 1990f). Because soil washing occurs in liquid and solid phases, volatile compounds emitted evolve primarily due to their vapor pressures in these phases. The waste streams also have the potential to be sources of VOC emissions.

Solvent extraction also may produce emissions during excavation and soil transport and from contaminated oversize rejects (U.S. EPA, 1990g). Because the solvent recovery process involves vaporization of the solvent, fugitive emissions are possible from this as well as other stages of the solvent process, including the waste streams.

Emissions from soil flushing may emanate from the soil surface, solvent storage vessels and spray system, and from locations where the contaminant-laden flushing solution surfaces.

4.8.3 Emission Estimation Procedures

No equations or models for predicting the air emissions from these processes have been identified.

4.8.4 Identification of Applicable Control Technologies

Carbon adsorption and fume incineration are typical controls used to treat collected emissions. In solvent extraction, volatile solvents are recovered and recycled.

4.9 Other Emerging Technologies

A broad range of technologies fall under this heading, with most being some type of physical or chemical waste treatment methods. Included in this category are emerging chemical treatment methods such as:

- Chemical oxidation using ozone or hydrogen peroxide;
- Hydrolysis of alkyl halides and other organics; and
- Dechlorination (e.g., using lime);

and physical treatment methods such as:

- In-situ thermal treatment or vitrification;
- Electrokinetics; and
- Ground freezing.

These methods have in common that they are undergoing development, little or no data are available regarding levels of air emissions, and air emission controls have not been evaluated for these applications. Further information is available in U.S. EPA, 1990h and U.S. EPA, 1991c. General considerations are discussed below.

In general terms, a chemical treatment method is one in which a reactive compound (or compounds) is added to the contaminated groundwater or soil to react with pollutants and form less harmful products. As the name implies, the effectiveness of this type of treatment depends greatly on the chemical properties of the pollutants. An example of this type of method is ozone treatment of contaminated groundwater. In this process, contaminated groundwater or wastewater is mixed in a continuous reactor with ozone and other oxidizing agents. The oxidizers react with the organic contaminants to form CO_2 and water.

Physical treatment involves the addition of energy or another treatment agent to physically transfer the pollutants to another state in which they are easier to dispose of or treat. The path of physical transfer can be adsorption, absorption, dissolution, or a change of state such as evaporation. An example of this method is in-situ vitrification. Electrodes are placed in the ground and a large current is applied. The soil heats and fuses. The electrodes are removed after the ground has sufficiently cooled (e.g., after one year).

The air emissions associated with chemical and physical waste treatment techniques that may be used at Superfund sites have not been characterized adequately for most methods. A broad spectrum of technologies are included in this category, and the types and sources of air emissions may vary greatly. For most chemical and physical treatment methods, however, the emissions of primary concern are VOCs, with emissions of semi-volatile organic compounds and particulate matter also of potential concern. Emissions are usually from either ground level area sources or low-level point sources. Point sources typically are associated with the treatment method, while area sources usually are associated with the handling of contaminated soil or water.

In general, two types of process air emission sources can be associated with chemical and physical treatment. First, transfer of the contaminants from the liquid- or solid-phase to air may be an inherent consequence of the treatment method. For example, in-situ thermal treatment volatilizes a significant fraction of the soil contaminants. In some cases, these air emissions are controlled by using a hood to collect the emissions and route them to an add-on control device for VOCs, such as carbon adsorption units. Second, fugitive emissions can be generated as a by-product of the treatment method. For instance, in ozone treatment of contaminated water, trace emissions of unreacted organic contaminants and ozone may occur.

Additional fugitive emissions from physical and chemical treatment methods can result from leaking valves, pumps, and flanges in the system, as well as from transfer or handling of the untreated contaminated material. Equipment leaks may be regulated under the CAAA regulations.

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Chapter 5
Point Source Controls for VOCs and SVOCs

Information about various control technologies whose primary use is to control air emissions of volatile organic compounds (VOCs) and semi-volatile organic compounds (SVOCs) is presented in this chapter. Control technologies addressed in this chapter are carbon adsorption, thermal oxidation, catalytic oxidation, condensers, internal combustion engines, biofilters, operational controls, membranes, and emerging technologies such as ultraviolet treatment. The discussion for each control technology includes a process description, applicability for remediation technologies, range of effectiveness, sizing criteria, and cost information.

5.1 Carbon Adsorption

5.1.1 Process Description

Carbon adsorption systems (CAS) are one of the most commonly used air pollution control devices for the reduction of VOC emissions from remediation processes. They are effective in removing a wide range of VOCs over concentrations from low ppbv to about 1,000 ppmv. The most common form of carbon used in CAS is granular activated carbon (GAC), though other adsorbents such as impregnated carbon, silica gel, or activated alumina may be used also. These alternate adsorbents typically cost more than GAC, but are more effective for certain corrosive gases or pollutants that do not have a high affinity for pure carbon (e.g., mercury, nickel, phosgene, or amines).

The physical principle behind any adsorption process is the Van der Walls attractive potential between the waste stream constituents and the GAC in the bed. The potential energy is given off as heat during adsorption. Since adsorption efficiency is an inverse function of temperature, the stream must be kept relatively cool. If the carbon is to be regenerated, then heat must be added to overcome the Van der Walls force, thus freeing the pollutants. The carbon then must be cooled prior to re-use, and the pollutants, once again airborne (or in some liquid solution), must be disposed of in some acceptable way. If the system is non-regenerable, then the carbon units themselves must be treated as solid waste and disposed of accordingly.

Carbon has a fixed capacity or number of active adsorption sites. As the adsorbing liquid/gas stream fills the sites in the adsorbent, a somewhat arbitrary, empirically-determined point is reached (called the "loading" point) where adsorption efficiency is decreased significantly. This is typically around 1 g VOC per 10 g carbon. If adsorption were continued beyond this point, then the "break through" point would be reached, and pollutants would no longer be controlled effectively. Eventually, "saturation" would be reached, where all sites are filled and virtually no adsorption occurs.

A number of CAS designs are commercially available. The three most common basic designs are canister systems with off-site regeneration, continuous regenerating systems, and dual bed systems with on-site batch regeneration as shown in Figures 5-1, 5-2, and 5-3, respectively. The canister system in Figure 5-1

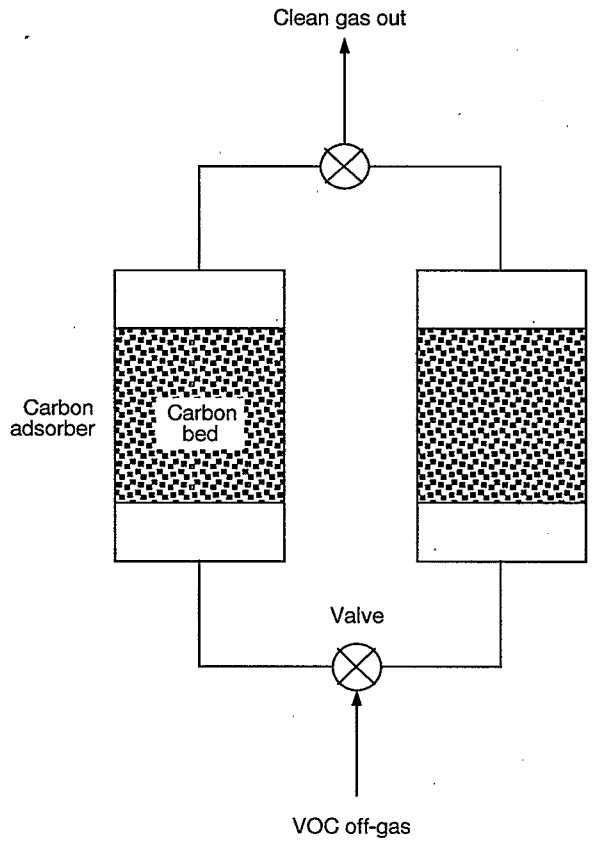


Figure 5-1. Schematic diagram of canister-based granular activated carbon adsorption system.

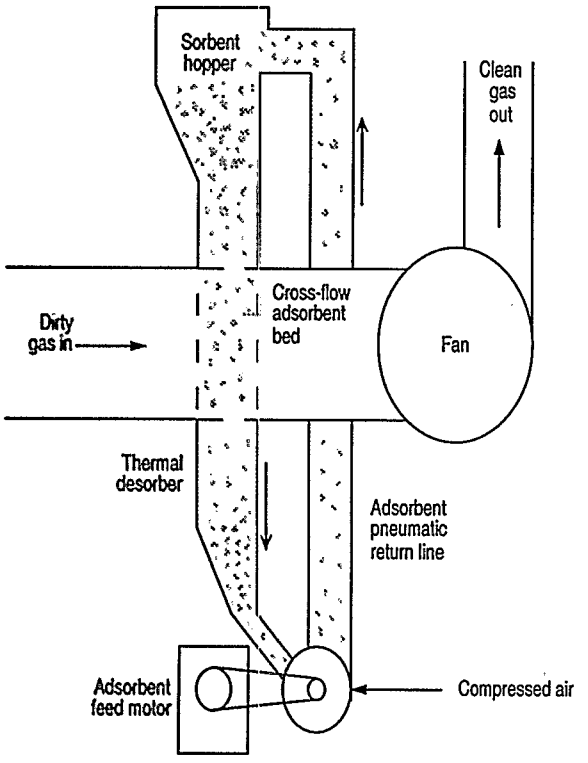


Figure 5-2. Schematic diagram of continuously regenerated carbon adsorption system.

shows two side-by-side canisters of activated carbon that can be used sequentially or in parallel. Carbon in 55-gallon drum canisters is available also. In Figure 5-2, a moving-bed system is illustrated, with adsorption occurring as the adsorbent falls through a baffle, while the waste stream passes across the baffle. The carbon is regenerated on its way back to the top of the baffle. These systems are used much less commonly than fixed-bed systems. In Figure 5-3, a standard fixed-bed system is shown, with two beds adsorbing while the third is desorbing. Regeneration typically is accomplished by passing steam through the carbon. The high temperature and water vapor strip most organic solvents from the carbon and the organics are captured with the condensed water leaving the system. Subsequent treatment is necessary to separate the organic fraction from the water before disposal or use of the solvent. A modification to steam regeneration is to use an inert gas to reactivate the carbon; an additional step (e.g., condensation) is required to separate the VOCs from the inert gas. Such systems are initially more expensive than steam regeneration systems, but potentially offer savings from reduced energy use and recovery of purer solvent.

The major components of a GAC control system include the pretreatment devices (de-humidifiers, absorbers, particulate filter, etc.), piping to carry the stream to the adsorbent, then the adsorption bed or canister followed by piping to other add-on controls or a stack. A regeneration unit is also present if the system uses regenerable technology; it can have either multiple-fixed beds or a moving bed. In the former, several beds usually are used in parallel, so that while some are being regenerated, others are in-line and adsorbing. The moving bed type is less common and the carbon is regenerated at one point while adsorbing at another.

The operational cycle for a carbon bed is adsorption, heat regeneration, drying, and cooling. The heat to regenerate the carbon must be greater than the heat released during adsorption. The operational cycle for a carbon canister is adsorption, replace-

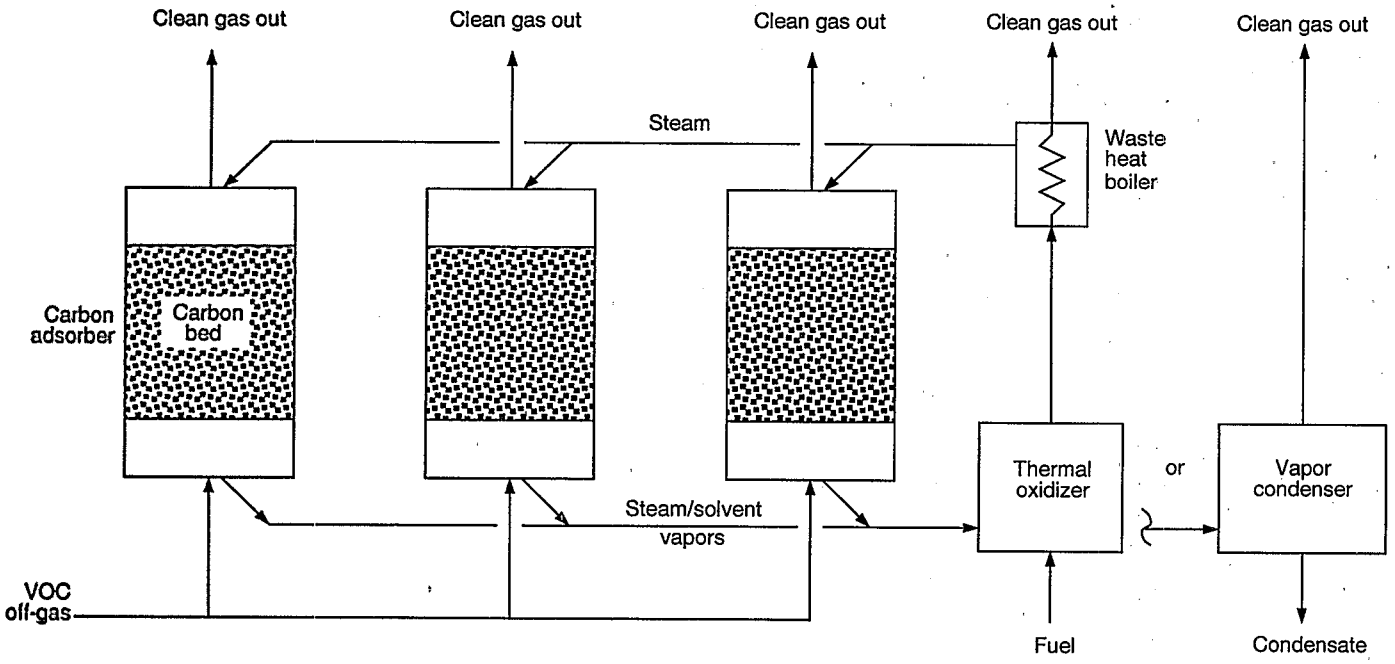


Figure 5-3. Schematic diagram of carbon adsorption system with on-site batch regeneration.

ment at the loading point, and either disposal or removal and subsequent off-site regeneration.

5.1.2 *Applicability to Remediation Technologies*

GAC is a likely candidate for the control for any site remediation involving a point source having low concentrations of VOCs emitted to the atmosphere. GAC systems are relatively cheap and easy to install, they can be either regenerable or disposable, and they handle many different types of contaminants. As one of the most widely-used control technologies, much technical information is available about these systems and there are numerous vendors.

For gas streams with VOC concentrations exceeding 1,000 ppmv, condensers, incinerators, or internal combustion engines become competitive in cost-effectiveness with GAC systems. GAC systems are also less efficient at higher temperatures or pressures. Further, they require low humidity in the incoming stream, since water binds to the active sites in the carbon. Plugging, fouling, and some corrosive gases also pose a problem for the adsorption of some waste stream constituents. Any of these drawbacks may be amended with pretreatment devices, although such pre-treatment usually will increase the total system cost.

The most substantial shortcoming of GAC systems is that only compounds with molecular weights in the 50 - 200 g/g-mol range have the proper adsorption properties. Also, pollutants are not destroyed, only transferred from one medium to another, inevitably leaving solid or liquid waste after treatment. In industrial applications, GAC systems often are used to capture and recycle valuable pure VOCs, but in remediation projects these VOCs usually are not of sufficient purity or value to warrant recycling. Disposal is almost always the final step.

Carbon canisters generally are used for remediation projects which are quite different from those appropriate for regenerating beds; cans usually are used for low volume, intermittent sources. If they are regenerated, it usually is done off-site by the carbon supplier. One problem that may occur for such systems is that they may be used past the effective adsorption point of the carbon and into saturation due to lack of monitoring and the disposable nature of canister carbon.

5.1.3 *Range of Effectiveness*

An unalterable limitation of adsorption is the molecular weight of the VOCs to be adsorbed. If the molecular weight of a VOC is too low the compound will not adsorb very readily. If the molecular weight is too high, the compound will be difficult to desorb from the carbon. This limitation can be circumvented to some degree by using different types of carbon. A typical range of effectively adsorbed molecular weights is between 50 and 200 g/g-mol. Other factors, such as polarity and molecular shape, may also affect adsorptivity.

A GAC system is most cost-effective when contaminant concentrations are low and the waste gas flowrate is low or variable. Carbon systems also are not readily available for flow rates exceeding 100,000 scfm. A properly operating GAC system at moderate flow rates and hazardous air pollutant (HAP) concentrations (e.g., ppm level) can have a removal rate of 70-99+%, depending on the pollutant and the operating temperature. As with other control devices, higher efficiencies are achieved at the cost of higher pressure drops across the adsorption unit.

Pretreatment may ameliorate other limitations of the technology. Certain operating conditions should be met: no fouling compounds (including solid or liquid particulates), less than 1,000 ppmv inorganics, and relative humidity below 50%. The efficiency of VOC adsorption decreases rapidly as the relative humidity rises above 50%. The relative humidity of the gas stream can be lowered by raising the temperature of the gas stream, but this can affect removal efficiencies. For adsorption to occur readily, the waste stream must be at a moderate temperature (100 - 130°F). Outlet VOC concentrations usually are required to be less than 10 - 50 ppmv. The effectiveness of CAS for various classes of compounds is summarized in Table 5-1.

5.1.4 *Sizing Criteria/Application Rates*

GAC systems are capable of handling concentrations from the ppb level to 25% of the lower explosive limit (LEL). For sizing a system, the total carbon requirement is the most important parameter. This will be a function of the volumetric carbon flow rate, VOC concentration, and VOC molecular weight of the waste stream, and carbon adsorption capacity, adsorption time, the removal efficiency required, and the number of beds. (For more detailed sizing discussions, see U.S. EPA, 1991 or U.S. EPA, 1990). For a fixed-bed adsorption system with a specific adsorption time, t, the following equation may be used (U.S. EPA, 1991):

$$W_c = 2(6.0\times10^{-5}) \cdot t \cdot Q \cdot C \cdot \frac{E}{100} \cdot \left(\frac{D_{HAP}}{A}\right) \qquad \text{(Eq. 5-1)}$$

where:

W_c = Weight of carbon required (lb);
t = Adsorption cycle time, (hr);
Q = Emission stream flow rate (scfm);
D_{HAP} = HAP density (gas)(lb/ft^3);
A = Adsorption capacity of carbon bed, (lb HAP/ 100 lb carbon);
C = Inlet concentration of HAPs (ppmv);
E = Removal efficiency (%)
2 = Factor for a two-bed system; and

6.0×10^{-5} = Conversion factor $\left(\frac{\text{min}}{\text{hr} \cdot \text{ppmv}}\right)$

A typical default value for A is 10. Adsorption capacities for some HAPs by a commonly-used type of activated carbon are given in Table 5-2. Adsorption capacities also can be calculated as a function of inlet concentration, temperature, etc. (see U.S. EPA, 1990).

5.1.5 *Cost Estimating Procedure*

The U.S. EPA has published detailed cost estimation procedures for GAC systems (U.S. EPA, 1990). Only a rough outline of that discussion is given in this section, and it should only be

Table 5-1. Applicability of CAS for Selected Contaminants

Contaminant class	Examples	CAS typically effective?	Comments
Aromatics	benzene, toluene	Yes	Standard application of GAC
Aliphatics	hexane, heptane	Yes	Standard application of GAC
Halogenated hydrocarbons	chloroform	Yes	Standard application of GAC
Light Hydrocarbons (MW < 50 or BP < 20°C)	methane, freon	No	Will not adsorb
Heavy Hydrocarbons (MW > 200 or BP > 200°C)	glycols, phenols	No [a]	Will not desorb or will not be adsorbed due to steric constraints
Oxygenated compounds	ketones, aldehydes	No [b]	Fire hazard
Certain reactive organics	1,1,1-trichloroethane, organic acids	No	Will react with and degrade GAC
Bacteria	coliform	Yes	Requires silver-impregnated GAC
Radioisotopes	^{131}I	Yes	Requires coconut-shell carbon
Certain inorganics	hydrogen sulfide, ammonia, hydrochloric acid	Yes	Requires impregnated GAC
Mercury	—	Yes [c]	Requires impregnated GAC

[a] Non-regenerable carbon systems may work.
[b] Not all oxygenated compounds are a problem.
[c] High levels of sulfur dioxide may "blind" the charcoal and reduce Hg removal efficiencies.

used as a preliminary cost-estimating tool. The total costs of a GAC system are broken down into three categories:

1. Equipment costs, including carbon and containers;
2. Installation, engineering, and indirect costs associated with purchasing and installing the system; and
3. Annual expenses.

These costs will vary depending on whether canister or beds are used, and also whether corrosive or non-corrosive gases are present in the waste stream.

Equipment Costs

Note: The costs in this section and throughout the document have been converted to 1992 dollars, assuming 5% per year compounded inflation. The cost for a carbon adsorption system is obviously a function of the total carbon requirement as well as other factors. However, the cost can be estimated strictly on the basis of the carbon, within some limitations. Primarily, this approach assumes that a non-corrosive waste stream is being used, so that a less-expensive stainless steel and inexpensive carbon may be used. In that case, the following formulae hold (Vatavuk, 1990):

Price for fixed bed regenerable: $P = 173\ W^{(.848)}$ $350 \leq W < 14{,}000$ lb (Eq. 5-2)

Modular adsorbents: $P = 6.24\ W^{(.968)}$ $110 \leq W < 5{,}700$ lb (Eq. 5-3)

Custom bed: $P = 44.0\ W^{(.86)}$ $14{,}000 \leq W < 222{,}000$ lb (Eq. 5-4)

W is the weight of carbon per unit.

Installation Costs

A general rule for carbon adsorption units is that installation costs are about 25% of the total unit for a packaged-type device, or 61% for a custom built device (Vatavuk, 1988). For the capital cost factors for any buildings, power, and other general components of the carbon adsorption system, refer to Section 5.2.5.

Annual Expenses

The VOC concentrations where GAC systems are cost effective relative to fume incineration are illustrated in Figure 5-4 (AMCEC, 1991). Systems have a return on investment in two to three years for industrial applications (AMCEC, 1991). Since systems have a 10-year average life-span, a salvage value is likely after a remediation project is completed. The carbon itself only lasts two years, and the typical cost for carbon is $1.80 to $2.00 per pound, depending on the total weight purchased (DCI, 1991). Other grades of carbon and impregnated carbons will have higher costs.

Relatively detailed cost estimating tables also have been developed (U.S. EPA, 1990). Estimation procedures for annualized carbon costs for fixed bed carbon adsorbers are given in Table 5-3. A cost-effectiveness diagram giving a rough guide for the applicability of CAS systems for varying vapor concentrations is presented in Figure 5-5. Non-regenerable systems are compared with automated and manual regenerable systems in this figure.

Annual costs for canister systems containing 150 lbs of BPL carbon are:

Quantity	Cost, each can
1-3	$920
4-9	$880
10-29	$830
>30	$780

For the case of waste streams involving corrosive gases, the system costs can be expected to be twice those of a regular system which approximates the increased cost of both the special adsorbent, as well as all metal work which must be resistant to the corrosive agents.

Table 5-2. Reported Operating Capacities for Selected Organic Compounds

Compound	Average inlet concentration (ppmv)	Adsorption capacity [a] (lb VOC/100 lb carbon)
Acetone	1,000	8
Benzene	10	6
n-Butyl acetate	150	8
n-Butyl alcohol	100	8
Carbon tetrachloride	10	10
Cyclohexane	300	6
Ethyl acetate	400	8
Ethyl alcohol	1,000	8
Heptane	500	6
Hexane	500	6
Isobutyl alcohol	100	8
Isopropyl acetate	250	8
Isopropyl alcohol	400	8
Methyl acetate	200	7
Methyl alcohol	200	7
Methylene chloride	500	10
Methyl ethyl ketone	200	8
Methyl isobutyl ketone	100	7
Perchloroethylene	100	20
Toluene	200	7
Trichloroethylene	100	15
Trichlorotriofluoroethane	1,000	8
Xylene	100	10

[a] Adsorption capacities are based on 200 scfm of solvent-laden air at 100° F (per hour).

Source: Marzone and Oakes, 1973.

5.2 Thermal Oxidation

5.2.1 Process Description

Thermal oxidation, also known as thermal incineration, is a commonly used approach for controlling volatile organic compound (VOC) emissions in waste gases. In thermal oxidation, contaminant-laden waste gas is heated to a high temperature (above 1000°F) where the VOC contaminants are burned with air in the presence of oxygen to form carbon dioxide and water.

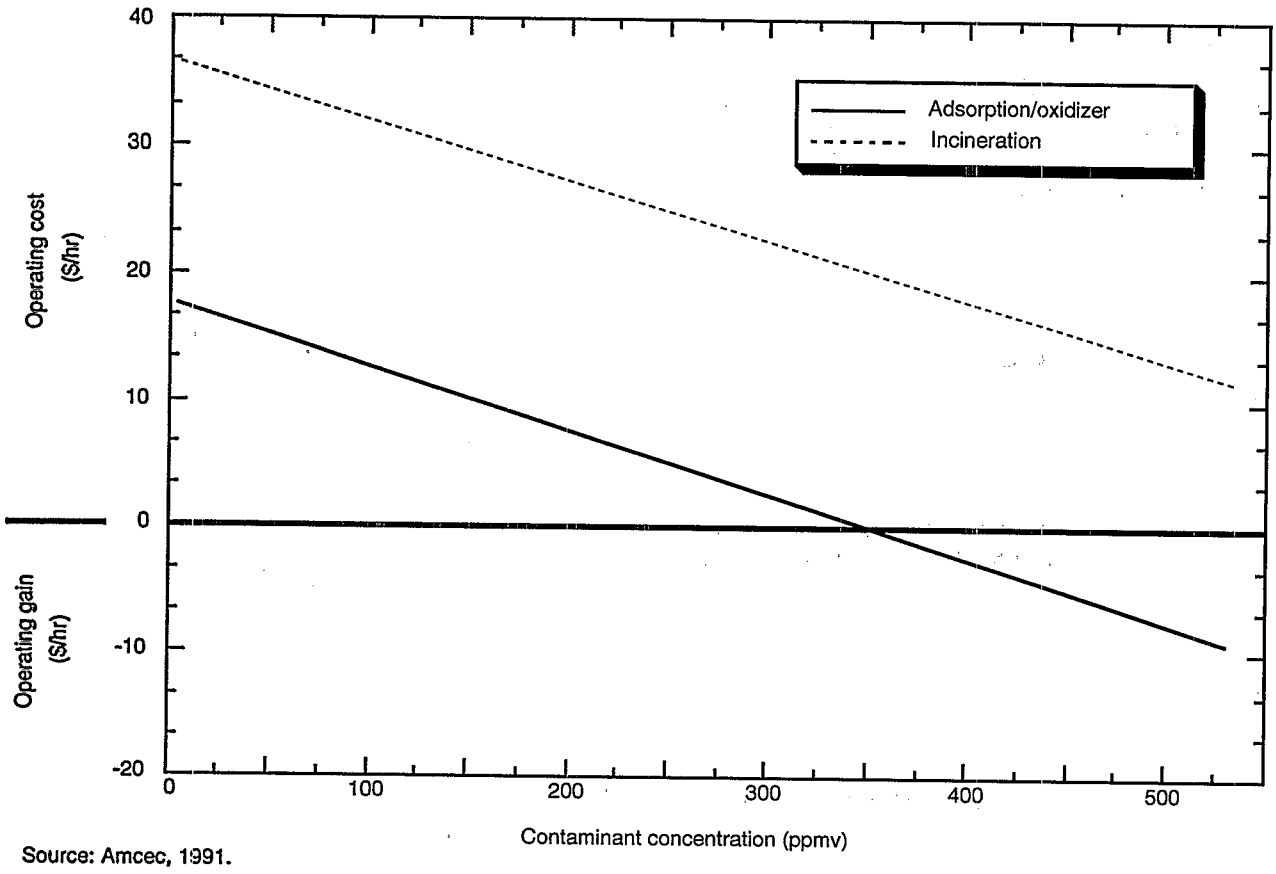
Figure 5-6 is a simplified schematic of a thermal oxidation system. This type of system, which is designed only for handling waste gases and not liquids or solids, often is referred to as a fume incinerator. The three key design parameters for fume incinerators are commonly called the "Three T's": temperature, residence time (also referred to as "retention time" or "dwell time") and turbulence. The "Three T's" have an interrelated effect on combustion performance. To achieve good combustion, the waste gas must be held for a sufficient time (usually 0.3-1.0 seconds) at combustion temperatures 100°F or more above the auto-ignition temperatures of the contaminants in the waste gas. Additionally, turbulent flow conditions must be maintained in the incinerator to ensure good mixing and complete combustion of the waste contaminants.

In a typical fume incinerator, waste gas is introduced into the combustion chamber as shown in Figure 5-6. In the combustion chamber the waste gas temperature is raised to the appropriate combustion range by burning auxiliary fuel. Because of the high combustion temperatures (1,000 to 1,600°F for most VOCs), refractory-lined chambers are required. At these temperatures, 95 to 99 percent of the VOCs in the waste gas are combusted (Katari, et al., 1987a).

In most cases, the flue gas from the combustor then passes through a heat exchanger where a portion of its sensible heat is used to preheat the incoming waste gas. The flue gas then is vented to the atmosphere through a stack downstream of the heat exchanger.

One way in which fume incineration systems differ from one another is in the type of heat recovery used. The heat exchanger design is important because it determines the amount of heat recovery. In turn, the fraction of heat which can be recovered from the flue gas will affect directly the amount of fuel required to operate the incinerator. Typically, two types of heat exchange systems are used: recuperative heat exchange and regenerative heat exchange. In a recuperative heat exchanger, hot gas travels on one side of a partition while cold gas passes on the other. Heat is transferred directly from the hot side to the cold side through the partition. This is the most common type of heat exchanger. Both counter-flow and cross-flow exchanger designs are used for this purpose. For a recuperative exchanger, heat recovery typically varies from 30-75%.

In a regenerative heat exchange system, energy is transferred indirectly from the hot stream to the cold stream. First, the hot flue gas is passed through a ceramic matrix to recapture as much of the energy as possible. The heated ceramic then is used to preheat the contaminated flue gas, which in turn is run through a second matrix to recapture its energy before being exhausted to the atmosphere. Vendors of regenerative systems typically guar-



Source: Amcec, 1991.

Figure 5-4. Fuel cost/gain vs. concentration of carbon and incineration systems at 50,000 scfm of solvent-laden air.

antec 80-95% heat recovery. As a result of the high heat recovery, fuel costs tend to be low compared to traditional thermal incinerators using recuperative gas-gas heat exchange for energy recovery. However, because the technology is relatively new, equipment and other capital costs tend to be high. For Superfund remediations that are short in duration (e.g., <36 months), the high capital and installed costs often make regenerative incineration unattractive since the period over which the equipment is depreciated is brief. The economics for regenerative thermal incineration are most favorable for the treatment of a dilute, large volume waste gas, since it would not require large amounts of auxiliary fuel. In industrial applications, regenerative thermal incineration is commonly used for controlling VOC emissions from process point sources such as paint spray booths or solvent degreasers.

An alternative method of heat recovery, which may be practical in some cases, is to produce low-pressure steam in a waste heat boiler. This alternative is only used in cases where low pressure steam is needed at or near the remediation site.

5.2.2 *Applicability to Remediation Technologies*

The applicability of thermal incineration depends on the concentration of oxygen and contaminants in the waste gas. The waste gas composition will determine the auxiliary air and fuel requirements. These requirements in turn will have a strong influence on whether thermal oxidation is an economical approach for controlling air emissions.

For most remediation technologies used at Superfund sites, the off-gases that require control are dilute mixtures of VOCs and air. The VOC concentration of these gases tends to be very low, while their oxygen content is very high. In this case auxiliary fuel is required but no auxiliary air is needed. However, if the waste gas has a VOC content greater than 25 percent of its LEL (e.g., some SVE-based clean-ups), auxiliary air must be used to dilute the contaminant to below 25 percent of its LEL prior to incineration.

If the remediation activity generates an off-gas that has a low oxygen content (below 13 to 16 percent), ambient air must be used to raise the oxygen level to ensure the burner flame stability. In the rare case when the waste gas is very rich in VOCs, using it directly as a fuel may be possible.

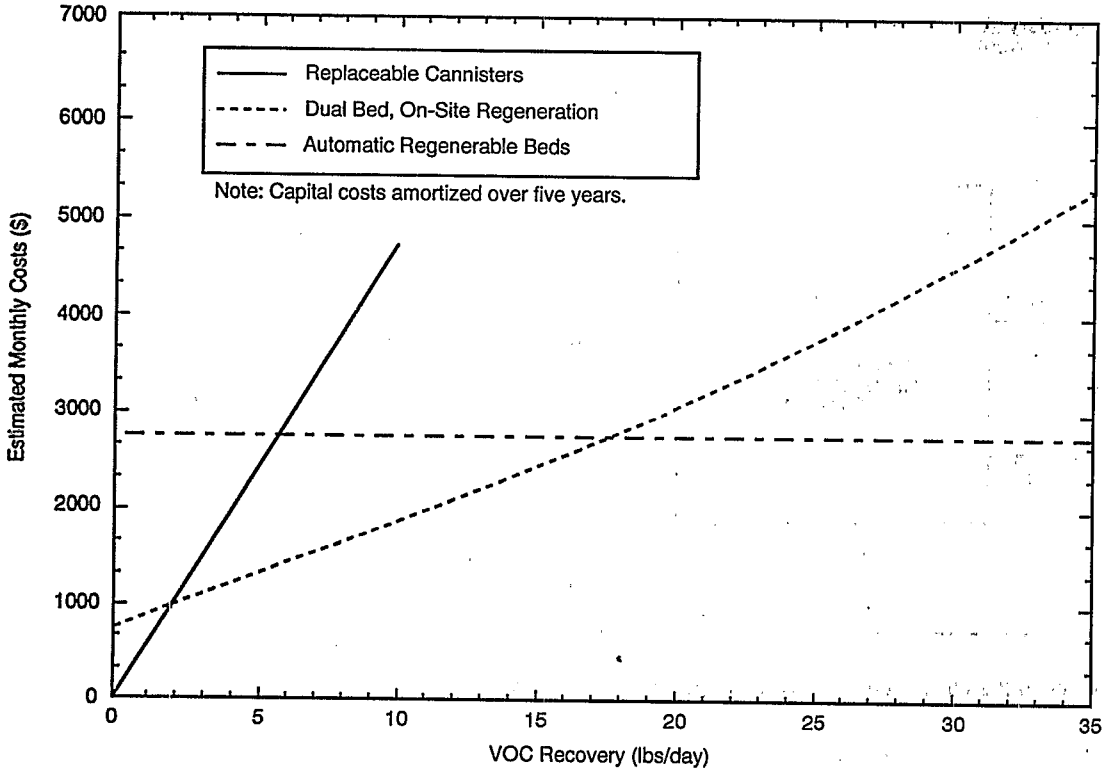
Information is presented in Table 5-4 for determining the suitability of a waste gas for incineration and establishing its auxiliary fuel and oxygen requirements. This same information is shown in Figure 5-7 in an alternative format.

Table 5-3. Equations for Carbon Adsorption Annualized Cost Estimate

Cost item	Equation
I. Direct costs	
a. Steam costs, C_s	$C_s = 3.5 \times 10^{-3} M_{VOC} (HRS) P_s$
	where: M_{voc} = Inlet VOC loading, lbs/hr HRS = Operating hours per year P_s = Steam price, $/10^3 lbs
b. Cooling water cost, C_{cw}	$C_{CW} = 3.43 C_s P_{cw} / P_s$
	where: P_{cw} = Cooling water price, $/10^3 gal (assumed to equal $0.225/10^3 gal)
c. Electricity	
1. Pressure drop, P_b, for regenerative systems (based upon superficial velocity of 60 ft/min)	$P_b = t_b (2.606)$
	where: t_b = Bed thickness, ft. carbon
	$t_b = \frac{0.0166 C_{req}{}^a}{LD}$
	C_{req} = carbon required L = vessel length D = vessel diameter
2. Pressure drop, P_c, for canister systems	$P_c = 0.0471 Q_c + 9.29 \times 10^{-4} Q_c^2$
	where: Q_c = Emission stream flowrate, ft^3/min
3. System fan horsepower, h_{psf}	$h_{psf} = 2.5 \times 10^{-4} (P_b \text{ or } P_c + 1) Q_c$
4. Bed cooling/drying fan, h_{dcf}	$h_{dcf} = 1.86 \times 10^{-4} (FR_{dcf}) (P_b + 1) (\theta_{dcf})$
	where: FR_{dcf} = (100) (C_{req}) / $\theta_{dry\text{-}cool}$ θ_{dcf} = cooling/drying cycle time, hr θ_{dcf} = 0.4 (θ_{reg}) (NA) (HRS) /θ_{ad} θ_{reg} = regeneration cycle time, hr θ_{ad} = adsorption cycle time, hr
5. Cooling water horsepower, h_{pcw}	$h_{pcw} = (2.52 \times 10^{-4} q_{cw} HS) / n$
	where: q_{cw} = Cooling water flowrate, gal/min H = Required head (usually 100 ft H_2O) S = Specific gravity of fluid n = Pump and motor efficiency
6. Required electricity usage per year, kWh	$kWh = 0.746 (h_{psf} + h_{pcw}) HRS + h_{dcf}$
d. Carbon replacement cost, CRC	$CRC = CRF_c (1.08 C_c + C_{cl})$
	where: CRF_c = Capital recovery factor for carbon C_c = Carbon cost, $/lb C_{cl} = Replacement labor cost, $/lb (typically about $0.05/lb)

[a] Assumes a two-bed system.

Source: U.S. EPA, 1991.



Source: U.S. EPA, 1991.

Figure 5-5. Activated carbon systems cost comparison.

If halogenated VOCs are present in the influent gas stream, then hydrochloric acid (HCl) may be produced in the thermal incinerator. HCl emissions are regulated and off-gas controls such as packed-column gas absorbers for HCl and other acid gases may be required.

5.2.3 Range of Effectiveness

Thermal incineration is a well-established method for controlling VOC emissions in waste gases. The control efficiency (also referred to as destruction and removal efficiency or DRE) for thermal incineration is typically 98% or higher. Factors which affect DRE include the three "T's" (temperature, residence time, and turbulence) as well as the type of contaminants in the waste gas. With a 0.75-second residence time, the suggested thermal incinerator combustion temperatures for waste gases containing nonhalogenated VOCs are 1,600°F and 1,800°F, respectively for 98 and 99 percent VOC destruction efficiencies. Higher temperatures (about 2,000°F) and longer residence times (approximately 1 second) are required for achieving DRE's of 98% or more with halogenated VOCs (Katari, et al., 1987a, U.S. EPA, 1991).

[1] In this discussion the term flowrate implies the flowrate at standard conditions which are assumed to be 60°F and 1 atm, following standard engineering practices.

5.2.4 Sizing Criteria

To size a thermal incinerator with a given residence time and estimate the capital and annualized costs, three pieces of data are required:

1) The flue gas flow rate;
2) The auxiliary fuel and air requirements;
3) Inlet VOC concentration (or heat content);
4) Inlet temperature; and
5) Combustion temperature.

Flue Gas Flowrate

For dilute waste gases the flue gas flowrate[1] is approximately equal to the waste gas flowrate. In cases where auxiliary air is required, the flue gas flowrate is roughly equal to the sum of the waste gas flowrate and the auxiliary air flowrate. The flue gas flowrate can be used in many correlations to size the incinerator and estimate equipment costs.

Auxiliary Fuel Requirement

The auxiliary fuel is usually the largest operating expense for a thermal incineration system. The fuel requirement can be estimated by making a heat balance around the incinerator system. The approach described below assumes heat losses to be negligible. In many cases this assumption is not valid and the fuel

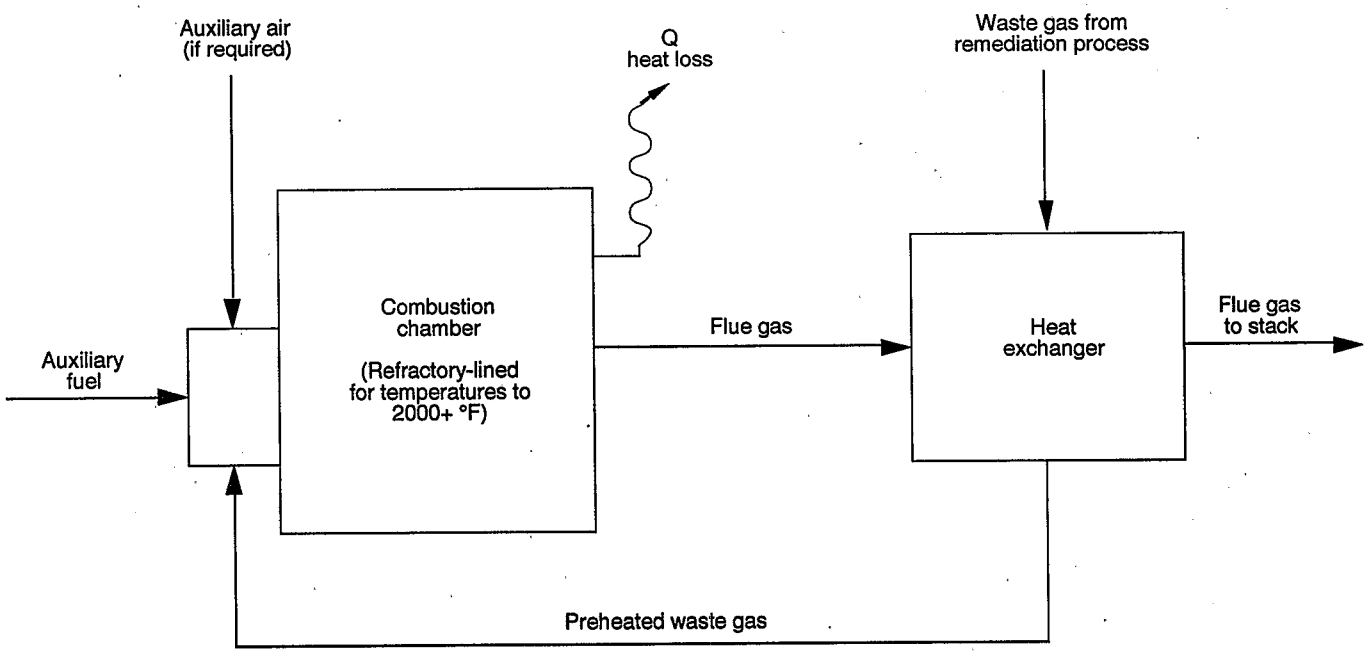
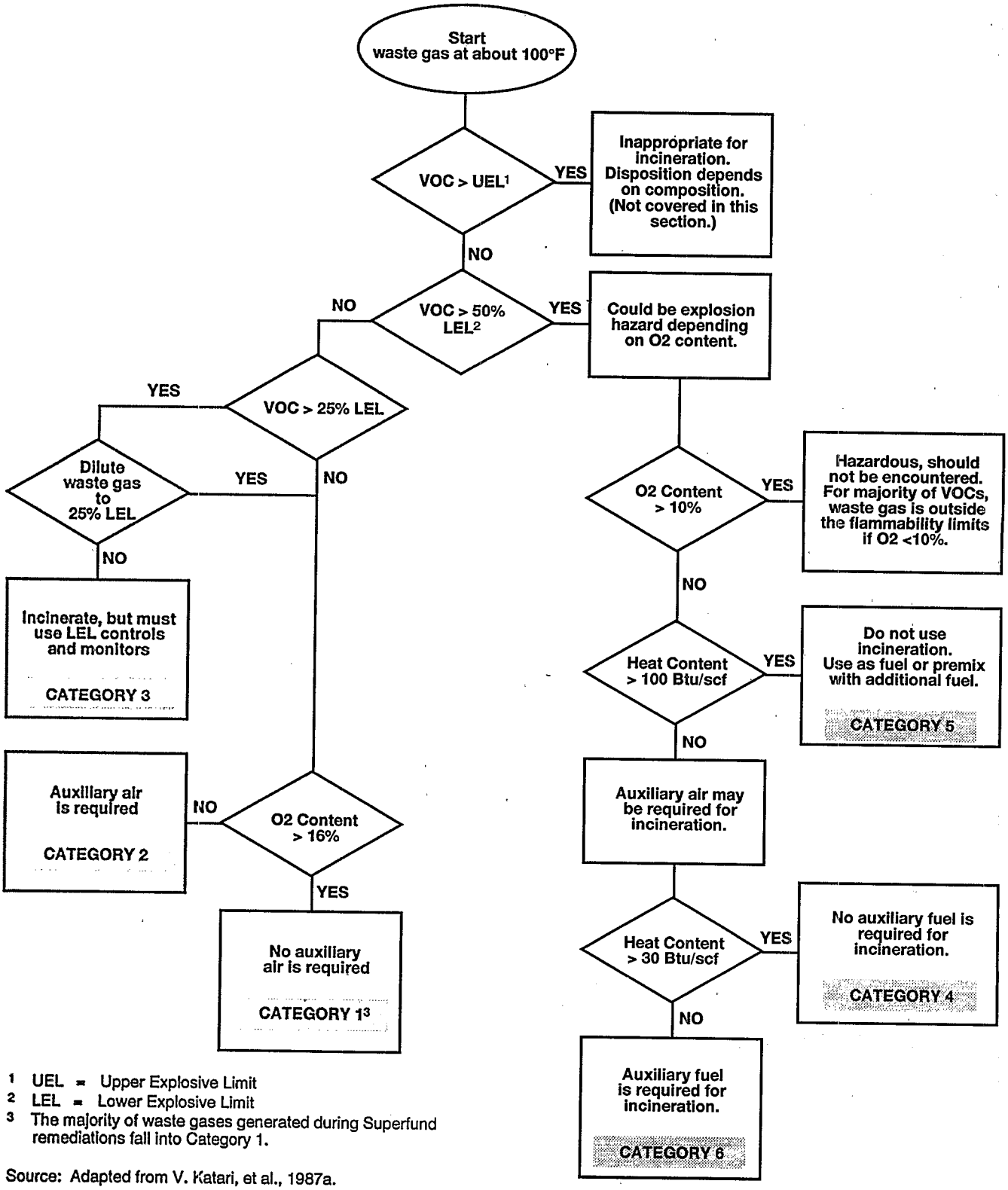


Figure 5-6. Schematic of thermal incineration system with recuperative heat exchanger.

Table 5-4. Categorization of Waste Gas Streams

Waste gas					
Category	Composition	O_2	VOC	Heat content	Auxiliaries and other requirements
1	Mixture of VOC, air, and inert gas	>16%	<25% LEL	<13 Btu/ft ^{3}	Auxiliary fuel is required. No auxiliary air is required.
2	Mixture of VOC, air , and inert gas	16%	25-50% LEL	13-26 Btu/ft ^{3}	Dilution air is required to lower the heat content to <13 Btu/ft^3. (Alternative to dilution air is installation of LEL monitors.)
3	Mixture of VOC, air and inert gas	<16%	—	—	Treat this waste stream the same as categories 1 and 2, except augment the portions of the waste gas used for fuel burning with outside air to bring its O_2 content to above 16%.
4	Mixture of VOC and inert gas	0-neglibible	—	<100 Btu/scf	Oxidize it directly with a sufficient a mount of air.
5	Mixture of VOC and inert gas	0-neglibible	—	>100 Btu/scf	Premix and use it as a fuel.
6	Mixture of VOC and inert gas	0-neglibible	—	Insufficient to raise gas temperature to the combustion temperature	Auxiliary fuel and combustion air for both the waste gas VOC and fuel are required.

Source: Adapted from Katari, et al., 1987a.



1 UEL = Upper Explosive Limit
2 LEL = Lower Explosive Limit
3 The majority of waste gases generated during Superfund remediations fall into Category 1.

Source: Adapted from V. Katari, et al., 1987a.

Figure 5-7. Flow chart for categorization of a waste gas to determine its suitability for incineration and need for auxiliary fuel and air.

requirements may be 10% higher to account for heat losses. The heat balance requires the following data:

1) The waste gas and flue gas flowrates (lb-mol/hr);

2) The incinerator combustion temperature (typically 1,600-2,000°F);

3) The waste gas temperature as it comes from the remediation system before it goes through a heat exchanger;

4) The concentration of VOCs in the waste gas;

5) The approximate heat capacity of the flue gas (Btu/lb-mol/°F); and

6) The fraction of the total heat release which is recovered in the heat exchange system.

Figure 5-8 shows a simple heat balance around an incinerator system. From the heat balance the fuel requirement (in MMBtu/hr) can be estimated as shown below:

$$Q_{fuel} = (1 - \eta) \cdot (Q_{sens} - Q_{rel}) \qquad \text{(Eq. 5-5)}$$

where:

Q_{fuel} = Fuel heat required, MM Btu/hr;
η = Fraction of heat recovered in the heat exchanger;[2]
Q_{sens} = Total sensible heat required to bring waste gas and auxiliary air to combustion temperature, MMBtu/hr; and
Q_{rel} = Heat release from complete oxidation of VOCs in the waste gas stream, MMBtu/hr.

Equations 5-6 and 5-7 can be used to estimate the terms required for Equation 5-5. Q_{sens} is calculated as indicated below:

$$Q_{sens} = m \cdot Cp \cdot (T_{comb} - T_{amb})/10^6 \qquad \text{(Eq. 5-6)}$$

where:

Q_{sens} = Total sensible heat required to the bring waste gas and auxiliary air to combustion temperatures, MM Btu/hr;
m = Mass of flue gas (waste gas plus auxiliary air), lbmol/hr;
Cp = Heat capacity of gas, Btu/lbmol/°F[3];
T_{comb} = Combustion temperature, °F; for non-halogenated volatiles, default temperature is 1,600°F; for halogenated volatiles use 2,000°F; and
T_{amb} = Ambient air temperature, °F.

[2] For recuperative heat exchange, η is typically 0.35-0.70. For regenerative heat exchange, η may be as high as 0.80-0.92.

[3] A rough estimate for Cp is to use the Cp of air which is approximately 6.91 Btu/lb-mol/°F.

Q_{rel}, which is the heat release from combusting the VOCs in the waste gas, can be estimated as follows:

$$Q_{rel} = m \cdot C_i \cdot H_{comb}/10^6 \qquad \text{(Eq. 5-7)}$$

where:

Q_{rel} = Heat release from complete oxidation of VOCs in waste gas stream, MM Btu/hr;
m = Flowrate of flue gas (waste gas plus auxiliary air), lbmol/hr;
C_i = Concentration of VOCs, ppmv;
H_{comb} = Heat of combustion of VOCs in the waste gas, MM Btu/lbmol.[4]; and
10^6 = Conversion Factor (ppmv).

Table 5-5. Typical Pressure Drops [a,b] for an Incineration System

Equipment type	Pressure drop (in. H_2O)
Thermal incinerator	4"
Heat exchanger 35% efficiency	4"
Heat exchanger 50% efficiency	8"
Heat exchanger 70% efficiency	15"

[a] Total system pressure drop equals the sum of pressure drops across all pieces of equipment in the system.
[b] This table is taken from V. Katari, et al., 1987a.

System Pressure Drop

The total pressure drop for an incinerator depends on the type of equipment included in the system as well as other design considerations. The total pressure drop across an incinerator system determines the waste gas fan size and horsepower requirements, which in turn determine the fan capital cost and electricity consumption (Katari, et al., 1987a).

An accurate estimate of system pressure drop would require complex calculations. A preliminary estimate can be made using the approximate values listed in Table 5-5. The system pressure drop is the sum of the pressure drops across the incinerator and the heat exchanger plus the pressure drop through the duct work.

The pressure drop can then be used to estimate the power requirement for the waste gas fan using the empirical correlation given below (U.S. EPA, 1990):

$$\text{Power} = 1.17 \cdot 10^{-4} \cdot V \cdot P/\varepsilon \qquad \text{(Eq. 5-8)}$$

where:

Power = Fan power requirement, kW-hr;
V = Waste gas flowrate, scfm;
P = System pressure drop, inches of water column; and
ε = Combined motor fan efficiency, dimensionless (approximately 60%).

[4] A rough estimate for H_{comb} is to use the heat of combustion of benzene which is approximately 1.42 MMBtu/lb-mol. Values for H_c for various VOCs are also available in standard chemical engineering reference books.

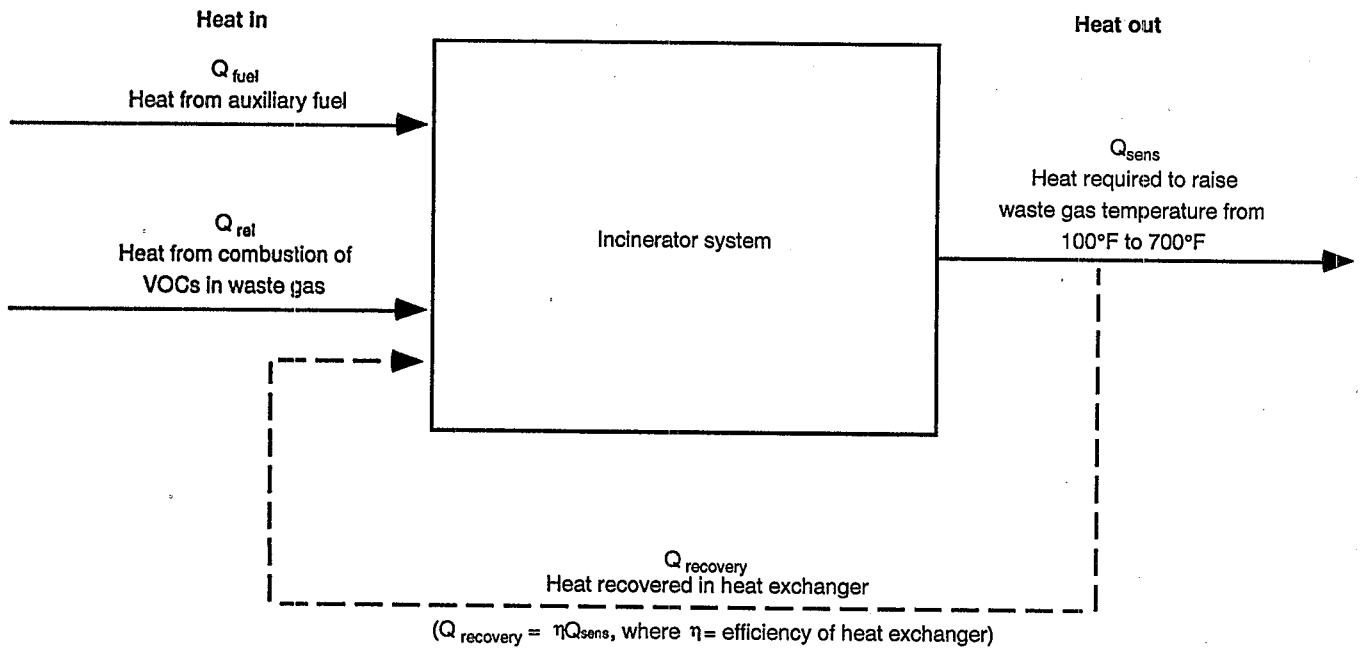
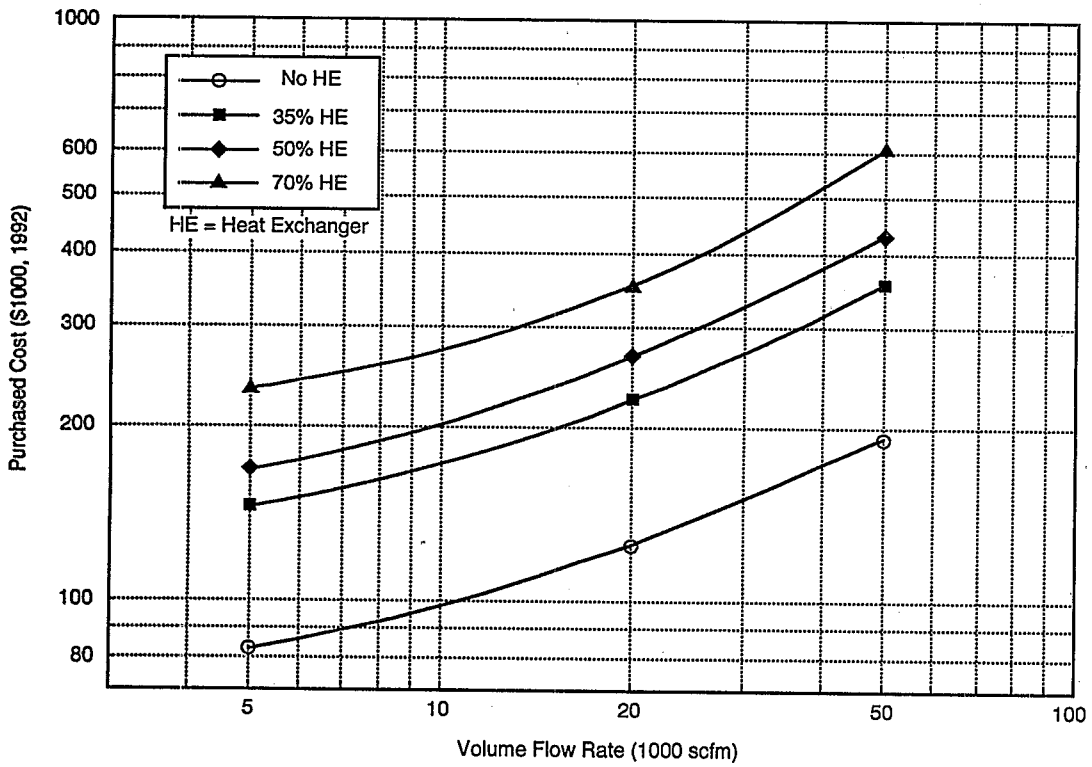


Figure 5-8. Incinerator heat balance.



Source: Adapted from V. Katari, et al., 1987b.

Figure 5-9. Thermal incinerator equipment cost estimates.
(Source: Adapted from V. Katari, et al., 1987b.)

5.2.5 *Cost Estimating Procedure*

The process of estimating capital and annual expenses for an incineration system can be divided into three parts. Estimates must be made for the following:

1) Equipment costs including incinerator, stack, and controls;

2) Installation, engineering, and indirect costs associated with purchasing and installing the control equipment; and

3) Direct and indirect annual expenses.

Equipment Costs

A typical incinerator system may include the following components: (1) a waste gas fan; (2) a refractory chamber with burner; (3) heat recovery equipment; (4) controls, instrumentation, and control panel; and (5) a stack. In addition, other equipment such as ductwork may be required to integrate the incinerator with the remediation process. The equipment costs for an incineration system generally can be estimated two ways: 1) by obtaining quotations from vendors, or 2) by using generalized cost correlations available in the literature.

The purchased cost of a typical incinerator system will vary widely depending on several design factors. Consequently, caution is required when using generalized cost correlations. Among the factors that influence the purchased cost of a thermal incineration system are the supplier's design experience, materials of construction, instrumentation, the type of heat exchanger used, and the nature of the installation (i.e., Do any factors exist that make installing the equipment unusually difficult?)

Thermal incinerator equipment costs are presented in Figure 5-9 as a function of flue gas flowrate at standard conditions of 60° and 1 atm (absolute). This figure is adapted from an article by Katari, et al., 1987b which used cost information from incinerator manufacturers to develop cost correlations. The equipment costs given represent the cost for a complete incineration system including a combustion chamber with burner, waste gas fan, inlet and outlet plenums, prepiping, prewiring, instrumentation and controls, a 10-ft stack, and in the case of heat recovery, a primary heat exchanger. Additional cost information is available in Vatavuk, 1990 and U.S. EPA, 1990. Cost estimates for systems to treat less than 500 scfm should be obtained directly from vendors.

Installation, Engineering, and Indirect Costs

The total capital investment (TCI — equipment costs plus installation, engineering, and indirect costs) for an incineration system can vary widely as a function of the total equipment cost. The TCI for a small skid-mounted unit to be placed at a preprepared site may be only 150-200% of the equipment cost. On the other hand, for a custom installation requiring extensive site-work (e.g., a typical Superfund site), the TCI may run as high as 300-400% of the purchased equipment cost.

One method for generating an estimate of installation, engineering, and indirect costs is to use the factor approach presented in Table 5-6 (Katari, et al., 1987b). Based on the approach given in this table, the TCI is approximately 160% of equipment costs, plus any costs for site preparation and construction.

Annual Expenses

Annual costs for incinerators can be estimated from factors given in Table 5-7. Determining these expenses requires an extensive amount of site-specific data. Fuel costs are typically the major direct annual cost. The system capital recovery is typically the largest indirect expense. Additional costs may be incurred due to monitoring requirements and permit activities.

5.3 Catalytic Oxidation

5.3.1 *Process Description*

Catalytic oxidation (also known as catalytic incineration) is a commonly applied combustion technology for controlling VOC emissions in waste gases. In catalytic oxidation a contaminant-laden waste gas is heated with auxiliary fuel to between 600 and 900°F. The waste gas is then passed across a catalyst where the VOC contaminants react with oxygen to form carbon dioxide and water.

Except for the addition of a noble or base metal catalyst, catalytic oxidizers are similar to thermal oxidation systems in their basic design and operation (see Section 5.2). For catalytic oxidation, the "Three T's" (temperature, residence time, and turbulence) are also important design variables. In addition, the catalyst type has significant effect on the system performance and cost.

A typical catalytic oxidation system is shown in Figure 5-10. As the figure shows, the waste gas stream is usually first passed through a primary heat exchanger to recover heat from the exhaust gases. Additional heat is then added to the waste gas by a natural-gas-fired or electric preheater. From the preheater the waste gas then passes into the catalyst bed.

The catalyst bed (or matrix) is generally a metal-mesh mat, ceramic honeycomb, or other ceramic matrix structure designed to maximize catalyst surface area. Catalysts may also be in the form of spheres or pellets which may operate in either a fixed-bed or fluidized-bed configuration. It is important that the preheat temperature not be too high regardless of the type of catalyst. The preheat temperature and the temperature rise across the catalyst due to combustion must not produce temperatures which are outside the recommended operating range for the catalyst. This could cause the catalyst bed to lose activity.

Downstream of the catalyst bed the hot exhaust gas passes through a heat exchanger where it gives up heat to the inlet gas streams. In a catalytic oxidation system recuperative heat exchange is used. Catalytic systems using regenerative heat exchange are in the developmental stage. In some systems a secondary heat recovery system such as a waste heat boiler may also be used.

5.3.2 *Applicability to Remediation Technologies*

The applicability of catalytic oxidation depends primarily on waste gas composition. As described in the preceding section on thermal incineration, waste gas composition will determine the

Table 5-6. Cost Factors for Thermal Incinerator Capital Costs

Cost Item	Cost factor (fraction of indicated cost)
Direct costs	
Purchased equipment	
Incinerator and auxiliary equipment	A
Instrumentation and controls	0.10 A
Taxes	0.03 A
Freight	0.05 A
Total equipment costs (TEC):	B = 1.18 A
Installation	
Foundations and supports	0.08 B
Erection and handling	0.14 B
Electrical	0.04 B
Piping	0.02 B
Painting	0.01 B
Insulation	0.01 B
Site preparation	SP
Building/construction	Bldg
Total Installation Costs (TIC):	0.30 B + SP + Bldg
Total Direct Cost (TEC + TIC):	1.30 B + SP + Bldg
Indirect costs	
Engineering and supervision	0.10 B
Construction/field expenses	0.05 B
Construction fee	0.10 B
Start-up	0.02 B
Performance test	0.01 B
Contingency	0.03 B
Total Indirect Costs:	0.21 B
Total Capital Investment	**1.61 B + SP + Bldg**

Source: V. Katri, et al., 1987b.

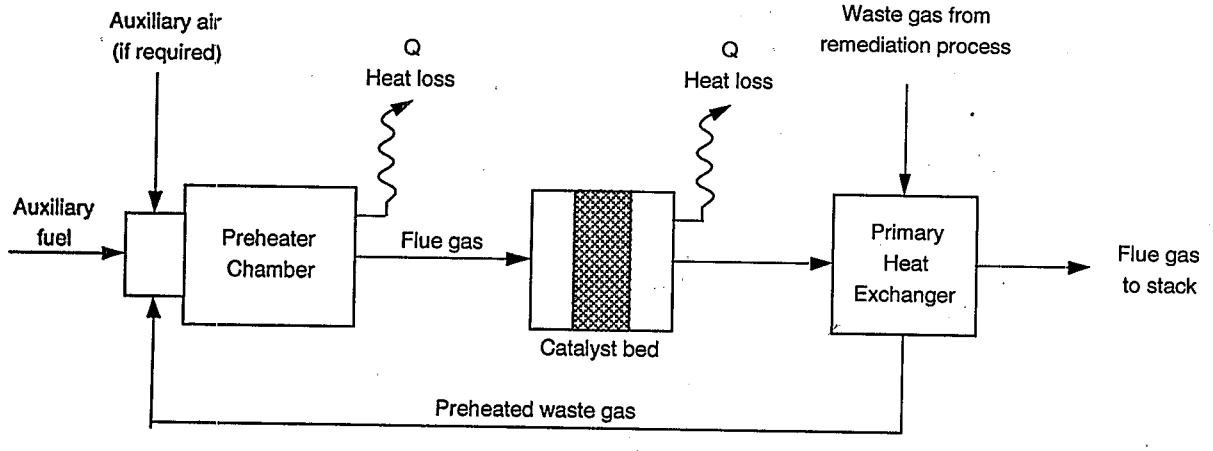


Figure 5-10. Schematic of catalytic oxidation system with recuperative heat exchanger.

Table 5-7. Cost Factors for Thermal Incinerator Annual Costs [a]

Itemized expenditures	Cost factor
Direct costs	
Labor	
Operating labor	0.5 h/shift
Supervision	15% of operating labor
Maintenance	0.5 h/shift
Maintenance materials	100% of maintenance labor
Utilities	
Electricity	See note b
Fuel	See note c
Indirect costs	
Overhead	60% of sum of operating, supervisory, maintenance labor and maintenance materials
Administrative charges	2% x TCI
Property tax	1% x TCI
Insurance	1% x TCI
Capital recovery	CRF x TCI (see note d)

a This table is taken from V. Katari, W. Vatavuk, et al., 1987b.
b Annual electricity costs can be estimated using waste gas fan power requirement, the annual operating hours, and the per kW-hr cost of electricity.
Annual Electricity Cost = Power Requirement (kW) · Operating Hours (hrs) · Electricity Cost ($/kW-hr)
c Annual fuel costs can be estimated using the system fuel requirement, the operating hours, and the per MM Btu cost of fuel.
Annual Fuel Cost = Fuel Requirement (MMBtu/hr) · Operating hours (Hrs) · Fuel Cost ($/MMBtu)
d The capital recovery factor is a function of the equipment life (typically about 10 years) and the interest rate.

auxiliary air and fuel requirements for combustion controls. These requirements in turn will have strong influence on whether catalytic oxidation is an economical approach for controlling air emissions. The waste gas composition is also important in that for catalytic oxidation to be effective the waste gas cannot contain catalyst poisons which would limit system performance.

A table and a flow chart for determining the suitability of a waste gas for catalytic oxidation and establishing its auxiliary fuel and oxygen requirements were presented in Section 5.2.2 for thermal oxidation; this same information is applicable to catalytic oxidation. While catalytic oxidation has traditionally not been widely used to control halogenated hydrocarbons, improved catalysts make this application more feasible (Kittrell, et al., 1991).

Table 5-8 presents a list of poisons/inhibitors which can significantly degrade the catalyst activity. The presence of any of these species in the waste gas stream would make catalytic incineration unfavorable.

If halogenated VOCs are present in the influent gas stream, then hydrochloric acid (HCl) may be produced in the catalytic oxidizer. HCl emissions are regulated and off-gas controls for HCl and other acid gases may be required.

Table 5-8. Common Catalyst Poisons

Sulfur
Chlorine
Chloride salts
Heavy metals (e.g., lead, arsenic)
Particulate matter

5.3.3 Range of Effectiveness

Catalytic oxidation is a well-established method for controlling VOC emissions in waste gases. The control efficiency (also referred to as destruction efficiency or DE) for catalytic oxidation is typically 90-95 percent. In some cases the efficiency can be significantly lower, particularly when the waste stream being controlled contains halogenated VOCs.

Factors which affect the performance of a catalytic oxidation system include the following:

1) Operating temperature;
2) Space velocity (the reciprocal of residence time);[5]
3) VOC composition and concentration;
4) Catalyst properties;

[5] Space velocity is defined as the volumetric flowrate of the flue gas entering the catalyst bed divided by the volume of the catalyst bed. Space velocity is the inverse of residence time and for a fixed bed catalytic oxidizer is in the range of 30,000-100,000 hr^{-1}.

5) Presence of poisons/inhibitors in the waste gas stream; and
6) Surface area of the catalyst.

The operating temperature of a catalytic incineration system is dependent on the concentration and composition of the VOCs in the waste gas stream as well as the type of catalyst used. In most cases, the temperature at the inlet of the catalyst bed is at least 600°F while the temperature at the outlet is less than 1200°F. The temperature, together with catalyst space velocity, has significant affect on system performance. 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, decreasing space velocity (i.e., increasing residence time in the catalyst bed), increases destruction efficiency. However, as is the case with thermal incinerators, it is not possible to predict beforehand the exact temperature and residence time needed to obtain a given DRE for a VOC mixture. Rough estimates can be made using simple models (Cooper and Alley, 1986). For example, temperatures reported for 80% DRE of 1,1,1-trichlorethane vary from 382°F to 661°F depending on the catalyst used.

The influence of temperature and space velocity on the effectiveness of a catalytic oxidation system are shown in Figures 5-11 and 5-12, respectively. The data shown in these figures are for a fluidized-bed catalytic oxidation system. The waste gas treated by this unit contained 10-200 ppmv of mixed VOCs, including aliphatic, aromatic, and halogenated compounds.

In designing a catalytic oxidation system temperature and space velocity are not the only variables which must be considered. The waste gas composition and catalyst type must be evaluated simultaneously since the type of catalyst chosen for a system places practical limits on the types of compounds that can be treated. For example, waste gases containing chlorine and sulfur can deactivate noble metal catalysts such as platinum. However, chlorinated VOCs can be treated by certain metal oxide catalysts.

The control efficiencies of some common VOC contaminants are shown in Table 5-9 at two different operating temperatures for the fluidized bed catalytic combustor discussed previously. As the data show, the destruction efficiency of a catalytic oxidation system can vary greatly for different contaminant types. The lowest destruction efficiencies typically are seen for chlorinated compounds.

5.3.4 Sizing Criteria

To size a catalytic oxidizer correctly and estimate the capital and annualized costs, three pieces of data are required:

1) The flue gas flow rate;
2) The auxiliary fuel and air requirements; and
3) The pressure drop across the system and waste gas fan power requirements.

Table 5-9. Destruction Efficiencies of Common VOC Contaminants in a Fluidized Bed Combustor

	Destruction efficiency at 650° F	Destruction efficiency at 950° F
	mean	mean
Cyclohexane	99	99+
Ethylbenzene	98	99+
Pentane	96	99+
Vinyl chloride	93	99
Dichloroethylene	85	98
Trichloroethylene	83	98
Dichloroethane	81	99
Trichloroethane	79	99
Tetrachloroethylene	52	92

Source: U.S. EPA, 1986..

Flue Gas Flowrate

For dilute waste gases the flue gas flowrate[6] is approximately equal to the waste gas flowrate. In cases where auxiliary air is required, the flue gas flowrate is roughly equal to the sum of the waste gas flowrate and the auxiliary air flowrate. For catalytic oxidation systems, the flue gas flowrate can be used in many correlations to size the catalyst and the overall system.

Auxiliary Fuel Requirement

The auxiliary fuel required for a catalytic oxidizer is significantly less than for a thermal incineration unit. In many cases auxiliary fuel requirements will be minimal for catalytic oxidation systems. However, the process of estimating fuel requirements is the same for both catalytic and thermal systems.

As described in Section 5.2.4, the fuel requirement can be estimated by making a rough heat balance around the oxidation system. The approach described below assumes heat losses to be negligible. In many cases this is not a valid assumption and the fuel requirements will be significantly higher than calculated by this simple approach. The heat balance requires the following data:

1) The waste gas and flue gas flowrates (lbmol/hr);
2) The average temperature across the catalyst bed (700-900°F);
3) The waste gas temperature as it comes from the remediation system before it goes through a heat exchanger;
4) The concentration of VOCs in the waste gas;
5) The approximate heat capacity of the flue gas (Btu/lbmol/°F); and
6) The fraction of the total heat release which is recovered in the heat exchange system.

A simple heat balance around a catalytic oxidation system is shown in Figure 5-13. From the heat balance the fuel requirement (in MMBtu/hr) can be estimated using the equations shown for thermal oxidation in Section 5.2.4.

[6] In this discussion the term flowrate implies the flowrate at standard conditions which are assumed to be 60°F and 1 atm, following standard engineering practices.

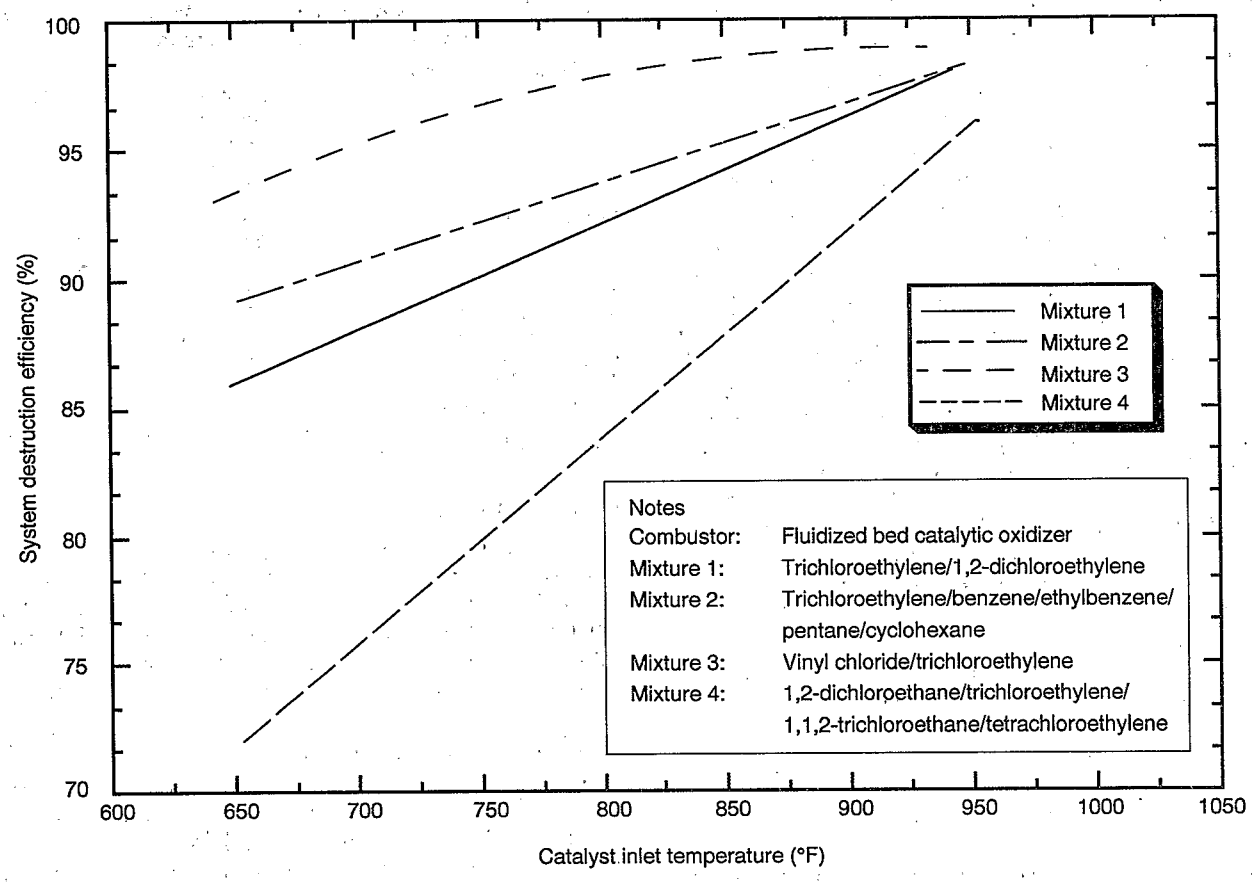


Figure 5-11. Effect of temperature on destruction efficiency for catalytic oxidation at 10,500 hr $^{-1}$ space velocity.

System Pressure Drop

The total pressure drop for an catalytic oxidizer depends on the type of equipment included in the system as well as other design considerations. The total pressure drop required across a catalytic oxidation system determines the waste gas fan size and horsepower requirements, which in turn determine the fan capital cost and electricity consumption (Katari, et al., 1987a).

An accurate estimate of system pressure drop would require complex calculations. A preliminary estimate can be made using the approximate values listed in Table 5-10. The system pressure drop is the sum of the pressure drops across the oxidizer and the heat exchanger.

As for thermal oxidation, the pressure drop can then be used to estimate the power requirement for the waste gas fan using the empirical correlation given below (U.S. EPA, 1990):

$$\text{Power} = 1.17 \cdot 10^{-4} \cdot V \cdot \Delta P/\varepsilon \qquad \text{(Eq. 5-9)}$$

where:

Power = Fan power requirement, kW-hr;
V = Waste gas flowrate, scfm[7];
ΔP = System pressure drop, inches of water column; and
ε = Combined motor fan efficiency, dimensionless (approximately 60%).

[7] 1 lb-mol at 60° F and 1 atm equals 379 scfm.

5.3.5 *Cost Estimating Procedure*

The process of estimating capital and annual expenses for a catalytic oxidizer can be divided into three parts. Estimates must be made for the following:

1) Equipment costs including combustor, catalyst, stack, and controls;
2) Installation, engineering, and indirect costs associated with purchasing and installing the control equipment; and
3) Direct and indirect annual expenses.

Table 5-10. Typical Pressure Drops [a,b] for a Catalytic Oxidation System

Equipment type	Pressure drop (in. H_2O)
Catalytic oxidizer	6"
Heat exchanger 35% efficiency	4"
Heat exchanger 50% efficiency	8"
Heat exchanger 70% efficiency	15"

[a] Total system pressure drop equals the sum of pressure drops across all pieces of equipment in the system.
[b] This table is taken from V. Katari, et al., 1987a.

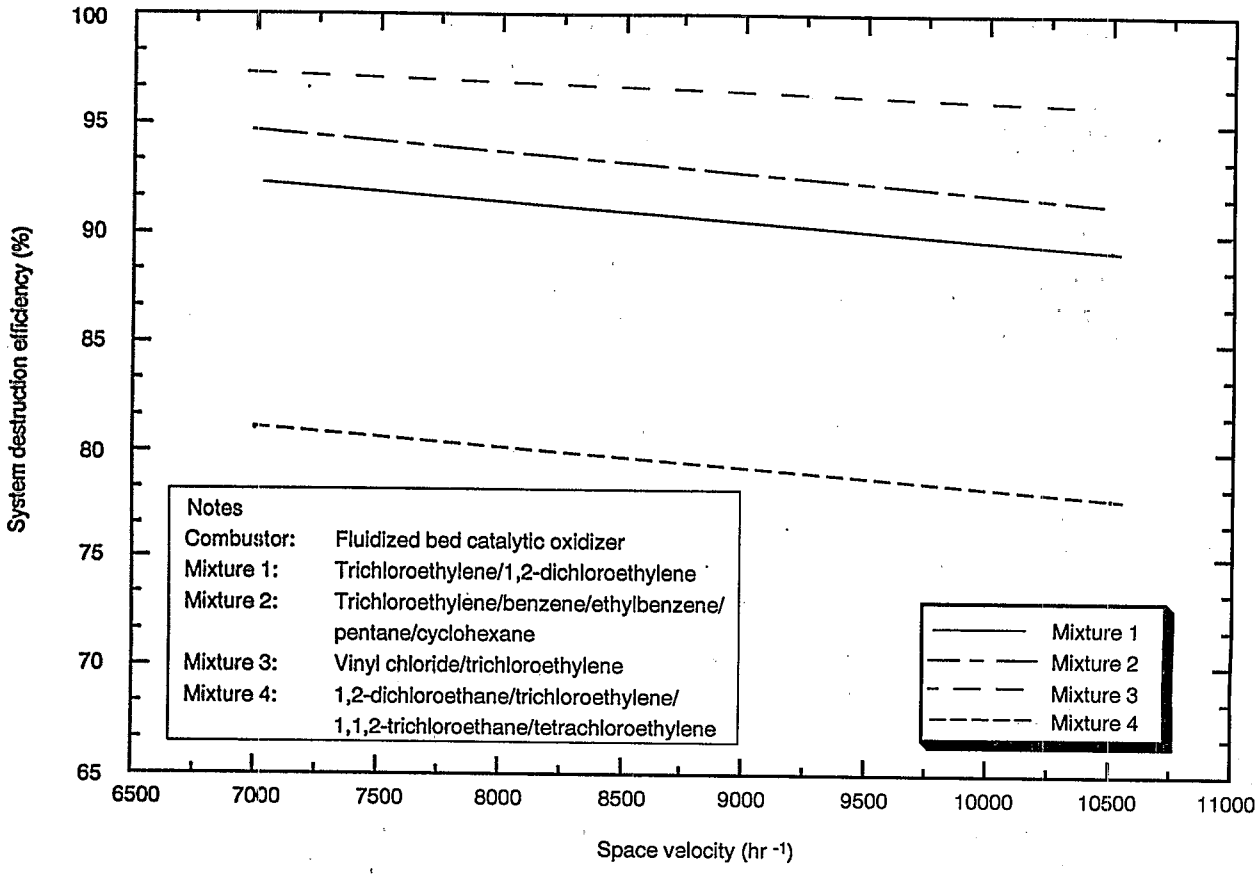


Figure 5-12. Effect of space velocity on destruction efficiency for catalytic oxidation at 720° F.

Equipment Costs

A typical catalytic oxidizer will include the following components: (1) a waste gas fan; (2) combustion chamber and preheater; (3) catalyst bed; (4) heat recovery equipment; (5) controls, instrumentation, and control panel; and (6) a stack. In addition, other equipment such as ductwork may be required to integrate the oxidizer with the remediation process. The equipment costs for an catalytic oxidation system can generally be estimated two ways: 1) by obtaining quotations from vendors, or 2) by using generalized cost correlations available in the literature.

The purchased cost of a typical catalytic oxidation system will vary widely depending on several design factors. Consequently, caution is required when using generalized cost correlations. Among the factors that influence the purchased cost of a catalytic oxidation system are the supplier's design experience, materials of construction, instrumentation, the type of catalyst used, the type of heat exchanger used, and the nature of the installation (i.e., Do any factors exist which make installing the equipment unusually difficult?)

Catalytic oxidizer equipment costs as a function of flue gas flowrate are shown in Figure 5-14 at standard conditions of 60°F and 1 atm (absolute). This figure is adapted from an article by Katari, et al., 1987b which used cost information from catalytic oxidizer manufacturers to develop cost correlations. The equipment costs given represent the cost for a complete oxidation system including a combustion chamber with burner, catalyst, waste gas fan, inlet and outlet plenums, prepiping, prewiring, instrumentation and controls, a 10-ft stack, and in the case of heat recovery, a primary heat exchanger.

Another set of cost correlations for catalytic oxidation systems have been published recently (van der Vaart, et al., 1991). Using data provided by several vendors, the authors developed relations between the equipment cost and the flue gas flowrate for different levels of heat recovery. Based on regressions the following correlations were established in 1988 dollars for fixed bed catalytic oxidizers having flowrates between 2,000 and 50,000 scfm (Q is the flowrate in scfm, EC is the equipment cost in dollars, and HR is the percent heat recovered):

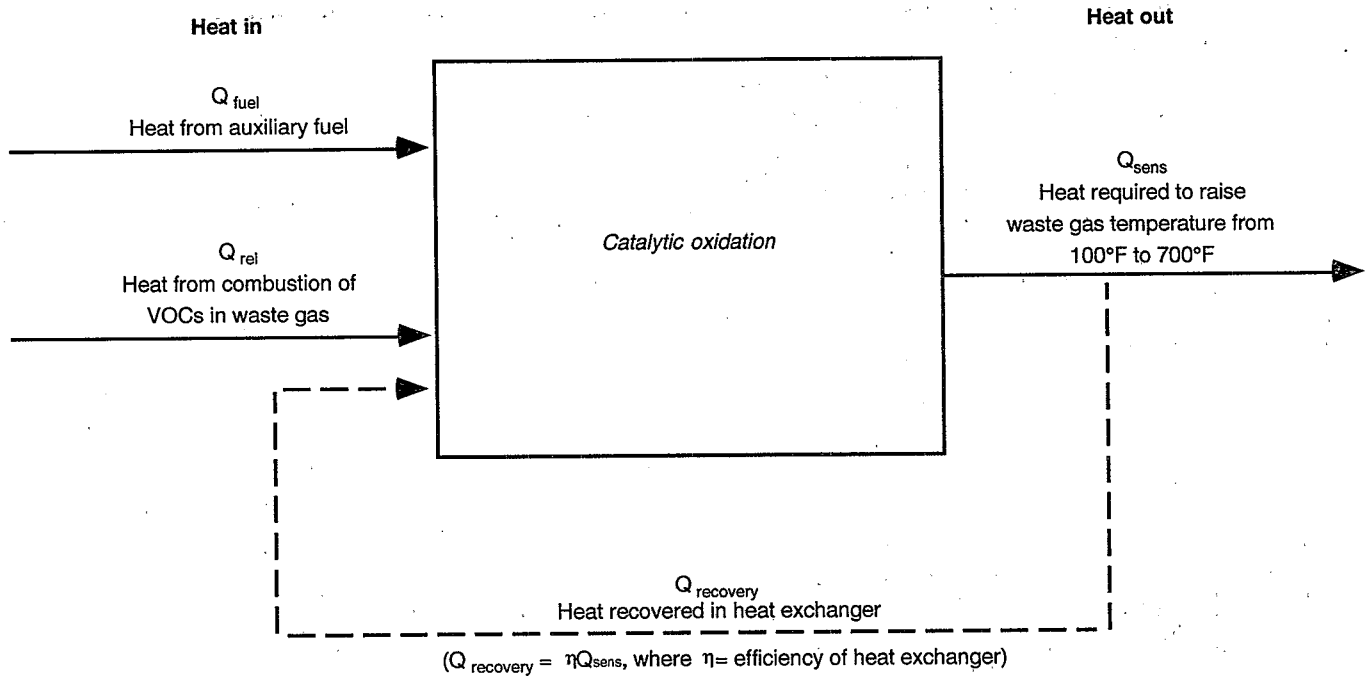


Figure 5-13. Heat balance for catalytic oxidation.

$$EC = 1100 \cdot Q_{tot}^{0.547} \quad HR = 0\% \qquad \text{(Eq. 5-10)}$$

$$EC = 3620 \cdot Q_{tot}^{0.419} \quad HR = 35\% \qquad \text{(Eq. 5-11)}$$

$$EC = 1220 \cdot Q_{tot}^{0.558} \quad HR = 50\% \qquad \text{(Eq. 5-12)}$$

$$EC = 1440 \cdot Q_{tot}^{0.553} \quad HR = 70\% \qquad \text{(Eq. 5-13)}$$

For fluidized-bed systems a second set of correlations, also in 1988 dollars, covering the range of 2,000-25,000 scfm were developed based on data from vendors:

$$EC = 8.48 \times 10^4 + 13.2 \cdot Q_{tot} \quad HR = 0\% \qquad \text{(Eq. 5-14)}$$

$$EC = 8.84 \times 10^4 + 14.6 \cdot Q_{tot} \quad HR = 35\% \qquad \text{(Eq. 5-15)}$$

$$EC = 8.66 \times 10^4 + 15.8 \cdot Q_{tot} \quad HR = 50\% \qquad \text{(Eq. 5-16)}$$

$$EC = 8.39 \times 10^4 + 19.2 \cdot Q_{tot} \quad HR = 70\% \qquad \text{(Eq. 5-17)}$$

The costs for fluidized-bed systems are higher, since these units are designed to handle waste streams with (1) higher heating values, (2) higher particulate contents, and (3) chlorinated species.

Cost estimates for systems to treat less than 2000 scfm should be obtained directly from vendors.

Installation, Engineering, and Indirect Costs

The total capital investment (TCI—equipment costs plus installation, engineering, and indirect costs) for a catalytic oxidation system can vary widely as a function of the total equipment cost. The TCI for a small skid-mounted unit to be placed at a preprepared site may be only 150-200% of the equipment cost. On the other hand, for a custom installation, requiring extensive site-work, the TCI may run as high as 300-400% of the purchased equipment cost.

One method for generating an estimate of installation, engineering, and indirect costs is to use the factor approach presented in Table 5-6 in Section 5.2.5. Based on the approach given in this table, the TCI is approximately 160% of equipment costs, plus any costs for site preparation and construction.

Annual Expenses

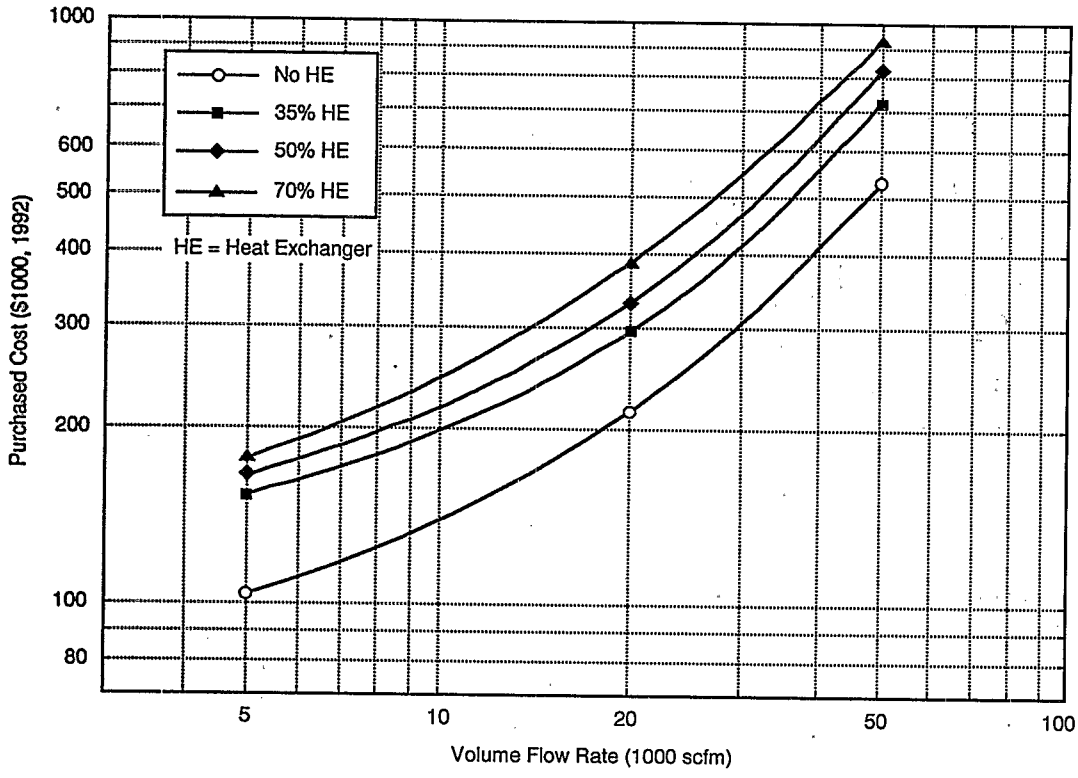
Estimating the annual expenses associated with using catalytic oxidation requires an extensive amount of site-specific data. Suggested factors for estimating thermal oxidizer annual costs are presented in Table 5-7 in Section 5.2.5. The only additional cost consideration for catalytic oxidizers is capital recovery for the catalyst material. This is a function of the catalyst life (e.g., 3 years) and the interest expense. Overall utilities, the annualized catalyst cost, and the system capital recovery are typically the largest expenses.

5.4 Condensers

5.4.1 Process Description

Condensers are primarily used to remove VOCs from gas streams prior to other controls such as incinerators or absorbers but can also be used alone to control emissions of high VOC concentration gas streams. Condensation is a recovery technique where the volatile components of a vapor mixture are separated from the remaining gas by a phase change. Condensation occurs when the partial pressure of the volatile components is greater than or equal to its vapor pressure. This situation can be achieved by lowering the temperature or increasing the pressure of the gas stream.

Figure 5-15a is a simple process flow diagram for condensation. A typical condensation system consists of the condenser, refrigeration system, storage tanks, and pumps. Figure 5-15b is



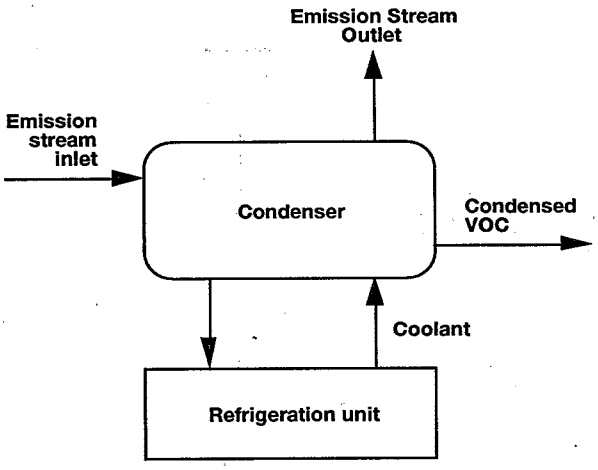
Source: Adapted from V. Katari, et al., 1987b.

Figure 5-14. Catalytic incinerator equipment cost estimates.

a more detailed process diagram of an entire condensation and recovery process. VOC off-gas is compressed as it passes through a blower. The exiting hot gas is routed to an aftercooler commonly constructed of copper tubes with external aluminum fins. Air is passed over the fins to maximize the cooling effect. Some condensation occurs in the aftercooler. The gas stream is cooled further in an air-to-air heat exchanger. The condenser cools the gas to below the condensing temperature in an air-to-refrigerant heat exchanger. The cold gas then is routed to a centrifugal separator where the liquid is removed to a collecting vessel. The aftercooler and heat exchanger may not be necessary for all condensing systems. Typically, further treatment of the gas stream is required for final polishing, such as a carbon adsorption unit, before the stream can be vented to the atmosphere.

Condensing systems usually contain either a contact condenser or a surface condenser. Contact condensing systems cool the gas stream by spraying ambient or chilled liquid directly into the gas stream. The spraying is usually accomplished in a packed column where surface area and contact time are maximized. Some contact condensers are simple spray chambers with baffles, while others have high velocity jets designed to produce a vacuum. Since the coolant comes into direct contact with the recovered contaminants, the contaminants and coolant must be separated or extracted before either can be reused. This separation process may lead to a disposal problem or secondary emissions. Contact condensers are more flexible, simpler, and less expensive to operate than surface condensers. Contact condensers usually remove more air contaminants due to greater condensate dilution.

In surface condensing systems, the coolant does not make contact with the gas stream. These condensers are usually the shell and tube or plate/fin type. Condensed vapor forms a film on the cooled surface and drains into a collection vessel for storage, reuse or disposal. Condensation can occur in the tubes or on the shell outside of the tubes. Typically, condensers are the shell and tube type with the coolant flowing on the inside of the tubes counter-currently to the gas stream. Condensation occurs on the outside of the tubes in this arrangement. The condenser is usually horizontal but vertical condensers also exist. Surface condensers require less water and produce 10 to 20 times less condensate than contact condensers. Surface condensers are more likely to produce a salable product. These type of condensers have a greater amount of maintenance due to the auxiliary equipment required.



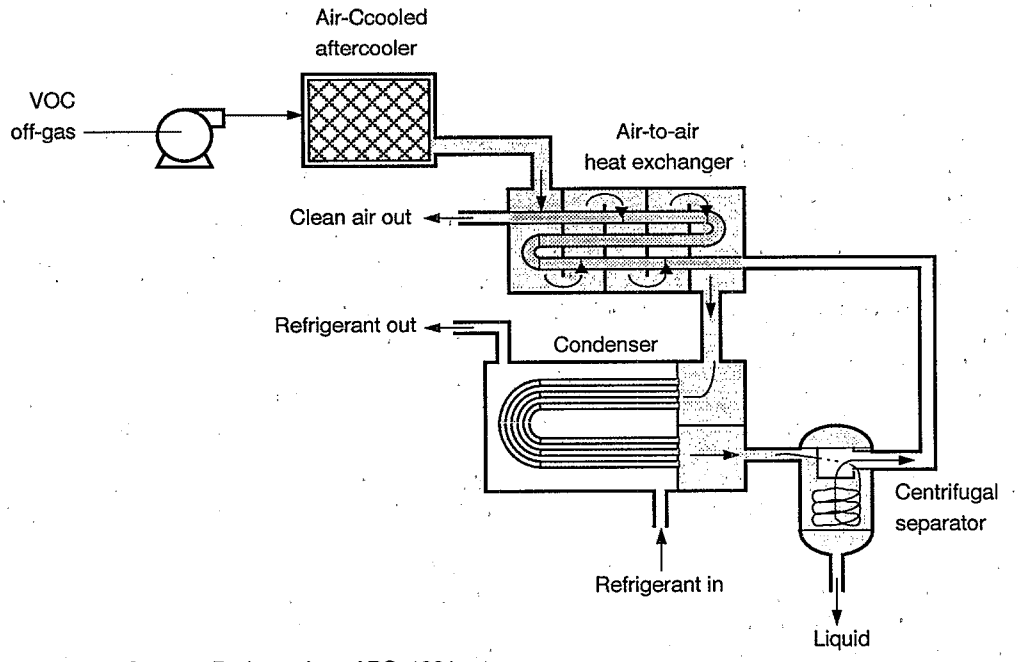
Source: Taken from U.S. EPA, 1991

Figure 5-15a. Process flow diagram for condensation.

5.4.2 *Applicability to Remediation Technologies*

Condensation generally is used to remove and recover VOCs prior to other control technologies. Condensation can be used alone to control emissions at high VOC concentrations, i.e., greater than 5000 ppmv. This type of VOC control is not suited for gas streams that contain organics with low boiling points (i.e., very low condensation temperatures <32°F) or gas streams with large quantities of inert or noncondensible gases (air, nitrogen, or methane). Condensation is a very efficient removal process for high concentration streams.

In most control applications, the emission stream will contain large quantities of noncondensible gases and small quantities of condensible compounds. Care should be taken in design and operation to ensure limited emissions of VOCs from discharged condensate, i.e., secondary emissions. Further subcooling of the condensate may be required to correct this situation. If uncondensible air contaminants are in the gas stream, these contaminants must be either dissolved in the condensate or vented to other control equipment. Since gas streams at Superfund sites will usually contain a variety of contaminants, the recovered stream may not be salable due to purity requirements. If so, the stream must be disposed of by incineration or some other method. Another consideration is the moisture content of the gas stream; any water in the stream will condense with the organic vapors creating a dilute solvent stream. If the gas is not treated below emission standards, the off-gas from the condenser must be treated further, usually with activated carbon. Disposal problems and high power costs are some of the disadvantages associated with condensation.



Source: Redrawn from APC, 1991a.

Figure 5-15b. Schematic diagram of a vapor condensation system.

5.4.3 *Range of Effectiveness*

Condensation has the capability of removing 50-95% of the condensible VOCs. The removal efficiency is dependent on the characteristics of the vapor stream and the condenser operating parameters. The efficiency depends on the nature and concentration of emission stream components. For example, compounds with high boiling points (low volatility) condense more readily compared to those with low boiling points. The temperature required to attain a given removal efficiency depends on the vapor pressure of the VOC at the vapor/liquid equilibrium. The condensation temperature can be determined from data relating vapor pressure and temperature. The coolant selection is based on the required condensation temperature. Some practical limits for coolant selection are presented in Table 5-11.

Table 5-11. Condensation Temperature Limits for Various Catagories of Coolants

Required condensation temperature (°F)	Coolant
80 -	Air
60–80	Water
45–60	Chilled water
-30–45	Brine solutions
-90 to -30	Freons

Source: Adapted from U.S. EPA, 1991.

The effect of volatility on the condensation temperature and removal efficiency is shown in Figure 5-16. The two components have varying atmospheric boiling points, as shown on the figure. For a given inlet concentration of contaminant, the removal efficiency increases for a given condensing temperature as the boiling point increases.

5.4.4 *Sizing Criteria*

Sizing the condenser involves several steps to determine the surface area of the condenser. For a condenser system containing a shell and tube heat exchanger, with condensate forming on the shell side, the following design procedure can be followed (U.S. EPA, 1991). The waste gas stream is assumed to be a two component mixture: a condensible component (VOC) and a noncondensible component (air). For estimating the condensation temperature, the gas stream consists of air saturated with a VOC component. For a given removal efficiency, the partial pressure in mm Hg for the contaminant in the exiting stream, $P_{partial}$, can be calculated:

$$P_{partial} = 760 \left\{ \frac{(1 - 0.01\,RE)}{\left[1 - (RE \times 10^{-8} HAP_e)\right]} \right\} HAP_e \times 10^{-6} \qquad \text{(Eq. 5-18)}$$

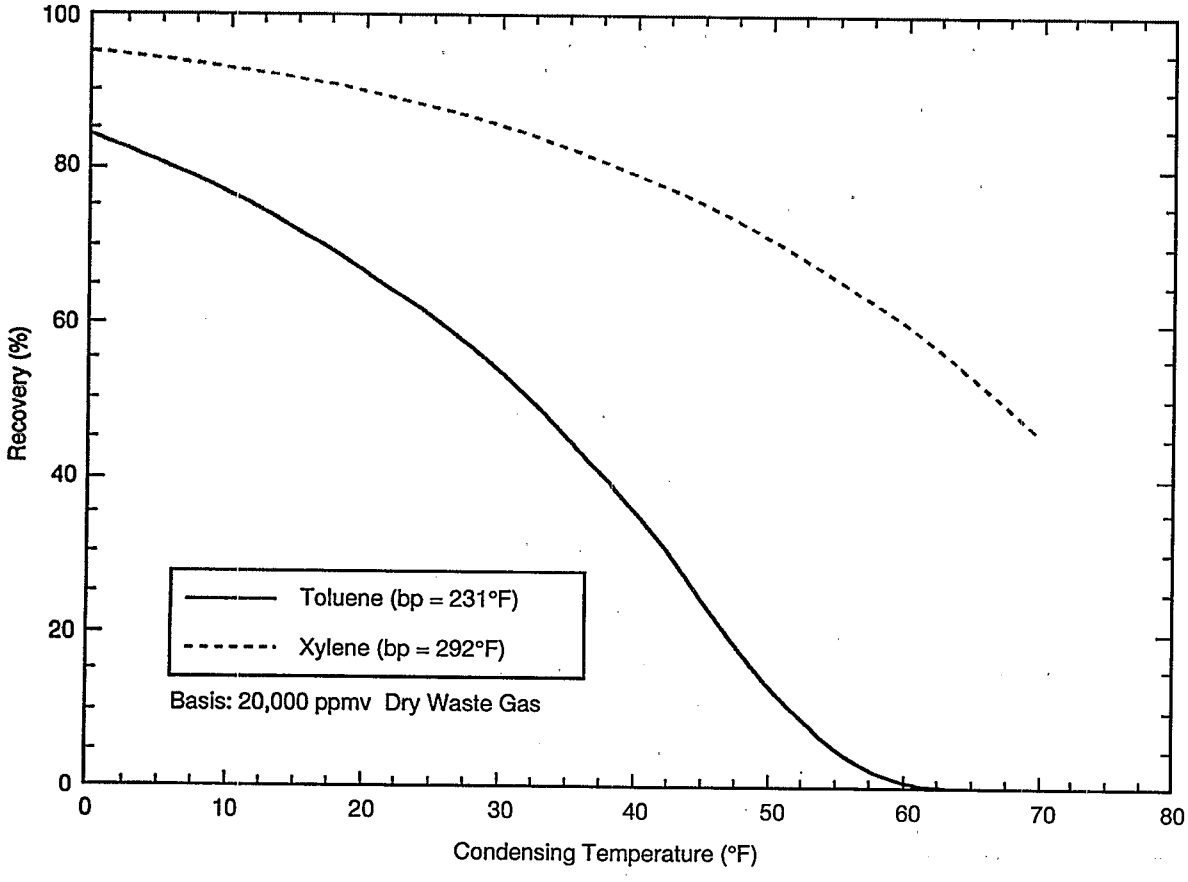


Figure 5-16. Example of condenser performance.

where:

RE = Removal efficiency, %; and
HAP_e = Contaminant concentration in entering gas stream, ppmv.

The condenser is assumed to operate at a constant pressure of 1 atmosphere. The condensing temperature can then be determined from equilibrium data where the calculated partial pressure of the hazardous air pollutant (HAP) is equal to its vapor pressure at that temperature. After the condensing temperature is determined, the appropriate coolant can be selected using Table 5-11 as a guide.

The heat load of the condenser can be determined from an energy balance:

$$H_{load} = 1.1 \times 60 (H_{con} + H_{noncon} + H_{uncon}) \quad \text{(Eq. 5-19)}$$

where:

H_{load} = Condenser heat load, Btu/hr;
H_{con} = Enthalpy of the condensed HAP; and
H_{noncon} = Enthalpy of the noncondensible vapors.

These parameters are defined in Table 5-12. Equations for determining these enthalpies are also given in this table. The factor 1.1 is included as a safety factor in the design.

Condenser systems are typically sized based on the total heat load and the overall heat transfer coefficient. The overall heat transfer coefficient is estimated from individual heat transfer coefficients and from coefficients of the gas stream and coolant. An accurate measurement of the individual coefficients can be made from physical/ chemical data for the gas stream, the coolant, and the specific shell and tube that is to be used. Some typical heat transfer coefficients for condensing systems are presented in Table 5-13. Condensers are sized from their area by the following equation:

$$A_{con} = H_{load}/U\Delta T_{LM} \quad \text{(Eq.5-20)}$$

where:

A_{con} = Condenser surface area, ft^2;
U = Overall heat transfer coefficient, Btu/hr-ft^2-°F; and

Table 5-12. Design Equations for Condensing Systems

Equations

$$H_{con} = HAP_{con} \left[\Delta H + C_{PHAP} (T_e - T_{con})\right]$$

$$H_{uncon} = HAP_{o,m}\, C_{PHAP} (T_e - T_{con})$$

$$H_{noncon} = \left[\left(\frac{Q_c}{392}\right) - HAP_{e,m}\right] C_{Pair} (T_e - T_{con})$$

$$HAP_{con} = HAP_{e,m} - HAP_{o,m}$$

$$HAP_{o,m} = \left(\frac{Q_c}{392}\right)\left[1 - HAP_e \times 10^{-6}\right]\left[\frac{P_{vapor}}{(P_e - P_{vapor})}\right]$$

$$HAP_{e,m} = \left(\frac{Q_c}{392}\right) HAP_e \times 10^{-6}$$

Nomenclature

C_p = Average specific heat of compound, Btu/lb-mol-°F
HAP_e = Entering concentration of HAP, ppmv
$HAP_{e,m}$ = Molar flow of HAP, inlet lb-mol/min
$HAP_{o,m}$ = Molar flow of HAP, outlet, lb-mol/nim
ΔH = Heat of evaporation, Btu/lb-mol
P_e = System pressure, mm Hg
P_{vapor} = $P_{partial}$
Q_c = Maximum flow rate, scfm at 77° F and 1 atm
T_{con} = Condensing temperature, °F
T_e = Entering emission stream temperature, °F

Source: U.S. EPA, 1991.

Table 5-13. Typical Overall Heat Transfer Coefficients in Shell and Tube Heat Exchangers for Condensing Vapor-Liquid Media

Shell side	Tube side	Design U (Btu/ °F-ft²-hr)	Fouling factor (hr-ft²-°F/Btu)
High-boiling hydrocarbons, V	Water	20-50	0.003
Low-boiling hydrocarbons, A	Water	80-200	0.003
Organic solvents, A	Water	100-200	0.003
Organic solvents high, NC, A	Water or brine	20-60	0.003
Organic solvents low NC, A	Water or brine	50-120	0.003

V = Vacuum
A = Atmospheric pressure
NC = Non-condensible gas present

Source: Adapted from Perry, 1973.

ΔT_{LM} = Logarithmic mean temperature difference, °F

$$= \frac{(T_e - T_{cool,o}) - (T_{con} - T_{cool,i})}{\ln [(T_e - T_{cool,o}) - (T_{con} - T_{cool,i})]}$$

T_e = Emission stream temperature, °F;
$T_{cool,o}$ = Coolant outlet temperature, °F = ($T_{cool,i}$ + 25); and
$T_{cool,i}$ = Coolant inlet temperature, °F = (T_{con} - 15)

The coolant flow rate can be determined from a simple heat balance:

$$Q_{coolant} = H_{load}/[Cp_{coolant}(T_{cool,o} - T_{cool,i})] \quad \text{(Eq. 5-21)}$$

where:
$Q_{coolant}$ = Coolant flow rate, lb/hr; and
$Cp_{coolant}$ = Average specific heat of the coolant, Btu/lb-°F.

The design procedures are more complicated for a mixture of condensible gases in a noncondensible gas. More information for determining the condensation temperature for these type of mixtures can be found in Ludwig, 1965 and Kern, 1950. Physical/chemical data can be found in Perry's Chemical Engineers' Handbook, Smith and Van Ness, 1959, and CRC, 1992. Walas, 1988 and Danielson, 1967 have more information on condenser design.

If a refrigerant is chosen for the coolant, then a refrigeration system also must be designed for the condensing system. The refrigeration capacity, Ref, in units of tons is determined from:

$$Ref = H_{load}/12{,}000 \text{ Btu/hr-ton} \quad \text{(Eq. 5-22)}$$

5.4.5 *Cost Estimating Procedure*

The following cost equations are for refrigerated surface condenser systems. These cost correlations are in 1990 dollars; a factor of 1.1025 should be applied to these figures to convert to 1992 dollars. The refrigeration unit equipment cost (EC_r) for packaged solvent vapor recovery systems can be determined by the following equations (Shareef, et al., 1991):

- Single stage refrigeration units (less than 10 tons)

$$EC_r = \exp(9.83 - 0.014T_{con} + 0.34\ln R) \quad \text{(Eq. 5-23)}$$

- Single stage refrigeration units (greater than or equal to 10 tons)

$$EC_r = \exp(9.26 - 0.007T_{con} + 0.627\ln R) \quad \text{(Eq. 5-24)}$$

- Multistage refrigeration units

$$EC_r = \exp(9.73 - 0.012T_{con} + 0.584\ln R) \quad \text{(Eq. 5-25)}$$

These costs were determined from vendor-supplied information. The equipment cost for packaged solvent vapor recovery systems, EC_p, is estimated to be 25% greater than the refrigeration unit cost. The purchased equipment cost, PEC_p, includes the packaged equipment costs and factors for sales tax and freight:

$$PEC_p = 1.08\ EC_p = 1.08\ (1.25\ EC_r) \quad \text{(Eq. 5-26)}$$

Equipment costs for custom solvent vapor recovery systems were developed by (Shareef, et al., 1991). The following equations can be used to determine the capital costs (limitations are noted):

$EC_{condenser} = 34A_{condenser} + 3775$; (Eq. 5-27)
$A_{condenser}$ = 38 to 800 ft² of 304 stainless steel tubes

$EC_{tank} = 2.72V_{tank} + 1960$; (Eq. 5-28)
V_{tank} = 50 to 5000 gallons, 316 stainless steel

The estimated cost of the precooler can be determined from the refrigeration unit costs by using Equations 5-23 to 5-25. The cost of auxiliary equipment such as ductwork, piping, fans, or pumps also needs to be determined by procedures outlined in (Vatavuk, 1990). The total equipment cost for custom systems and the purchased equipment cost can be described by:

$$EC_C = EC_r + EC_{condenser} + EC_{tank} + EC_{precooler} + EC_{auxiliary} \quad \text{(Eq. 5-29)}$$

$$PEC_C = 1.18EC_C \quad \text{(Eq. 5-30)}$$

The total capital investment can then be determined for packaged and custom systems by the following:

$$TCI = 1.15PEC_p \text{ or } TCI = 1.74PEC_C \quad \text{(Eq. 5-31)}$$

The total annual operating cost correlations are summarized in Table 5-14. This table contains the basis for calculating direct

Table 5-14. Annual Cost Factors for Refrigerated Condenser Systems

Cost items	Factor
Direct Annual Costs, DC	
Operating labor	
Operator	1/2 hour per shift
Supervisor	15% of operator
Operating materials	
Maintenance	
Labor	1/2 hour per shift
Material	100% of maintenance labor
Electricity	
at 40° F	1.3 kW/ton
at 20° F	2.2 kW/ton
at -20° F	4.7 kW/ton
at -50° F	5.0 kW/ton
at -100° F	11.7 kW/ton
Indirect Annual Costs, IC	
Overhead	60% of total labor and maintenance material costs
Administrative charges	2% of total capital investment
Property tax	1% of total capital investment
Insurance	1% of total capital investment
Capital recovery [a]	13.15% x total capital investment
Recovery Credits, RC	
Recovered VOC	Quantity recovered x operating hours
Total annual costs:	**DC + IC - RC**

[a] Assuming a 15-year life at 10%.

Source: Reprinted from Shareef, et al., 1991.

annual costs, indirect annual costs, and recovery credits. The recovery credit, RC, may not be applicable if the product purity is not high enough for resale. The recovery credit can be determined from the quantity of VOC recovered:

$$RC = W_{VOC,con}\ \theta_s\ p_{VOC} \qquad \text{(Eq. 5-32)}$$

where:

$W_{VOC,con}$ = Quantity of VOC recovered (lb/hr);
θ_s = System operating time (hr/yr); and
p_{VOC} = Resale value of recovered VOC ($/lb).

Other cost correlations can be found in U.S. EPA, 1991 and Walas, 1988.

5.5 Internal Combustion Engines

5.5.1 Process Description

The principle of operation of a control device that incorporates an internal combustion engine (ICE) is to use a conventional automobile or truck ICE as a thermal incinerator. The physical difference between ICE units and incinerators is primarily in the geometry of the combustion chamber. A simplified schematic of a typical ICE-based system is shown in Figure 5-17. The major components include the engine itself (standard automobile or truck engine), supplemental fuel supply (usually propane or natural gas), carburetor, off-gas lines from remediation system, and additional air emission control devices (adsorbent bed, catalytic converter, etc.). Some pretreatment device also may be required, since ICE units require a "clean" waste stream containing no acids and low levels of particulate matter.

Supplemental fuel is required when the VOCs in the waste stream are at insufficient concentrations to support combustion. This requirement is especially common for system start-ups, remediation projects with low VOC extraction rates, and sources such as SVEs that produce changing VOC concentrations over time. Concentration ranges of 60,000 to 100,000 ppm at flowrates of 1.7 - 2.0 m^3/min (60 - 70 acfm) are possible (RSI, 1991a). However, additional oxygen may be required to dilute the gas stream if the VOC level exceeds 25% of the lower explosive limit. The carburetor must be modified to include two input valves (in addition to the change allowing gaseous rather than liquid fuel).

A major advantage to the technology is the mobility of an ICE unit. This advantage may be enhanced if all power needs are met by the ICE, and no external power source is needed to drive the remediation equipment. The ready availability of automobile parts and wide knowledge of their operation are other advantages; even the catalytic converter as an add-on control is inexpensive if an automobile manufacturer's unit is used.

5.5.2 Applicability to Remediation Process

ICEs may be used for VOC control from any point source where the air stream meets certain criteria. To be economically attractive the stream should be of relatively small flow rate

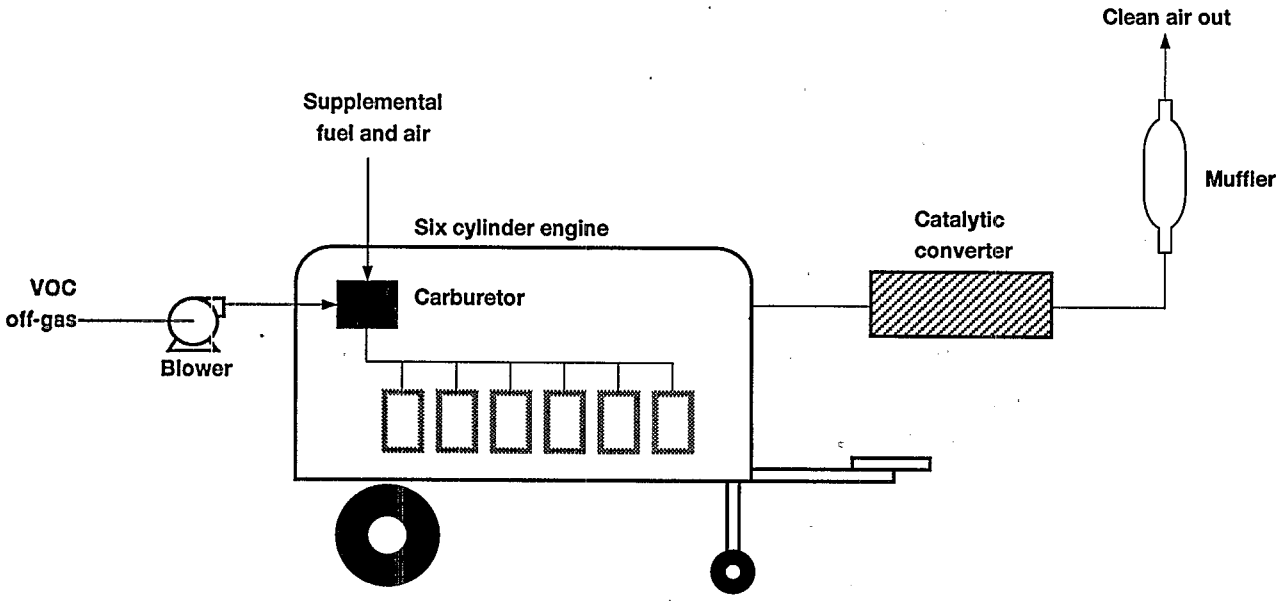


Figure 5-17. Internal combustion engine-based VOC control system.

(<1,000 cfm) since the largest ICE is only capable of a few hundred cfm, and it should contain high concentrations of VOCs (>1,000 ppm) or else supplemental fuel costs would become excessive. For applications involving large flow rates of dilute waste gas, however, the technology still may be potentially cost-effective if used in conjunction with a condenser, membrane, or other pre-treatment concentrator.

ICEs have been used for years to control landfill gases, but they have been applied to hydrocarbon destruction only since 1986, primarily for SVE and air stripping. Their use is most common in California, where the majority of ICE system manufacturers are located (Pedersen and Curtis, 1991). Their use at Superfund sites is expected to be limited to the control of VOC emissions from small-scale SVE systems and perhaps to small-scale air strippers. In general, a relative lack of information exists concerning details of ICE technology for site remediation purposes. Their use to date, is limited due to the relatively small flow rates (hundreds of cfms) that these units are able to handle. To date, the limited available literature has focused on ICE use for SVE, landfill capping, and air stripping applications.

The use of ICEs is especially attractive when it replaces the need for electrical power to the site by using the engine to run vacuum fans, etc. This use saves not only utility costs, but equipment costs as well. DREs of 99+% may be achieved, usually with a catalytic converter in place. Other advantages of ICEs over other VOC destruction systems are in mobility and size. The potential problems of excessive noise and labor requirements (for monitoring fuel intake) may be avoided by the use of computer-controlled air-to-fuel ratios and sophisticated muffler systems. ICE systems with automated controls are recommended for Superfund applications.

5.5.3 Range of Effectiveness

ICE systems typically can achieve destruction efficiencies of 99% or greater. A recent report (Pedersen and Curtis, 1991) contains the results of several studies listing removal efficiencies of different VOCs by ICEs for various SVE and air stripping systems. These results are presented in Table 5-15. Additional case study information for specific ICE units is summarized below.

One vendor, VR Systems, has a series of portable ICEs that are designed for use with SVE systems and also can perform tank degassing. These units burn up to 100 kg/hr (220 lb/hr) of hydrocarbons. They use liquid propane or natural gas as a supplementary fuel, and are computer-controlled for higher DREs and less labor requirements.

The Soil-Scrub(R) process (K-V Associates, Falmouth, MA) was used with a heat-assisted SVE system (HWC, 1988). An ICE was the primary control for this system, followed by a catalytic converter and a GAC bed. Gasoline-soaked soil was first encapsulated in plastic sheets, then the soil was heated to 100°C. The final DRE was 99.9% upon exiting all controls. The entire remediation process took 36 hours, and the treated soil contained no detectable benzene, toluene, and xylenes and only 82 ppm oil.

A thermal vacuum spray aeration/compressive thermal oxidation system (Robert Elbert & Associates, Santa Barbara, CA) incorporating an ICE has been used for groundwater remediation (HWC, 1988). Heat (110°F) and vacuum (12" Hg) were used to preferentially evaporate gasoline from water, and the vapor was sent to an ICE. The system can strip and oxidize 120 lbs hydrocarbons/ day; the treated water had 32 ppm contaminants and the waste gas had 70 ppm. It required approximately 0.75 gal fuel/hr. Two limitations to the process were noted: over-rich

Table 5-15. Destruction Efficiencies of ICEs for SVE Systems

Parameter	Initial concentration (ppm)	After catalytic converter (ppm)	Removal efficiency (%)	Reference
THC	38,000	89	99.76	Millican, 1989
	200,000	39	99.98	Millican, 1989
THC	318,832	16 ppm	99.99	Wayne Perry, 1989
Benzene	995	ND[1] (<10 ppb)	99.99	Wayne Perry, 1989
Ethylbenzene	125	ND (<10 ppb)	99.99	Wayne Perry, 1989
Toluene	1,005	0.014	99.99	Wayne Perry, 1989
Xylenes	1,550	<11.5 ppb	99.99	Wayne Perry, 1989
TPH (non-methane)	49,625	225	99.56	RSI, 1989
Methane HCs	741	109	85.29	RSI, 1989
Benzene	380	0.8	99.79	RSI, 1989
Toluene	400	1.1	99.73	RSI, 1989
Xylenes	114	0.7	99.39	RSI, 1989
Ethylbenzene	18	<0.5	—	RSI, 1989
TPH	65,450	30	99.95	Rippberger, 1989
	34,042	14.5	99.96	Rippberger, 1989
	30,500	1.4	99.99	Rippberger, 1989
	39,000	4.7	99.99	Rippberger, 1989
Benzene	1,094	67	93.88	Rippberger, 1989
	470	1.6	99.66	Rippberger, 1989
	785	0.63	99.92	Rippberger, 1989
	730	0.056	99.99	Rippberger, 1989
THC	58,000	160	99.72	RSI, 1989
Benzene	1,400	0.13	99.99	RSI, 1989
Toluene	720	0.024	99.99	RSI, 1989
Ethylbenzene	77	0.062	99.92	RSI, 1989
Total xylenes	320	0.13	99.96	RSI, 1989
THC	26,000	140	99.46	RSI, 1989
Benzene	960	0.024	99.99	RSI, 1989
Toluene	840	0.020	99.99	RSI, 1989
Ethylbenzene	91	ND (0.02)	100.00	RSI, 1989
Total xylenes	360	0.080	99.98	RSI, 1989

[1]Nondetectable

Source: Pedersen and Curtis, 1991.

combustion conditions may be met if the remediation process occurs in a well, and the system can be smothered with excessive water vapor.

5.5.4 *Sizing Criteria/Application Rates*

The sizing of an ICE device is based on the volumetric flow rate of the waste stream to be treated. Information from several vendors is summarized below (VR Systems, 1991 and RSI, 1991b).

VR Systems has various SVE-ICE systems with controllers ranging in sizes from 25 to 1,000 scfm. This largest system is actually several engines in parallel, and can destroy about 20 lb/hr of hydrocarbons. RENMAR, on the other hand, reports that their SVE system is able to accommodate 100 to 200 scfm of input gas (depending on the loading) for every 300 cubic inches of engine capacity (Pedersen and Curtis, 1991). RSI manufactures a system that can accommodate either SVE or air stripping. Their ICE unit can handle up to 80 cfm of VOC-laden air.

5.5.5 *Cost Estimating Procedure*

Only limited cost data are available. A recent listing of several commercially available systems and their prices is given in Table 5-16.

One vendor (RSI, 1991a) compares this technology to a carbon adsorption system; consider an example case of a $2 carbon cost per pound of hydrocarbon adsorbed. If an ICE system leases for $200 per day, burns $100 per day of supplemental fuel, and destroys 15 lbs/hr of hydrocarbon, then the cost per lb is $300/(24 x 15) = $0.83. For this example, the cost-effectiveness cross-over occurs at a VOC extraction rate of around 8 pounds/hour, at which point the carbon becomes preferable.

One ICE manufacturer, RENMAR, claims an SVE system uses only 25% of useful power so that excess power is available for site lighting, etc., and thereby increasing the cost-effectiveness of an ICE system. In general, however, the excess power produced will depend on the difference between the work needed to extract the vapors and the energy available in the vapors.

Table 5-16. Costs for Some Commercially Available ICE Systems

Vendor	System size (scfm)	Cost capital	Cost lease per month	Op. expense	Comments
RSI	30-60	$59,500	by distrib.	$1,000	For SVE and groundwater systems. Includes 8 hours start-up labor.
RENMAR	100-200	$52,100	$4,630		Prices updated from 1989 levels.
VR Systems:					Includes operating cost: lease based on 3 months. Custom built only.
Model V-3	0-250	$73,450	$6,980		
Model V-4	0-500	$98,880	$9,775		
Model V-5	0-1,000	custom	—		
Environmental techniques	100	$40,250			Includes operating and maintenance. Training for oxygen recording system: $2,700.

Source: Vendor-supplied data.

5.6 Soil Beds/Biofilters

5.6.1 Process Description

Biofiltration is an emerging technology for controlling volatile organic compound (VOC) emissions in waste gas streams. Biofiltration has been extensively used in Europe, especially for odor control. Biofiltration has been demonstrated at full-scale (Leson and Winer, 1991). In the biofiltration process, the waste gas is vented through a biologically active material where the biodegradable VOCs are oxidized into carbon dioxide and water. Physical sorption and chemical degradation may also occur and contribute to the overall removal efficiency. Figure 5-18 is a schematic of a typical single-bed biofilter system. Since the biofilter system is biologically sensitive, the temperature and moisture of the gas and filter bed are extremely important in design considerations. Radial blowers are used to transport the waste gas to the humidifier. The humidifier saturates the gas stream to 95% relative humidity, which prevents drying out of the filter material. The effect of the filter drying out is death of the microorganisms and a resultant loss of control efficiency.

Some systems have automatic irrigation from the top of the filter (soil) bed. The gas stream then enters the gas distribution system below the filter. As the gas diffuses through the filter, air contaminants will diffuse into the wet, biologically active layer (biofilm) where degradation occurs. Clean gas diffuses out the top of the filter. Excess drainage from the filter bed is the only potential source of wastewater discharge. In particular, where drainage contains organic contaminants that are regulated, the drainage is recycled to the humidifier to minimize wastewater discharge. Since particulates in the waste stream may clog the humidifier and the biofilter, a pre-filter may be required. A heat exchanger may also be required to heat or cool the waste gas stream if temper-atures are not within the optimum range (i.e., 20-40°C).

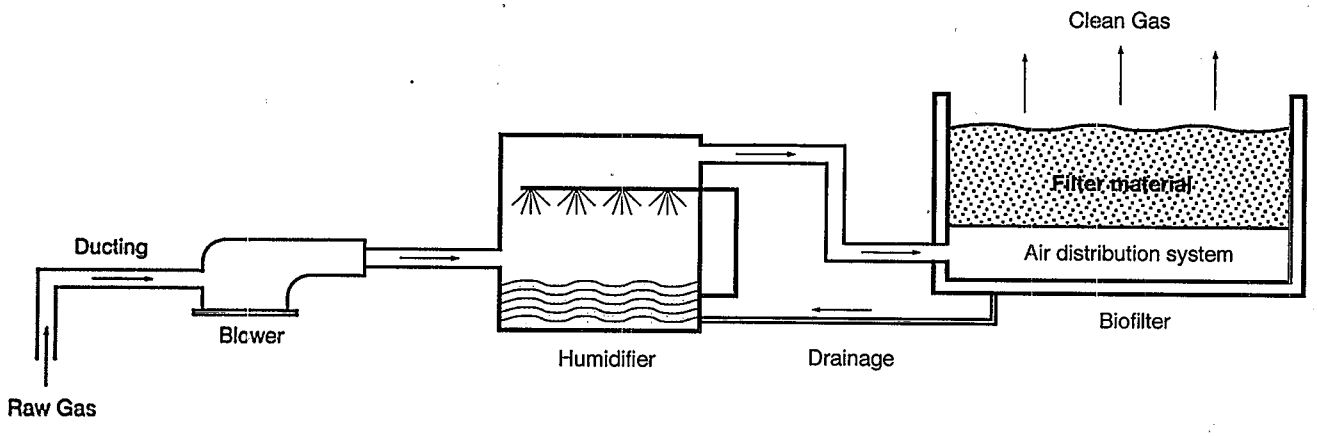


Figure 5-18. Schematic of an open, single-bed biofiltration system.

Typically, the filter material is compost, peat, wood chips, or soil with an inert material such as polystyrene particles or porous clay. As the VOCs are degraded, water, carbon dioxide, mineral salts, and biomass are generated. Mineralization leads to compaction of the filter material which causes an increase in back pressure. Typically the filter material is turned over after 2 years of operation and usually replaced 1-2 years after turning over the filter to prevent back pressure problems (Leson and Winer, 1991).

The most common biofilter system is an open, single-bed system. The clean gas is vented directly to the atmosphere in an open biofilter. Enclosed, multiple-bed systems can be stacked and have been employed for low maintenance and space constraint situations.

5.6.2 *Applicability to Remediation Technologies*

The applicability of biofiltration is dependent on the characteristics of the waste gas. Typical biodegradable contaminants include: alcohols, ethers, aldehydes, ketones, amines, sulfides, and certain monocyclic aromatics (xylene, benzene, toluene and phenol). Waste streams containing chlorinated solvents are not readily biodegradable and are not appropriate for emissions control by biofiltration.

Biofiltration, as a VOC control technology, results in the complete degradation of the biodegradable contaminants and avoids the cross media transfer of pollutants. A major requirement, and thus limitation, of biofiltration is the absence of biologically toxic substances in the waste gas, such as heavy metals. The technology is limited to biodegradable components.

Since biofiltration is biologically sensitive, the potential system failures represent areas that should be considered when evaluating this technology. An undersized filter can result in VOC air emissions due to insufficient treatment. Since the filter is sized by off-gas flow rate and concentration, the off-gas should remain within these design parameters during operation to prevent the loss of control efficiency. Inadequate preconditioning of the off-gas for temperature, moisture, particulates, or toxic constituents can also result in the complete loss of control efficiency.

Intermittent off-gas streams can be treated with a biofilter assuming the flow rate and concentration of the gas stream are within the design values. Filter beds can survive shut down periods of at least two weeks without any significant reduction in biological activity. Shut down periods up to two months are feasible with nutrient addition and aeration of the filter (Leson and Winer, 1991).

Biofiltration is not known to be used as a control technology at any Superfund sites, but this technology would be an appropriate VOC control for large volume gas streams with low concentrations (e.g. certain soil vapor extraction systems). One potential use of biofiltration is odor control at Superfund sites assuming the odor constituents are biodegradable. Since odor problems usually are caused by compounds with low odor thresholds, off-gas concentrations often will be relatively low (Leson and Winer, 1991). Biofiltration also may be an appropriate treatment for VOCs that have already been reduced by a primary control device. The lower concentration off-gas stream would require a smaller filter size, which results in lower capital costs.

5.6.3 *Range of Effectiveness*

Biofiltration usually is cost effective for large volume gas streams with relatively low concentrations (< 1000 ppm as methane) of easily biodegradable contaminants (Leson and Winer, 1991). Maximum influent VOC concentrations have been found to be 3000-5000 mg/m^3 (Leson and Winer, 1991). For optimum efficiency, the waste gas should be 20-40°C and 95% relative humidity. The filter material should remain at 40-60% moisture by weight and have a pH between 7 and 8 (Leson and Winer, 1991). For most easily biodegradable constituents, control efficiencies greater than 90% are achievable (APC, 1991b). Degradation rates for common air pollutants are typically from 10 to 100 g/m^3-hr (Leson and Winer, 1991).

The key parameters affecting the control efficiency of a biofiltration system include the environmental conditions in the filter material, biofilter design, filter size, and waste gas composition. The filter must also have a large reactive area and low pressure drops; therefore, compaction must be kept to a minimum.

5.6.4 *Sizing Criteria*

Typical biofilter systems have been designed to treat 1,000-150,000 m^3/hr waste gas with the systems having 10-2,000 m^2 of filter area (Leson and Winer, 1991). The depth of biofilter material is typically three to four feet. The size of a biofilter system is dependent on the following parameters:

1) The loading rate of waste gas;
2) The concentration of compounds in the waste gas; and
3) The rate of degradation of the compounds per unit volume.

Surface loads up to 300 m^3/hr of waste gas per m^2 filter area are feasible without excessively high back pressures (Leson and Winer, 1991). The type of filter material affects the pressure drop across the filter. The effect of filter material on pressure drop is shown in Figure 5-19 as a function of the surface loading rate.

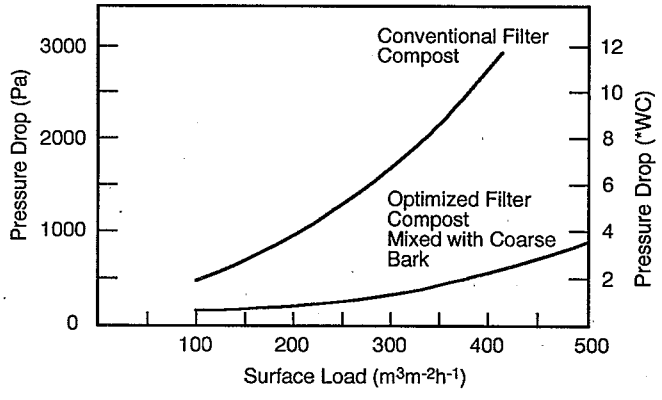


Figure 5-19. Pressure drop for two filter materials as a function of surface loading rate.

Higher surface loads render the biofilter more susceptible to dehydration and heat losses caused by insufficient raw gas conditioning. The filter's large mass often provides sufficient buffer capacity to prevent breakthroughs during peak loadings, which allows sizing based on average hourly peak loads (Leson and Winer, 1991).

The removal process in biofilters has been postulated to be controlled initially by a first-order-type biodegradation rate, but to be limited by transport properties at low inlet air flow rates (Miller and Canter, 1991). Pilot testing of industrial waste gas streams with multiple contaminants is usually required, rather than modelling, to accurately size the full scale system.

5.6.5 Cost Estimating Procedure

Capital costs have been estimated at \$60-95 per ft^2 filter area for installed open, single-bed biofilter systems. Costs of open, multiple-bed systems are approximately two times these costs. Enclosed systems have been estimated to cost between \$95-525 per ft^2 filter area, depending on the size of the biofilter and the degree of process control (Leson and Winer, 1991). Operating costs are \$0.35-1.60 / 100,000 SCF, not including filter replacement costs (APC, 1991b; Leson and Winer, 1991). Maintenance costs are about one labor hour per square meter of filter per year.

5.7 Operational Controls

Operational controls are those procedures or practices inherent to the operation (and design) of control systems that can be followed to minimize the overall long-term emissions. Among these are:

- Adequate system design and installation;
- Startup testing;
- Preparation of standard operating procedures for operators;
- Control of operating variables to minimize emissions;
- Monitoring of system performance;
- Minimization of process upsets and startups; and
- Preventative and routine maintenance.

Obviously, a properly designed and operated control system is necessary to achieve the required emission control efficiency or emission limits. The use of experienced contractors and vendors will help ensure that the system design and installation are done correctly. Startup testing is advisable, with as many test conditions examined, as possible, and all meaningful data recorded and evaluated. Systematic checks of wiring, direction of fan and pump rotation, integrity (leak tightness), etc. should be made. The startup testing results should be incorporated into the formal standard operating procedures (SOPs) prepared for and followed by the operators of the equipment.

Superfund remedial actions tend to present special problems that affect control system operation and effectiveness. The waste or soil to be treated tends to be highly heterogeneous which results in off-gas streams with variable composition. Further, the remediation activities themselves tend to start and stop due to problems with equipment, weather, schedule, etc., therefore the control systems frequently may encounter non-steady state conditions (e.g. startup). The control efficiencies reported in this document are based on steady-state operating conditions and emissions will be significantly higher during startup, process upsets and excursions, or when the off-gas stream is out of design specifications.

Operating variables can be controlled to minimize emissions. The most obvious variable to control is the treatment rate; e.g., the lower the feedrate to an incinerator, the lower the mass of potential emissions. Other variables such as the aeration rate for biodegradation systems, also directly influence emissions. Controlling operating variables to minimize emissions is not always straightforward. There may be a number of competing variables that must be balanced for optimal control system performance. For example, reheating of off-gas streams prior to carbon adsorption systems frequently is done to lower the relative humidity of the gas stream and improve performance. However, the higher temperature can affect performance negatively. These two competing requirements must be offset. Similarly, pressure drop versus control efficiency and operating cost is often an issue.

To properly operate control devices, the system design and performance must be understood. Performance data can be generated by routine monitoring of influent and effluent emission levels, pressure drops, operating temperatures, and so on. Operators should maintain the monitoring system so that plugged lines, water in the lines, etc. don't result in misleading readings.

Proper maintenance is another obvious requirement for successful control system operation, including routine inspection of the equipment and implementation of corrective action when needed.

5.8 Membrane Technology

5.8.1 Process Description

Membrane technology is an emerging control process for volatile organic compound emissions in waste gas streams. The membrane module acts to concentrate the organic solvent by being more permeable to organic constituents than air. The imposed pressure difference across a selective membrane drives the separation of the solvent from the gas stream.

A schematic of a typical membrane separation process is shown in Figure 5-20. The pressure difference is caused by either a vacuum pump on the permeate side of the membrane module (Figure 5-20a) or a compressor before the membrane separator (Figure 5-20b). Collected VOC emissions are transported to the membrane module by either a blower or compressor. The imposed pressure difference across the membrane drives the separation of the feed gas into a concentrated stream (permeate) and a depleted residue gas stream. Most of the organic contaminant is transferred through the membrane with some gas permeating the membrane. The stripped off-gas is either vented or recycled to the VOC source.

The concentrated permeate stream must be treated further to either recover or dispose of the contaminants. In membrane systems, the membrane functions to concentrate the VOCs in the stream. The permeate may be treated in various ways. The process configurations for recovering the contaminants are shown in Figure 5-21.

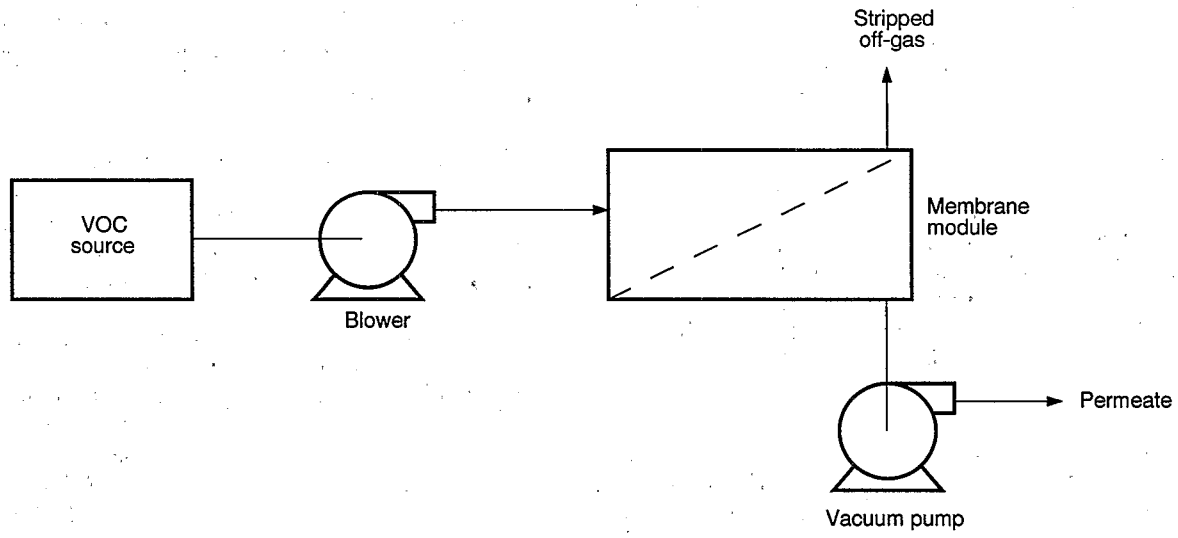


Figure 5-20a. Membrane separation system with vacuum pump.

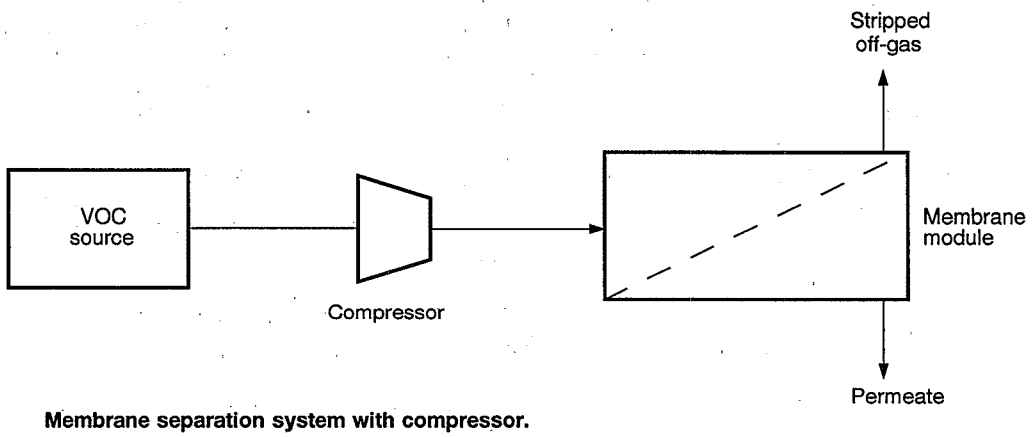


Figure 5-20b. Membrane separation system with compressor.

In Figure 5-21a, the recovery system consists of a carbon adsorption system to collect the solvent. The solvent is recovered during the steam regeneration process. The vapor stream from the regeneration process is condensed and then decanted to separate the water from the recovered solvent. Membrane Technology and Research, Inc. (MTR) has developed and patented a process (Baker, et al., 1984) to recover the solvent by condensation after concentration by the membrane (Figure 5-21b). Figure 5-21c represents a membrane system that collects the solvent by direct condensation of the permeate and polishes the stripped gas stream with activated carbon to remove any residual VOCs. Incineration also can be used to destroy the contaminants in the concentrated stream.

The membrane module itself consists of an ultrathin layer of a selective polymer supported on a porous sublayer. The polymer layer acts as the selective barrier; the microporous substructure provides mechanical strength for the module. Typical membrane materials include rubber (silicone and nitrile), PVC, neoprene, silicone polycarbonate, and other polymer compounds. In a spiral-wound membrane module, layers of the polymer are supported on a mocroporous structure. The module can also be in the hollow tube form. Either a blower and vacuum pump or a compressor is required to supply the pressure differential required for separation across the membrane. Other equipment requirements depend on the process configuration.

5.8.2 Applicability to Remediation Technology

Membrane technology as a control device for VOC emissions is an emerging technology. Some of the theoretical aspects of the technology are being developed; at this time, only very limited practical applications exist. Typically, a membrane separation system would be used as a concentrator prior to other VOC control devices. The concentrated waste stream generated from the membrane module could be used to reduce the size and, therefore, the capital and operating requirements of the primary VOC control device.

The industrial applications that are best suited for membrane technology are situations that require a high quality recovered product and situations where carbon adsorption will not work

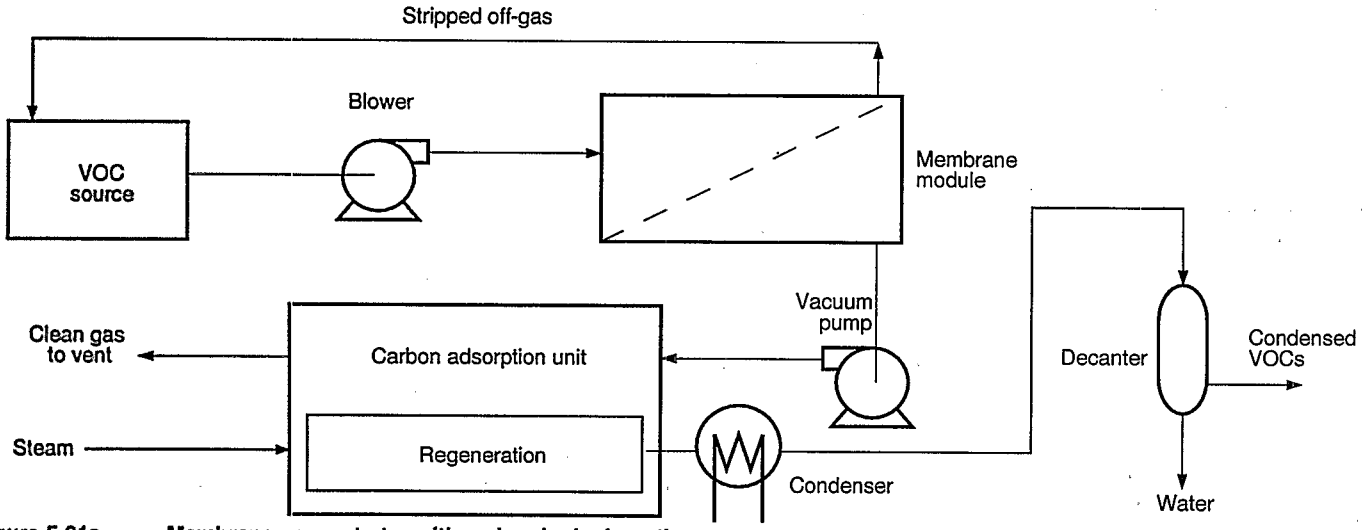


Figure 5-21a. **Membrane concentrator with carbon bed adsorption recovery system.**

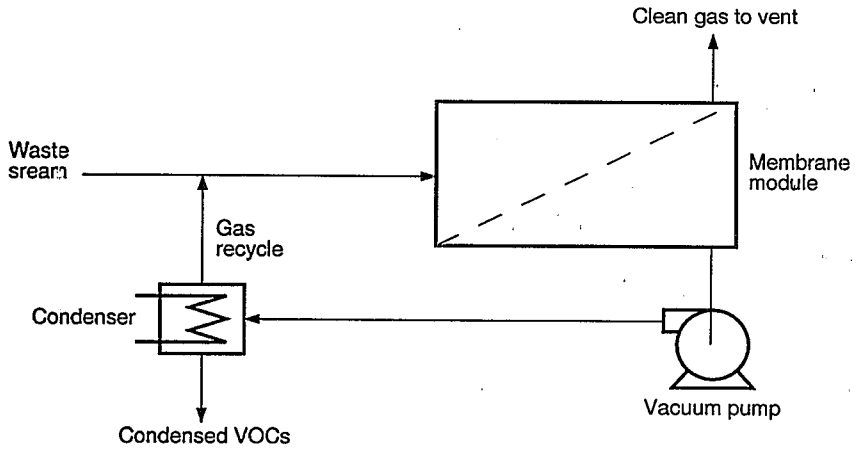


Figure 5-21b. **MTR single-stage membrane system.**

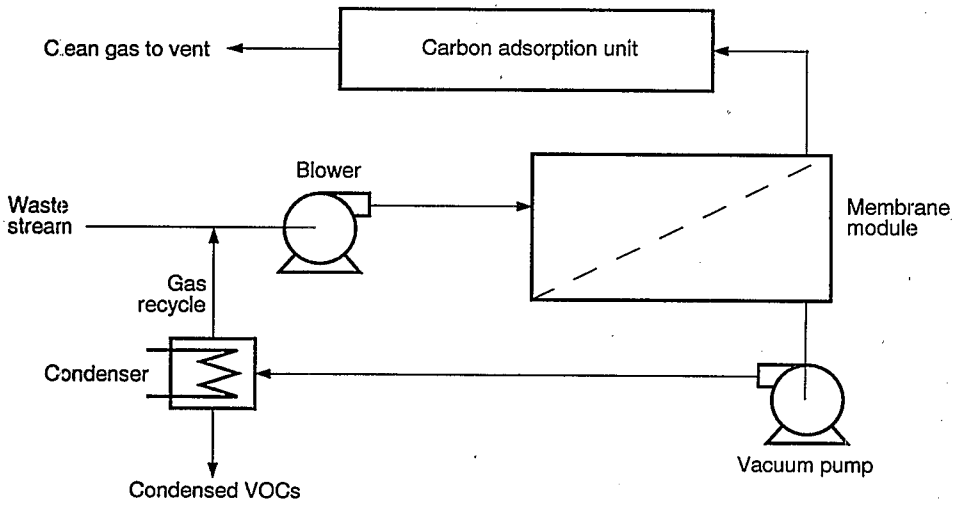


Figure 5-21c. **Single-stage membrane separation system with carbon bed adsorber polishing.**

(e.g. recovery of ketones or aldehydes due to fire hazard or 1,1,1 - trichloroethane due to its reactivity with the carbon). Several options are available for further treatment of the permeate. Direct condensation of the solvent is feasible at higher concentrations, especially for solvents that are expensive or where recovery is necessary. Incineration would be appropriate if the concentrated stream has a high heating value and the solvent is inexpensive. Carbon adsorption may also be an alternative for treating the permeate stream. The solvent can be collected in a carbon adsorption unit and recovered by a steam regeneration process. Overall, a membrane concentrator can result in cost savings, improvement in the reduction of emissions and the reduction of energy requirements for incineration (Hummel and Nelson, 1990).

5.8.3 Range of Effectiveness

Membrane technology has been reported to be applicable for low volume, high concentration off-gases (APC, 1991a). Gas streams containing 0.05 - 20% organics are suitable for membrane processes. Membrane separation processes are very efficient bulk concentrators. The permeate stream concentration may be 10 to 50 times the VOCs concentration of the inlet gas stream.

The control efficiency of membrane separation technology is influenced by the following factors:

1) The solvent permeability; and
2) The separation factor.

The permeability is the solvent flux across the membrane. The permeability of a solvent is related to its diffusivity and solubility. For organic vapors, the permeabilities usually increase with concentration and at high pressures (Baker, et al., 1987).

The separation factor is defined as the degree of concentration the membrane can achieve and is related to the selectivity of the membrane. The separation factor refers to the relative permeabilities of the solvent and gas. A higher separation factor results in a more efficient separation process. Both of these parameters are dependent on operating conditions such as the pressure ratio (permeate-side pressure/inlet pressure) and the membrane material.

For high removal efficiency, the membrane material should exhibit high permeability and good selectivity for the solvents to be recovered. The membrane should be durable and stable to withstand normal wear during operation.

Membrane performance is determined by the selectivity and the pressure (Peinemann, et al., 1986). The relationship between these parameters can be described by the following equation:

$$C_2'' = \frac{1}{2}\frac{1}{\gamma}\left[C_2' + \gamma + \frac{1}{\alpha-1} - \sqrt{\left(C_2' + \gamma + \frac{1}{\alpha-1}\right)^2 - \frac{4\gamma C_2'\alpha}{\alpha-1}}\right] \quad \text{(Eq. 5-33)}$$

where:

C_2'' = Permeate concentration of solvent gas;
C_2' = Feed concentration of solvent gas;
γ = Pressure ratio = total permeate pressure (p'') / total feed pressure (p'); and
α = Selectivity = permeability to solvent / permeability to air.

A graphical representation of the relationship of pressure ratio and permeate concentration is shown in Figure 5-22. This relationship is described by Equation 5-33. The relationship simplifies when $\alpha >> 1/\gamma$ where the concentration is dependent only on the pressure ratio. When $\alpha << 1/\gamma$, the permeate concentration is determined by the selectivity (Peinemann, et al., 1986).

Permeability data can be found as a function of pressure and selectivity for various membrane materials and contaminants in Baker, et al., 1987. Other references with test data include: Strathman, et al., 1986 and Peinemann, et al., 1986.

5.8.4 Sizing Criteria

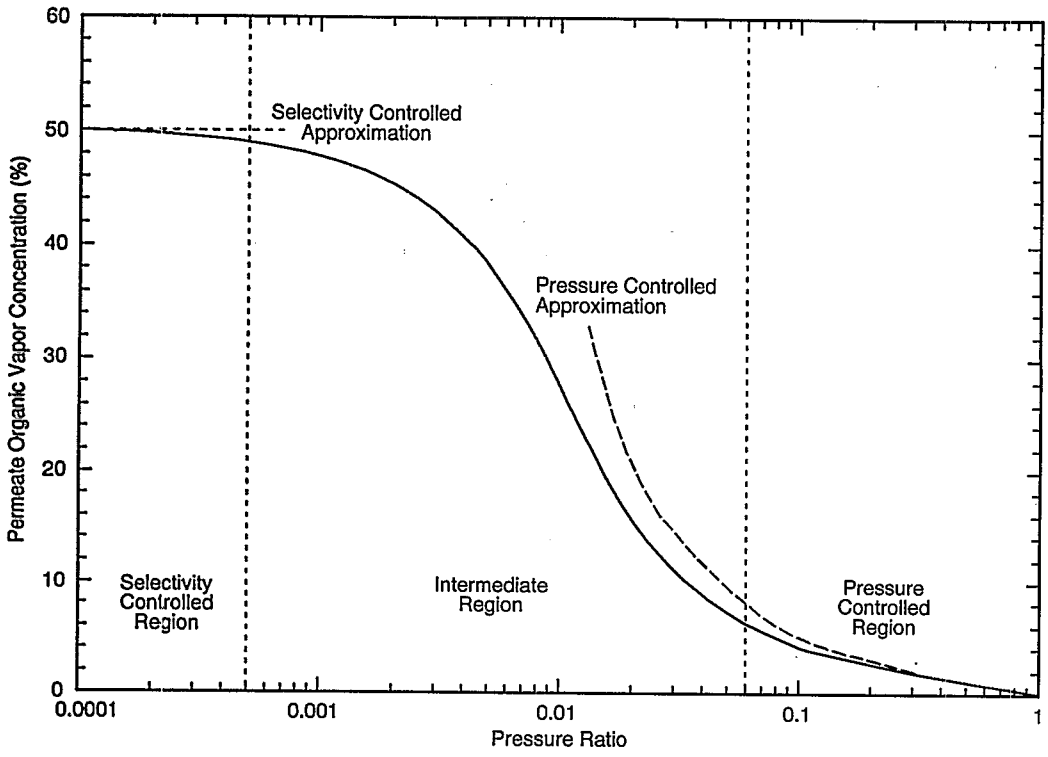
The optimum membrane selectivity is chosen to balance the capital costs of the membrane area and the cost of pumping energy. Since the solvent flux decreases as the membrane selectivity, increases, the membrane area required to treat a given amount of solvent increases. The optimum membrane selectivity is the lowest selectivity that will produce the desired permeate concentration. The energy requirement for a low selectivity membrane, however, is greater since a higher volume of gas must be pumped to meet the permeate requirements (at a fixed permeate pressure). The selection of the membrane must therefore balance the membrane area and energy requirements (Peinemann, et al, 1986).

The fundamental mass and energy balance equations governing the design and performance of a single-stage gas permeation system is presented by Weller and Steiner, 1950. Further analysis was performed by Pan and Habgood for the cross-flow pattern, which applies to the spiral-wound membrane. The simplifying assumptions for their analyses are: permeabilities of both components are constant, negligible pressure drop across flow paths, and negligible mass transfer resistances except for permeation through the membrane. The error introduced by assuming constant permeabilities was not found to be excessive in test studies for most cases (Hummel and Nelson, 1990).

The equations describing membrane performance simplify considerably as the feed concentration approaches zero. The equations are outlined below (Pan and Habgood, 1974):

$$F = 1 - \left(\frac{x}{x_f}\right)^{\left[\frac{\alpha}{(1-\gamma)(\alpha-1)}\right]-1} \quad \text{(Eq. 5-34)}$$

$$\frac{x}{x_f} = \frac{\left[1 - \left(\frac{x}{x_f}\right)^{\frac{\alpha}{(1-\gamma)(\alpha-1)}}\right]}{F} \quad \text{(Eq. 5-35)}$$



Source: Redrawn from Peinemann, et al., 1986.

Figure 5-22. Calculated permeate solvent concentrations produced by a membrane with a selectivity of 200 and a feed organic vapor concentration of 0.5%. The three different operating regions for this type of membrane are shown.

$$R_f = \frac{F}{(1-\gamma)} \qquad \text{(Eq. 5-36)}$$

where:

- F = Fraction permeated (stage cut);
- x_f = Mole fraction of solvent in feed gas;
- x = Mole fraction of solvent in residue off-gas;
- y = Mole fraction of solvent in permeate;
- γ = Pressure ratio;
- α = Selectivity (permeability of solvent/permeability of nitrogen); and
- R_f = Dimensionless membrane area.

These equations are valid for finite $1/x_f$ provided that $1/x_f$ is greater than both α and $1/\gamma$. An outline of the design procedures for a spiral-wound membrane module is shown in Figure 5-23. The membrane area can be calculated from the following equation (Hummel and Nelson, 1990):

$$S = \frac{\gamma\, R_f\, d\, L_f}{Q_a\, P} \qquad \text{(Eq. 5-37)}$$

where:

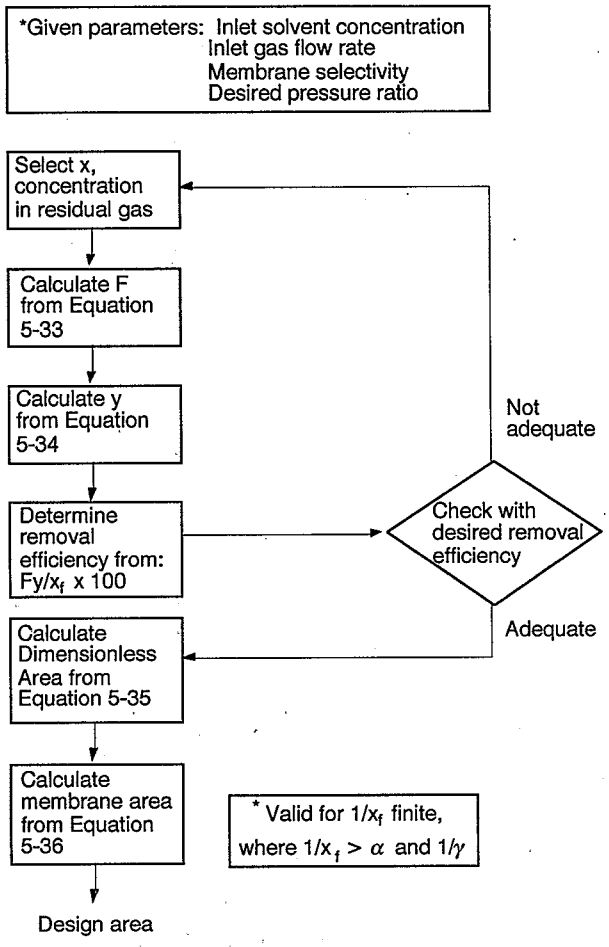
- S = Membrane area, ft²;
- d = Membrane thickness, ft;
- L_f = Inlet molar flowrate, lb-mol/hr;
- P = Feed side pressure, psia; and
- Q_a = Permeability of solvent, lb-mol ft/hr psi ft² = (flux)·d/S· (partial pressure).

The permeability of the solvent, Q_a, is determined experimentally from testing at the appropriate operating conditions.

One consideration that should be taken into account for the design of a membrane separation unit is the lower explosion limit (LEL). A membrane preconcentrator handling flammable vapors in the presence of oxygen (i.e., air) could result in shifting the concentration within the explosive range (higher than the LEL value).

5.8.5 *Cost Estimating Procedure*

The cost of implementing membrane technology as a control mechanism for VOCs must be considered with the additional components needed to comprise the complete system. The membrane usually acts as a concentrator with the permeate stream requiring further treatment to collect or destroy the contaminants. As stated before, further treatment may consist of carbon adsorption (residue off-gas or permeate stream), condensation, or incineration. A more concentrated stream that is to be incinerated has less of an energy requirement than a diluted stream. In this case, incineration will be more economical. Solvent recovery by



Source: Adapted from Hummel and Nelson, 1990.

Figure 5-23. Design procedure for a spiral-wound membrane, based on Pan and Habgood principles.

condensation may be more feasible for a more concentrated stream. In the case of recovering the solvent by carbon adsorption and steam regeneration, the addition of the membrane preconcentrator was not found to be cost effective even with the decreased gas flowrate since the carbon required to collect the solvent remained the same (Hummel and Nelson, 1990).

The capital cost of the membrane is directly related to its surface area. The costs of the membrane module and other system costs associated with the membrane unit are presented in Table 5-17. These costs do not represent any permeate treatment costs. The system costs were not clearly defined and may include vacuum pump or compressor costs. Some cost estimates for designs found in the literature are presented in Table 5-18. Any specifics on the estimate are provided in the table. The cost of the system will be very dependent on the treatment requirements of the permeate and off-gas streams.

Cost information for capital and operating costs are presented in Table 5-19. The effects of plant size, membrane flux, and inlet feed concentration are considered.

An extensive cost estimate was prepared for the system shown in Figure 5-21a by Hummel and Nelson, 1990. The base case was considered to be recovery of the solvent with a carbon adsorption unit alone. The cost estimate evaluated the effect of membrane selectivity, control efficiency, origination of pressure differential (compressor or vacuum pump), inlet gas flow rate, and solvent concentration for toluene and CFC-113. The results for a 100 ppmv CFC-113 gas stream at an inlet of 250 acfm are shown in Figure 5-24. The estimate includes the cost of solvent recovery by carbon adsorption and steam regeneration, which as stated before, does not seem to be the most economical approach. Further data can be found in the reference.

5.9 Emerging/Miscellaneous Controls

A number of emerging technologies for VOC control have received attention in recent years. The two emerging technologies that have been best demonstrated, biofilters and membranes, have been discussed in detail in earlier subsections. A third emerging VOC control technology, ultraviolet (UV) photolysis, is discussed below.

5.9.1 Process Description

Ultraviolet light technologies have been used for the destruction of toxic organics in aqueous solutions since about 1988. In some cases, UV light has been used alone for treatment; in others, UV light has been used in conjunction with ozone and hydrogen peroxide, which serve as oxidants (Roy, 1990). Figure 5-23. Design procedure for a spiral-wound membrane, based on Pan and Habgood principles.

Recently, direct UV photolysis of organics has been achieved experimentally using a broad spectrum of high intensity ultraviolet light. Experiments have included treatment of water, air, and soil. The authors have claimed that the direct UV photolysis process can disintegrate toxic organics into non-toxic byproducts. Ultraviolet Energy Generators, Inc. (UVERG) have claimed the Wekhof Direct UV Photolysis Process to be "both the most efficient and clean method of organics destruction in water, gas, and in soil" (Wekhof, 1991).

Purus, Inc. has also developed a direct UV photolysis process for on-site cleanup of organic contaminants. The company claims its systems, which use xenon UV flashlamps, convert organic contaminants into harmless byproducts. Purus, Inc. has adver-

Table 5-17. Costs for the Membrane Module and Other System Costs

Membrane module	Other system costs	Source of cost information
$231/m²	$231/m²	Nitto Denko (Japan)
54/m²	54/m²	(Peinemann, et al., 1986)
201/m²	252/m²	(Stattman, et al., 1986)
Best cost estimate		
160/m² [a]	60/m² [b]	

[a] Cost basis for membrane, an approximate average of the cost data.
[b] Cost basis for other system costs was reduced to $60/m² since cost data from other sources included equipment not within the membrane system.

Adapted from Hummel and Nelson, 1990.

Table 5-18. Design Specifications and Costs for Components of Membrane Control Systems

Case	System	Specifics		Cost ($)		Source
1	Vacuum pump and blower	Inlet conc.	0.5 vol%	Membrane	54,700	Peinemann, et al., 1986
		Permeate conc..	4.4 vol%	Other system	54,700	
		Residue conc.	0.1 vol%	Blower	40,200	
		Feed flow	1400 scfm	Pump	295,000	
		Volume recovered	1000 l/day			
		Mem area	1020 m^2	Total	444,600	
		Mem. selectivity	150			
		Pressure ratio	0.05			
2	Vacuum pump and blower; carbon adsorption recovery unit	Inlet conc.	100 ppm CFC-113		736,500	Hummel & Nelson, 1990
		Removal eff.	57%			
		Feed flow	2500 CFM			
3	Compressor; carbon adsorption	Inlet conc.	1000 ppm CFC-113		437,500	Hummel & Nelson, 1990
		Removal eff	57%			
		Feed flow	2500 CFM			
4	Vacuum pump	Permeate conc.	50 wt%	Membrane	91,100	Baker, et al., 1985
		Inlet conc.	0.5 sol%	System	91,100	
		Feed flow	10,000 scfm	Pump	13,400	
		Volume recovered	6 l/min	Install & other	20,000	
		Mem. area	1700 m^2			
		Mem. solvent flow	5 l/m^2 day	Total	215,600	

tised a commercial system for treatment of contaminated air emissions by UV photolysis.

A flow diagram for a direct UV photolysis system is shown in Figure 5-25. In a typical direct UV photolysis system, contaminated air enters one or more processing chambers in which the contaminants are subjected to a broad spectrum of UV light emitted by UV flashlamps. The organic contaminants absorb varying wavelengths of UV light. The absorbed energy causes the bonds of the organic molecules to break apart. Under ideal conditions, the carbon atoms of the molecules, along with oxygen present in the air, may simply form carbon dioxide. If analysis indicates sufficient removal of contaminants, the treated air stream may be released to the atmosphere (Purus, 1991).

5.9.2 Applicability to Remediation Technologies

UV photolysis may be effective in destroying volatile organic compounds (VOCs) in contaminated air streams. Contaminants that could be removed from air streams by UV photolysis may include volatile chlorinated organic compounds (e.g., trichloroethylene (TCE) and methylene chloride) and volatile organic compounds present in gasoline and petroleum products (e.g., benzene and toluene).

UV photolysis has not been reported in the literature as a control technology for air emissions at Superfund sites. This technology may be appropriate to control emissions of toxic organic compounds released by wastewater and groundwater treatment technologies such as biological treatment and air stripping. It also may be appropriate in treating air emissions

Table 5-19. Effect of Plant Size, Membrane Flux, and Feed Concentration on Capital and Operating Costs for Membrane Systems

Parameter		Capital costs ($) [a]	Operating costs ($) [b]
Plant size (scfm)	Area (m^2)		
10,000 [c]	1,700	215,800	67,100
5,000	850	31,500	33,600
2,000	340	71,400	13,400
500	85	30,700	3,350
Membrane flux	Area (m^2)		
(l/m^2 day)			
10.0	850	131,500	52,000
5.0 [c]	1,700	215,800	67,100
2.5	3,800	362,600	97,600
1.0	8,500	759,200	188,800
Feed concentration	Membrane flux		
(vol %)	(l/m^2 day)		
0.5 [c]	5.0	215,800	67,100
0.25	2.5	215,800	48,800
0.1	1.0	215,800	37,800
0.05	0.5	215,800	34,000

[a] Membrane module costs assumed to increase directly in proportion to membrane area. Others increase in proportion to the square root of plant size.
[b] Operating costs are assumed to be proportional to the solvent flow through the plant. Includes module replacements costs (3-year lifetime).
[c] Base case.

Source: Adapted from Baker, et al, 1985.

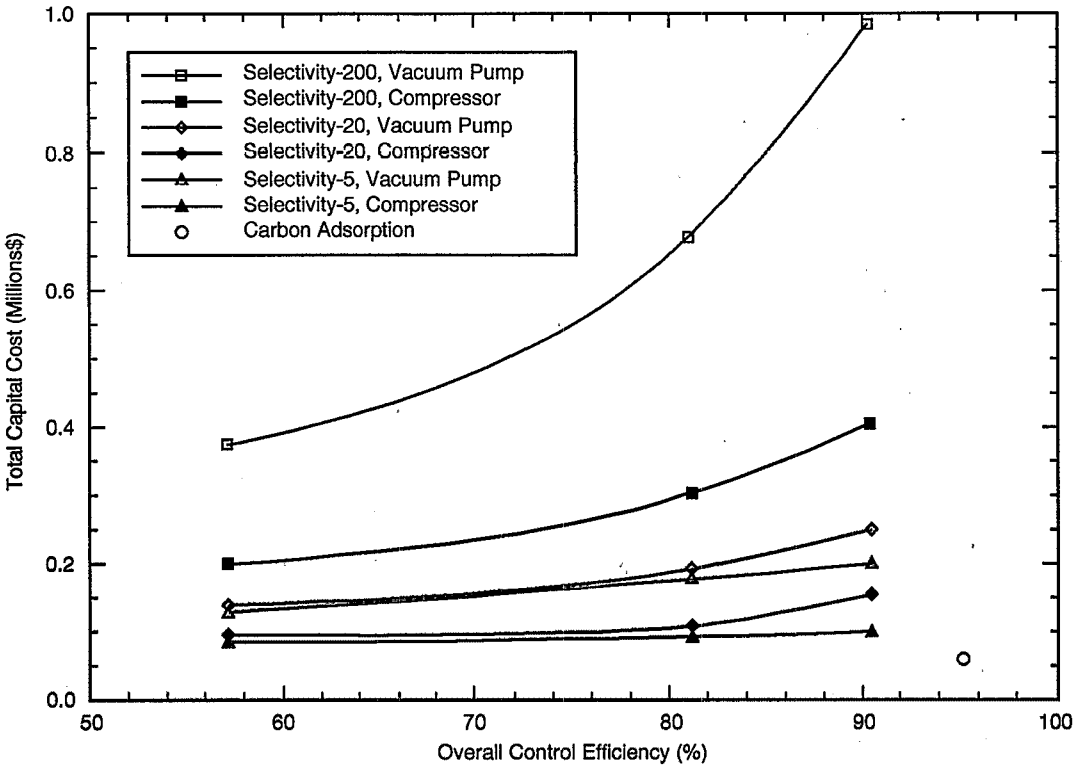


Figure 5-24. Capital cost comparison (250 acfm, 100 ppm, CFC-113 feed).

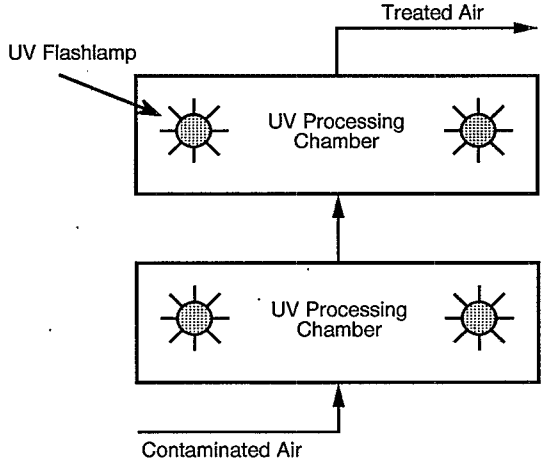


Figure 5-25. Schematic of direct UV photolysis.

from in situ remediation of soil by vacuum extraction. UV photolysis would have the advantage of destroying toxic organic compounds rather than transferring the compounds to another medium (e.g., activated carbon).

5.9.3 Range of Effectiveness

Since studies examining the destruction of organics through treatment of contaminated air streams by UV photolysis have been limited, the range of conditions over which this treatment may be effective is unclear. One study indicated that the concentration of TCE in an air stream was reduced by UV photolysis from 300,000 ppb to 100 ppb for a residence time of approximately 3 seconds (Purus, 1991). Without additional data, the general effectiveness of this technology for Superfund applications can not be determined.

5.9.4 Sizing Criteria

No specific sizing criteria are available for treating air emissions by UV photolysis. The size of a UV photolysis system will depend primarily on the following parameters:

1) The flow rate of the contaminated air stream;
2) The concentrations of destructible compounds in the air stream; and
3) The refractoriness of the compounds.

Pilot UV photolysis tests would be performed on a sample air stream to determine the appropriate size for a full-scale system.

5.9.5 Cost Estimating Procedure

No cost estimates have been reported in the literature for vapor-phase treatment using full-scale direct UV photolysis units. Although Wekhof (1991) estimates costs for treatment of wastewater and soil by UV photolysis, the costs for treatment of air streams is not estimated. Costs for treatment of contaminated air emissions by the Purus, Inc. direct UV photolysis process are not available.

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Chapter 6
Point Source Controls for Particulate Matter, Metals, Acid Gases, and Dioxins and Furans

Information is presented in this chapter about various control technologies whose primary use is to control emissions of particulate matter (PM), metals, acid gases, and dioxins and furans. Control technologies addressed in this chapter are fabric filters (i.e., baghouses), wet and dry electrostatic precipitators (ESPs), wet scrubbers, dry scrubbers, operational controls, and miscellaneous technologies such as HEPA filters. Quench chambers, cyclones, and venturi scrubbers are covered under wet and dry scrubbing. The discussion for each control technology includes a process description, applicability for remediation technologies, range of effectiveness, sizing criteria, and cost information.

The Superfund applications of the control technologies covered in this section are limited almost exclusively to incineration and thermal desorption. The controls may each be somewhat effective at removing particulate matter, metals, acid gases, and dioxins. They tend to be used in series so that the overall removal efficiency for the train of air pollution controls (APCs) meets design specifications. For example, an on-site incinerator may have a series of control devices: 1) cyclone, quench tower, baghouse, and wet scrubber; or 2) spray tower (quencher) and baghouse; or 3) cyclone, water quench, and packed tower (HMCRI, 1991). Many other combinations also may be used.

6.1 Fabric Filters

6.1.1 Process Description

Fabric filters are a type of air pollution control device designed for controlling particulate matter emissions from point sources. A typical fabric filter consists of one or more isolated compartments containing rows of fabric bags or tubes. In a fabric filter, particle-laden gas passes up along the surface of the bags then radially through the fabric. Particles are retained on the upstream face of the bags, while the clean gas stream is vented to the atmosphere. The filter is operated cyclically so that it alternates between long periods of filtering and short periods of cleaning. During cleaning, dust that has accumulated on the bags is removed from the fabric surface and deposited in a hopper for subsequent disposal.

Fabric filters will collect particle sizes ranging from submicron to several hundred microns in diameter at efficiencies generally in excess of 99 percent. Gas temperatures up to about 500°F, with surges to approximately 550°F can be accommodated routinely. Most of the energy used to operate a fabric filter system appears as pressure drop across the bags and associated hardware and ducting. Typical values of pressure drop range from about 5 to 20 inches of water column.

Important process variables in a fabric filter system include particle characteristics, gas characteristics, and fabric properties. The most important design parameter is the air-to-cloth ratio, and the usual operating parameter of interest is the pressure drop across the filter system. Baghouses can be operated on an intermittent or continuous basis. In the latter case the system is usually divided into sections, so bags can be taken off-line for cleaning. When cleaning must be done off-line the system tends to be more expensive since extra cloth area (capacity) is required.

Fabric filters often are categorized by the method used to clean the dust-cake off of the filter. Using this method of categorization, three common types of filters are: 1) shaker filters, 2) reverse-air filters, and 3) pulse-jet filters. The process flow diagram for a typical shaker filter is shown in Figure 6-1.

In a shaker filter, the bags are hung on a framework that is oscillated by a motor controlled timer. In this type of system the baghouse usually is divided into several compartments. The flow of gas to each compartment periodically is interrupted and the bags are shaken to remove the collected dust. The shaking action produces more wear on the bags than other cleaning methods. For this reason, the bags used in this type of filter are usually heavier and made from durable fabrics.

In the second type of fabric filter, reverse air filters, gas flow to the bags is stopped in the compartment being cleaned, and a reverse flow of air is directed through the bags. The advantage of this approach is that is "gentler" than shaking, which allows the use of more fragile or lightweight bags.

The third type of baghouse, pulse-jet fabric filters, are by far the most common type for Superfund applications. In this type of system a blast of compressed air is used to expand the bag and dislodge the collected particles. One advantage of pulse jet fabric filters is that bags can be cleaned on line, which means that fewer bags (less capacity) are required for a given application.

6.1.2 Applicability to Remediation Technologies

Three factors that affect the feasibility of using a baghouse to control particulate emissions are the flue gas temperature, the gas stream composition, and the particle characteristics. The tem-

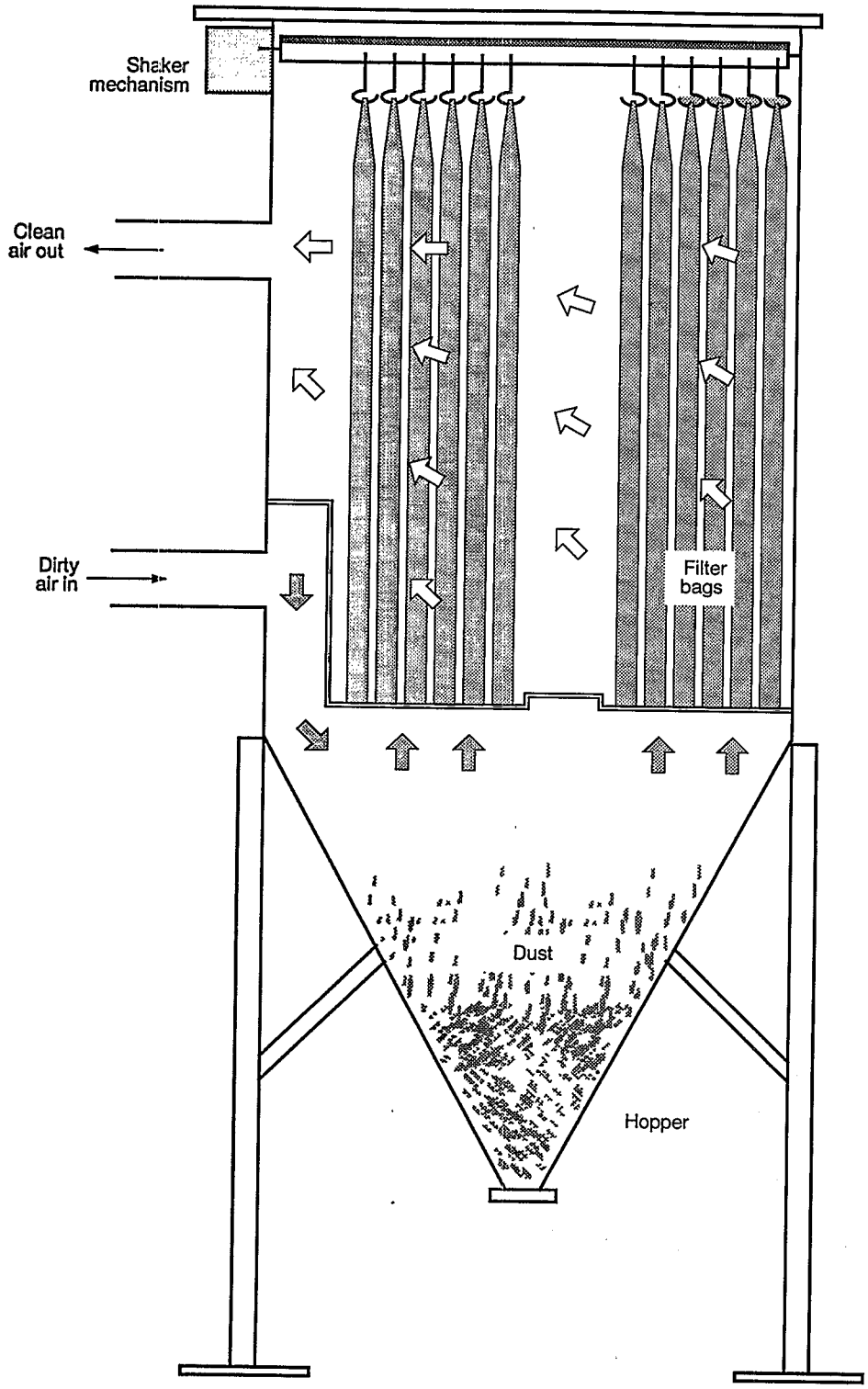


Figure 6-1. Fabric filter process flow diagram.

perature of the waste gas stream to be cleaned must be above the dewpoint of any condensibles in the stream, but below the maximum temperature for the fabric. Condensibles will wet the filter cake and make cleaning very difficult, as well as increase the pressure drop across the filters. Other gas stream and particle characteristics also must be considered in since fabric filters may not be suitable for certain types of gas streams or particles. For example, a fabric filter may not be suitable for an application in which the waste gas particulate matter contains a significant fraction of acid mist. Also, "sticky" or adhering particles might preclude the use of a baghouse. For baghouses operated in cold climates that use compressed air, shelters should be constructed around the equipment to prevent freezing of condensed moisture in the air compressor lines.

Since baghouses are used only as particulate controls on dry waste gases, their use as controls for Superfund site remediations are limited to cases where incineration or thermal desorption are being used to remediate the site. Baghouses frequently are used in conjunction with dry scrubbers. Baghouses are also highly effective for the removal of heavy metals.

6.1.3 *Range of Effectiveness*

A well designed fabric filter can achieve collection efficiencies in excess of 99 percent, although optimal performance of the system may not occur for a number of cleaning cycles as the new filter material is "broken in." The fabric filter collection efficiency is related to the pressure drop across the system, component life, filter fabric, cleaning method and frequency, and the air-to-cloth (A/C) ratio.

Modifications to improve performance include changing the A/C ratio, using a different fabric, or replacing worn or leaking filter bags. Collection efficiency can also be improved by decreasing the frequency of cleaning or allowing the system to operate over a greater pressure drop before cleaning is initiated.

6.1.4 *Sizing Criteria*

The key parameter in fabric filter design is the air-to-cloth ratio. The A/C ratio, or filtration velocity, is a defined as the actual volumetric flow rate (acfm) divided by the total active, or net, fabric area. 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 installations. A ratio is usually recommended for a specific dust and a specific cleaning method.

The ranges of recommended A/C ratios for many different dusts and fumes are summarized in Table 6-1. A conservative estimate for the A/C ratio of particulate matter generated in Superfund remediations would be 3.0 for woven fabric and 10.0 for a felt fabric. The A/C ratio and the emission stream flowrate (Q) can be used to calculate the net cloth area (A_{nc}) as shown below in Equation 6-1:

$$A_{nc} = \frac{Q}{\text{A/C ratio}} \qquad \text{(Eq. 6-1)}$$

where:

Table 6-1. Air-To-Cloth Ratios

Dust	Shaker/woven reverse-air/woven	Pulse jet/felt reverse-air felt
Alumina	2.5	8
Asbestos	3.0	10
Bauxite	2.5	8
Carbon black	1.5	5
Coal	2.5	8
Cement	2.0	8
Fly ash	2.5	5
Graphite	2.0	5
Gypsum	2.0	10
Lime	2.5	10
Limestone	2.7	8

Source: U.S. EPA, 1990.

A_{nc} = Net cloth area, ft^2;
Q = Waste gas flowrate, acfm; and
A/C ratio = Air-to-cloth ratio, $acfm/ft^2$.

The net cloth area is the area that must be active at any point in time; it is not the total required cloth area. The gross cloth area (A_{tc}) is the total cloth area in the fabric filter, including that which is out of service at any point for cleaning or maintenance. Given the net cloth area, an estimate of the gross cloth area can be made using factors given in Table 6-2 and Equation 6-2 shown below:

$$A_{tc} = A_{nc} \cdot C \qquad \text{(Eq. 6-2)}$$

where:

A_{tc} = Total cloth area, ft^2;
A_{nc} = Net cloth area, ft^2; and
C = Design factor based on size (Table 6-2), dimensionless.

6.1.5 *Cost Estimating Procedure*

The equipment costs for a fabric filter system can generally be estimated two ways: 1) by obtaining quotations from vendors, or 2) by using generalized cost correlations available in the literature.

Table 6-2. Approximate Guide to Estimate Gross Cloth Area

Net cloth area (ft^2)	Gross cloth area (ft^2)	
1-4,000	Multiply by	2.0
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
above 180,001	Multiply by	1.04

Source: U.S. EPA, 1990.

The purchased cost of a fabric filter system will vary widely depending on several design factors. Consequently, caution is required when using generalized cost correlations. Among the factors that influence the purchased cost of a baghouse are the supplier's design experience, materials of construction, instrumentation, the method of cleaning, and the nature of the application (i.e., Are there any factors, such as "sticky" particles, that make the application difficult?).

Baghouse equipment costs as a function of gross cloth area for cleaning systems are presented in Figure 6-2. This figure is adapted from U.S. EPA, 1990. The equipment costs given represent the cost for a fabric filter system without bags. A rough estimate of the bag cost can be made by assuming $1.00/ft^2. A more accurate estimate requires knowledge of the fabric type and the cleaning technique (see U.S. EPA, 1991).

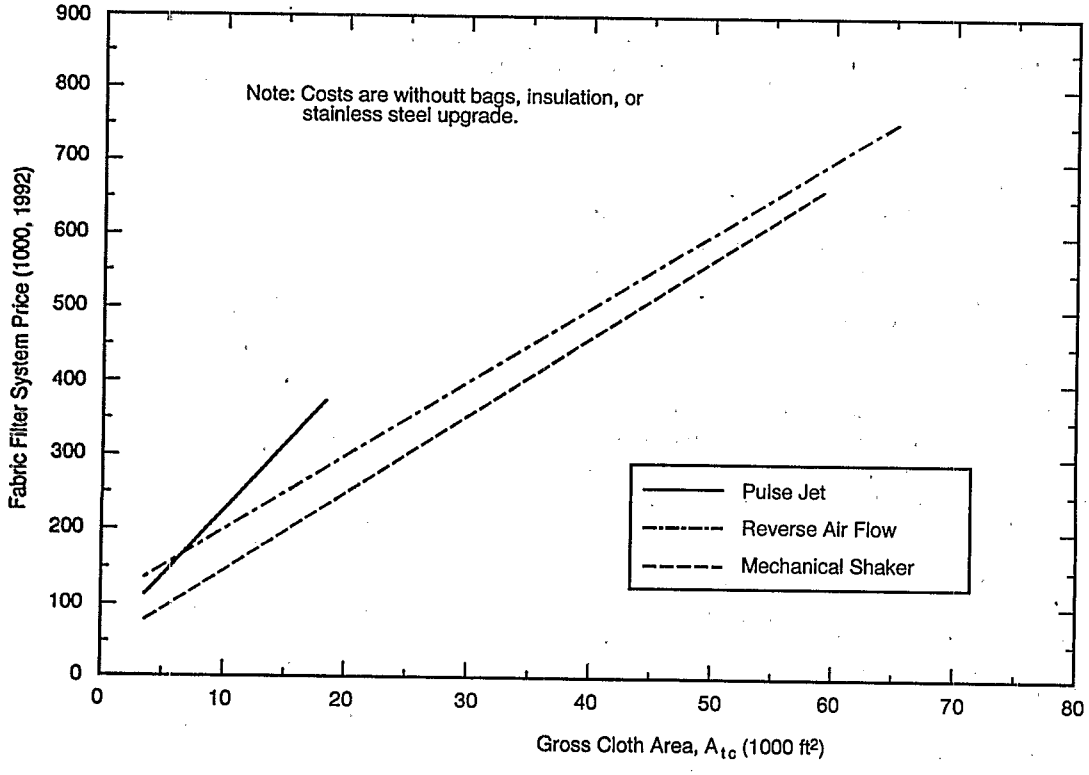
The installation and engineering costs for a fabric filter system can be estimated using the factor method presented in Table 6-3.

6.2 Electrostatic Precipitators

6.2.1 Process Description

Electrostatic precipitators (ESPs) are point-source particulate matter control devices that use an electrostatic field to charge particulate matter contained in a 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 are collected in a hopper at the bottom of the ESP.

A typical dry electrostatic precipitator is shown in Figure 6-3. The major components of the ESP include: gas inlet, discharge electrodes, collecting electrodes, rappers, cable from rectifier, wire-tensioning weights, hopper baffles, hopper, shell, and support frame. The gas enters the ESP and passes through a series of discharge electrodes. The discharge electrode is usually a small diameter wire and a plate or cylinder, which together create a nonuniform electric field. The electrodes typically are negatively charged and create a corona around the electrode. A negative charge is induced in the particle matter as it passes through the corona. A grounded surface, or collector electrode, surrounds the discharge electrode. The charged particle collects on the collecting electrode, which is typically a plate. The charged particles are neutralized by the collecting electrode. Common types of collecting electrodes used in ESPs are presented in Figure 6-4. The particulate matter is removed from the plate by rappers. This device strikes the collecting electrode to dislodge the collected particles, which then fall by gravity into a hopper. The intensity, frequency and number of blows is determined as part of the design. Removal of the particles is essential to ensure that the particulates collected do not act as an insulator, thereby decreasing the ability of the ESP to function. Reentrainment of the particles must be minimized to ensure adequate control efficiency. The particles are collected in the hopper and can be disposed when necessary.



Source: Adapted from U.S. EPA, 1990.

Figure 6-2. Fabric filter equipment cost.

Table 6-3. Cost Factors for Fabric Filter Installation and Engineering

Cost item	Cost factor (fraction of indicated cost)
Direct costs	
Purchased equipment	A
Fabric filter w/bags	0.10 A
Instrumentation	0.03 A
Taxes	0.05 A
Freight	
Total Equipment Costs:	**B = 1.18 A**
Installation	0.04 B
Foundations and supports	0.50 B
Erection and handling	0.08 B
Electrical	0.01 B
Piping	0.02 B
Painting	0.07 B
Insulation	SP
Site preparation	Bldg.
Building/construction	
Total Installation Costs:	**0.72 B + SP + Bldg.**
Total Direct Costs (TEC + TIC):	**1.72 B + SP + Bldg.**
Indirect costs	
Engineering and supervision	0.10 B
Construction/field expenses	0.20 B
Construction fee	0.10 B
Start-up	0.01 B
Performance test	0.01 B
Contingency	0.03 B
Total Indirect Costs:	**0.45 B**
Total Direct + Total Indirect Costs = Total Capital Investment:	**2.17 B + SP + Bldg.**

Source: U.S. EPA, 1990.

Several types of ESPs are commonly used. Plate-wire precipitators are used to treat high volumes of gases. For example, flat plate ESPs can handle flow rates of 100,000 to 200,000 cfm. At Superfund sites, weighted-wire ESPs are the most commonly used type of ESP (Donnelly, 1991). Another commonly used type of ESP is a tubular ESP.

An alternative to "rapping" for removing the particles is washing the sides of the ESP with water, either intermittently or continuously, i.e., a wet electrostatic precipitator. In wet ESPs, water is sprayed on the incoming gas stream to achieve a saturated condition.

The electric charge is transferred to liquid droplets. The liquid containing the particles becomes charged, is collected, and thereby washes away from the gas stream. A potential disadvantage to wet ESPs is that the collected waste stream may present a solids and liquid handling problem.

Another operating arrangement is the two-stage ESP. In this system, the gas stream passes through a corona discharge prior to entering a separate collection area. The two-stage ESPs are usually used for gas flow rates less than 50,000 cfm.

The most important variable to be considered in the design of an ESP is the collection plate area. Collection plate area is a function of the desired collection efficiency, gas stream flowrate, and particle drift velocity. The 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. Unfortunately, there are no easy empirical approaches to calculate drift velocity from these variables. Vendors typically rely on experience to estimate pressure drop.

6.2.2 Applicability to Remediation Technology

Electrostatic precipitators are very efficient particulate matter control devices. Efficiencies of 99 percent or more are attainable. ESPs are capable of removing very small particulates (0.01 micron up to 70 micron diameter particles) and can treat dry or wet particles (Brunner, 1984). Wet ESPs typically are not affected by the insulation effect and are able to collect gaseous or condensible contaminants along with the particulate matter. The use of ESP technology incurs a relatively high capital cost and the control efficiency is sensitive to variable gas stream conditions, such as dust loading, flow rate, and temperature. Another limitation for ESPs is the type of particles that can be removed, which

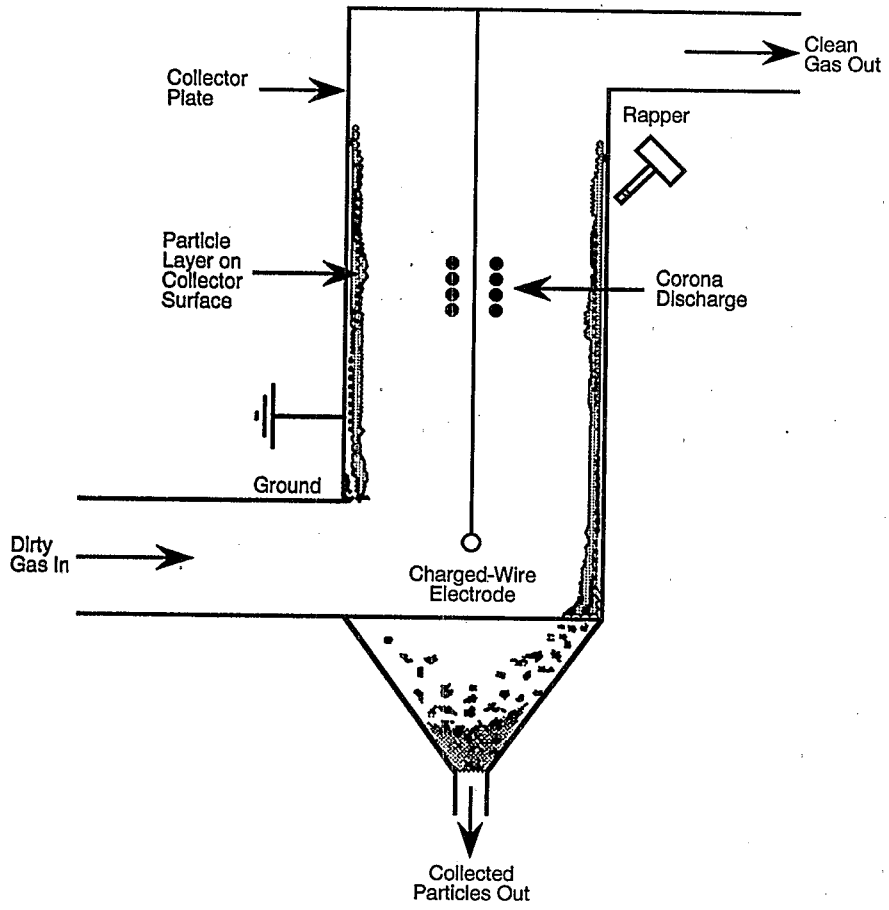
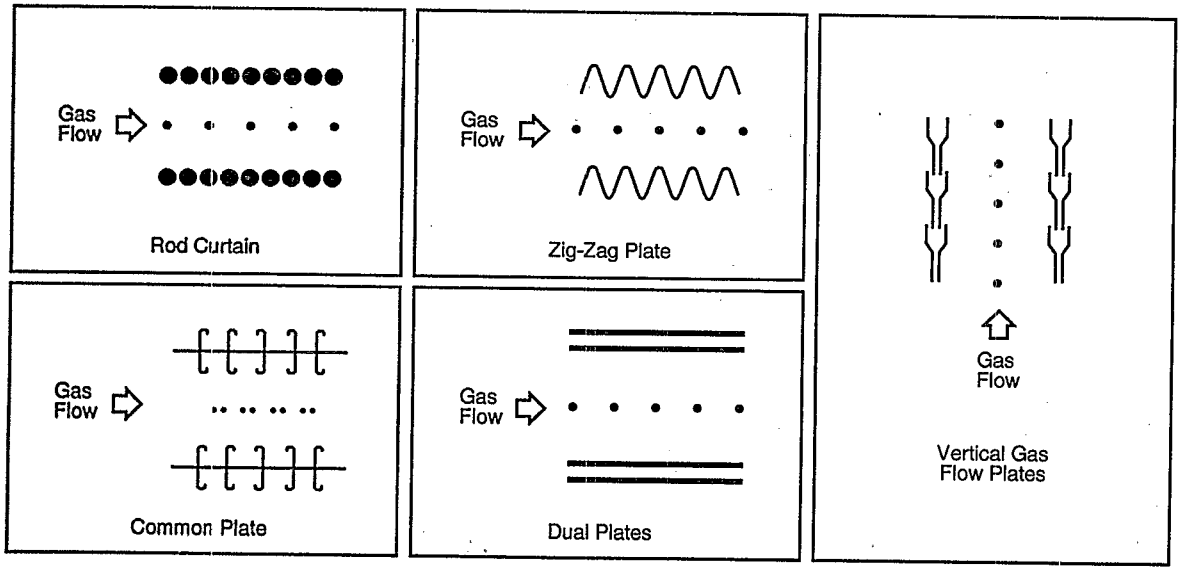


Figure 6-3. Electrostatic precipitator process flow diagram.



Source: Redrawn from Danielson, 1973.

Figure 6-4. Special collecting electrodes used in electrostatic precipitators.

is dependent on the resistivity of the particles. Wet ESPs have some added disadvantages: corrosion potential and wastewater treatment.

Since ESPs are used only as particulate controls on point sources, their use as controls for Superfund site remediations is usually limited to cases where incineration or thermal desorption is used to clean up the site.

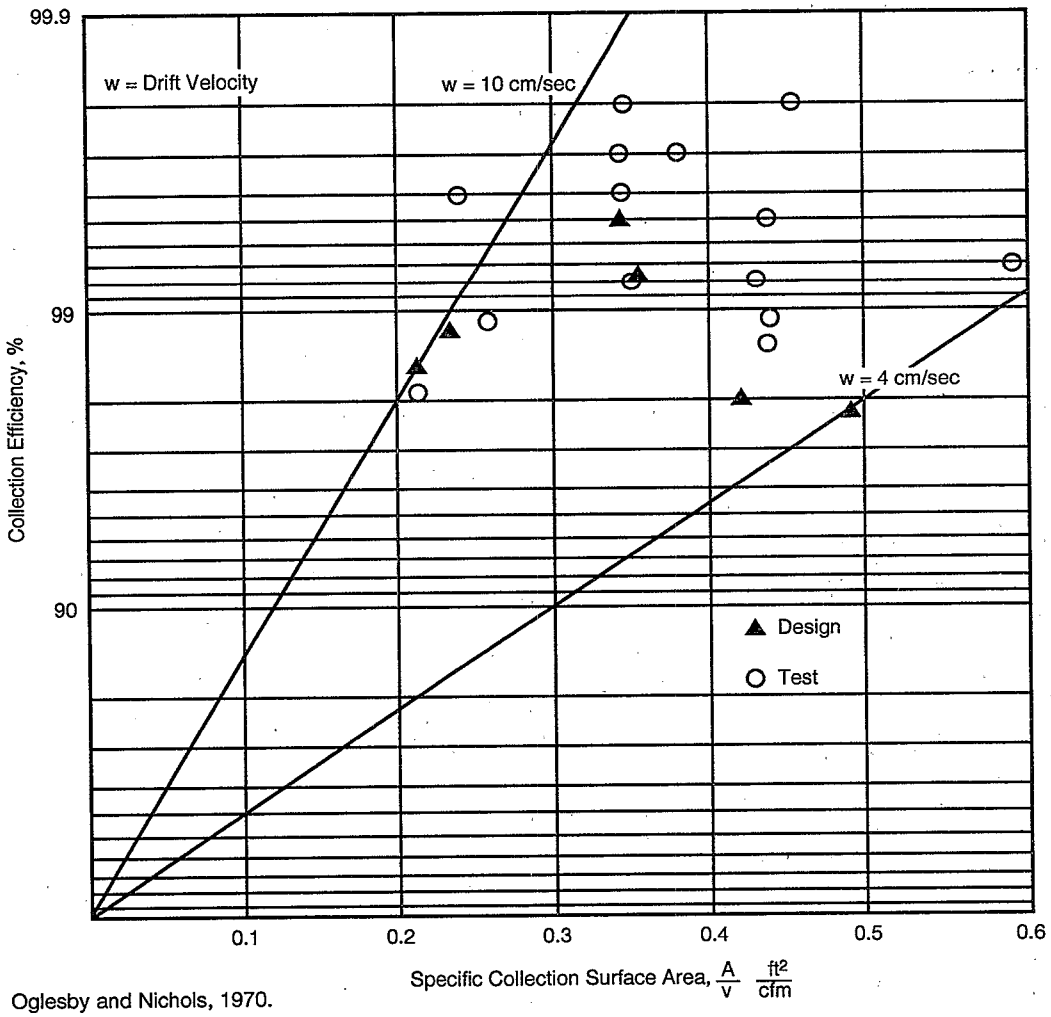
6.2.3 Range of Effectiveness

ESPs control particulates effectively down to the sub-micron range. The key parameters affecting the control efficiency of ESPs include the following:

- Particulate composition, density, and resistivity;
- Gas stream temperature and pressure;
- Gas stream velocity;
- Power; and
- Plate area.

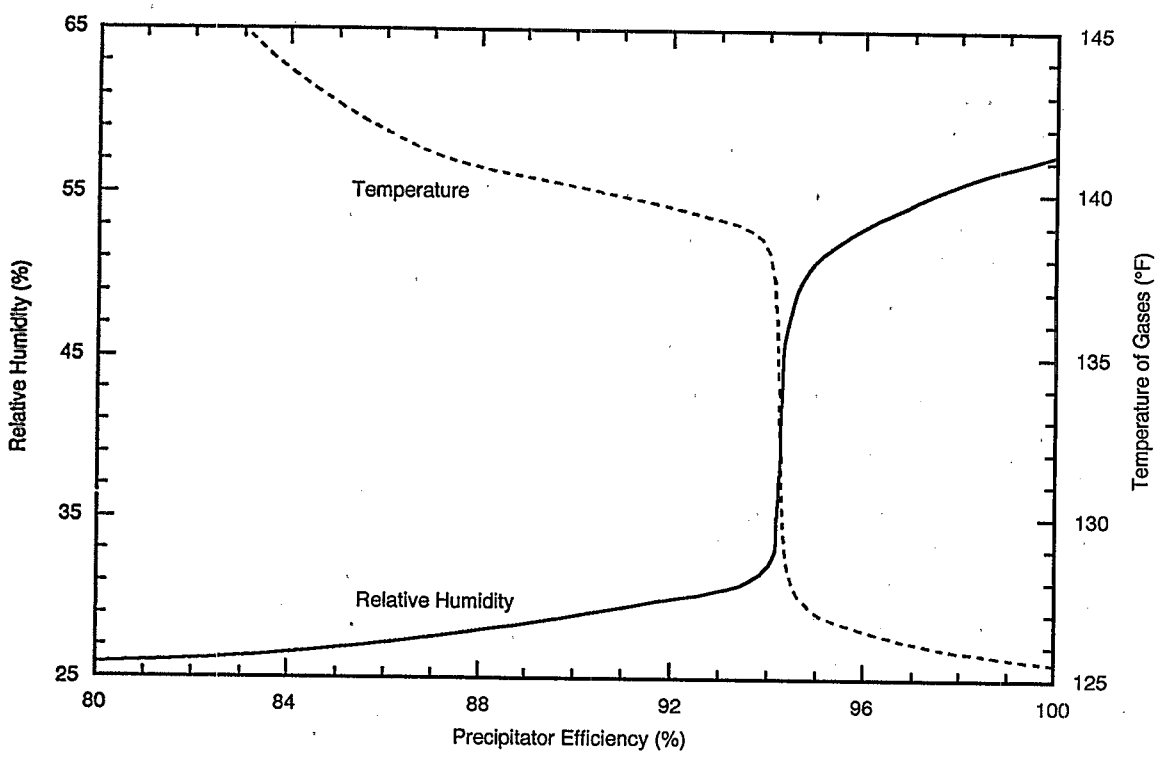
The particulate composition, density, and resistivity affect the particle drift velocity. In turn, the drift velocity, along with the control efficiency and gas flow rate, are used to determine the collection plate area, which ultimately determines the cost of the ESP. The relationship of the specific collection area (collector area normalized by volumetric flow rate) and control efficiency is shown in Figure 6-5.

The resistivity is important for determining the ability of an ESP to collect a specific material. The optimum resistivity range for adequate control efficiency is 10^4 to 10^{10} ohm-cm. Particles with low resistivities impose special considerations on ESP design. These type of particles (resistivities from 10^4 to 10^7 ohm-cm) are difficult to collect in an ESP because the particles tend to lose their charge and 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. Particles with high resistivities can also cause ESP operating difficulties. High resistivity particles accumulate on the collection plates and insulate the collection plate, thus reducing the attraction between particles and collecting plate. In these cases, using an oversized ESP and more frequent cleaning or rapping of the collector plates may be necessary.



Source: Oglesby and Nichols, 1970.

Figure 6-5. Relationship between collection efficiency and specific collection area for municipal incinerators.



Source: Redrawn from Brunner, 1984.

Figure 6-6. Effect of gas stream temperature and humidity on collection efficiency for a specific ESP.

An alternative to oversizing the ESP is the use of conditioning agents to reduce the resisitivity of the particles. The resistivity is dependent on temperature, moisture conditions in the gas, and the concentration of electronegative gases (e.g., SO_2). The effect of temperature and humidity on the precipitator efficiency for a given ESP installation is shown in Figure 6-6.

The gas velocity should be maintained within an optimal range to ensure that continuous reentrainment, which usually occurs at high gas velocities, is not a large risk. The optimum range is usually 2-4 ft/sec (Brunner, 1984). The amount of delivered power also affects the control efficiency, since the best collection usually occurs at the highest electric field, i.e., the highest voltage. Too high a voltage, however, may result in discharging from the wires to the plates and thereby decrease RE and increase power costs. The relationship of control efficiency and delivered power for municipal incinerators is shown in Figure 6-7.

6.2.4 Sizing Criteria

Typical ESP design criteria are presented in Table 6-4. As indicated, the key design parameters include:

- Particulate composition, density, and resistivity;
- Flue gas temperature and moisture;
- Inlet particulate loading and collection efficiency;
- Specific collection area;
- Number of fields;
- Flue gas velocity;
- Collector plate spacing;
- Rapping frequency and intensity; and
- Transformer rectifier power levels.

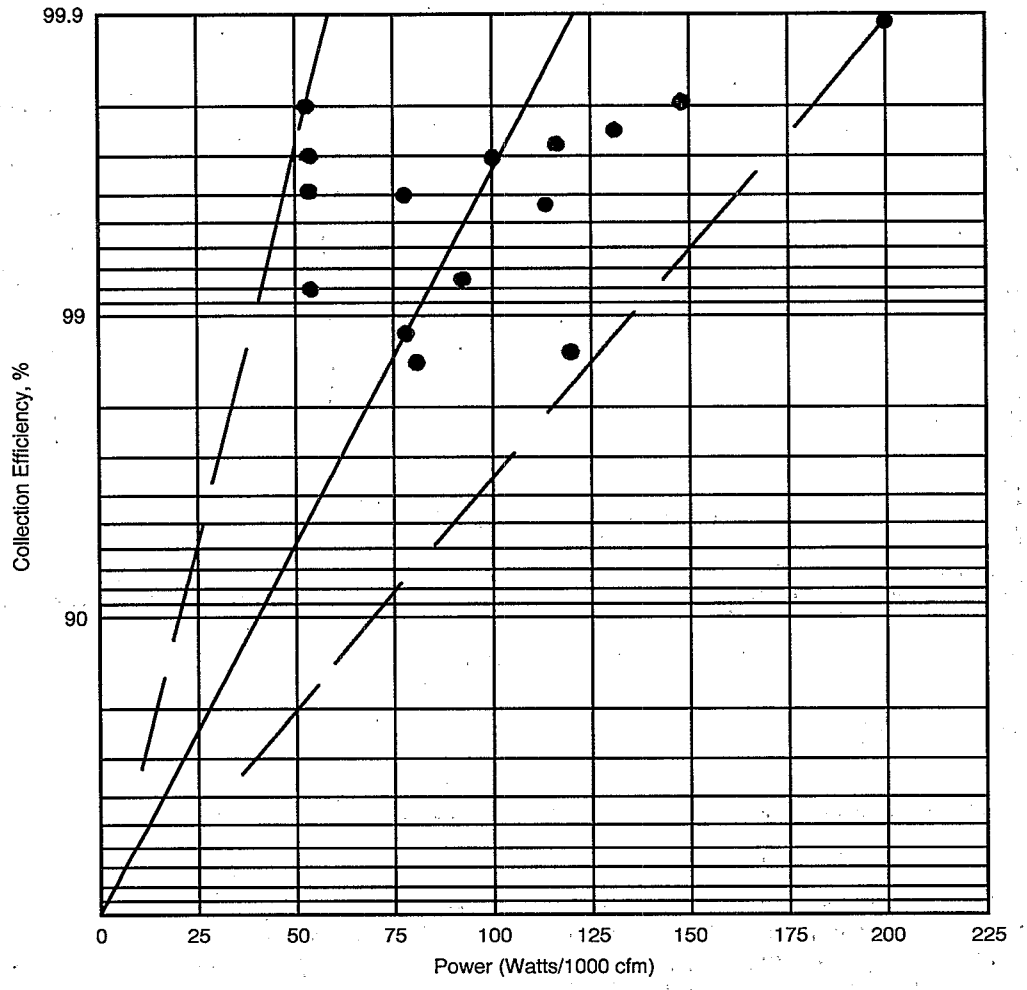
The most important front end design parameter is the specific collection area (SCA). The SCA can be estimated from the following equation (Vatavuk, 1990):

$$SCA = \frac{-\ln\left(1 - \frac{CE}{100}\right)}{W_e} \qquad \text{(Eq. 6-3)}$$

Table 6-4. Typical Design Parameters for Electrostatic Precipitators

Parameters	Value
Particulate loading (gr/acf)	0.5-5.0
Required efficiency (%)	98.0-99.9
Number of sections	2-4
SCA (ft ^{2}/1000 acfm)	350-500
Average secondary voltage (kv)	35-55
Average secondary current (mA/1000 ft ^{3})	30-50
Gas velocity (ft/sec)	3.0-3.5

Source: U.S. EPA, 1990.



Note: Delivered power = secondary voltage x secondary current

$$\text{Input power} = \frac{\text{Delivered power}}{\text{Power supply efficiency}}$$

Source: Oglesby & Nichols, 1970.

Figure 6-7. Relationship between collection efficiency and delivered corona power for municipal incinerators.

where:

SCA = Total collector plate area/gas volumetric flowrate, ft^2/kacfm;
CE = Particulate matter control efficiency, %; and
w_e = Effective migration (drift) velocity for the particle, m/s.

The SCA can be determined easily from Equation 6-3 assuming the drift velocity is known. Typical particle drift velocities for incineration dust are given in Table 6-5. However, many times, the drift velocity is not known, especially for incineration applications where a wide range of contaminants are found in the particulate matter.

A more complex procedure for determining the specific collector area has been published (Lawless and Sparks, 1984). This procedure, however, does not apply to the smaller two-stage ESP

Table 6-5. ESP Drift Velocities for Incinerator Fly Ash in Units of cm/sec

Particle source	ESP unit	Design efficiency 95	99	99.5	99.9
Incinerator fly ash [a]	Plate-wire	15.3	11.4	10.6	9.4
Incinerator fly ash [b]	Flat-plate	25.2	16.9	21.1	18.3

[a] 200° F; no back corona
[b] 250° F; no back corona

Source: Adapted from U.S. EPA, 1990.

systems, which could be typical at Superfund sites. These systems are usually packaged modules that are sized and sold on the basis of waste gas volumetric flow rate. Further design information can be found in Vatavuk, 1990 and Oglesby and Nichols, 1970. A secondary consideration in the design of an ESP is the material of construction. For example, stainless steel must be used for corrosive applications.

Often the ESP design is inadequate and once the system is installed optimization in the field may be required. Basic design problems include undersized equipment, reentrainment, or high resistivity particles. Agents can be injected to the system to alter the resistivity to achieve higher removal efficiencies. The ESP can also be manipulated effectively if performance is monitored closely. The following measurements should be taken periodically to ensure the collection efficiency is within design parameters: dust loading at ESP inlet and outlet, gas velocity distribution, electrical voltage and current input, gas composition, and dust resistivity (Oglesby and Nichols, 1970).

6.2.5 Cost Estimating Procedure

A cost analysis was performed by Vatavuk, 1990 for various ESP systems ranging from 10,000 - 1,000,000 ft² in size. A cost correlation for ESPs based on plate area based on this analysis is presented in Figure 6-8. The cost of material can have a significant affect on the cost of the ESP. The cost factors for upgrading from carbon steel to another more specialized material are shown in Table 6-6. The costs for two-stage ESPs are presented in Figure 6-9. This figure contains costs for the basic system and for packaged systems.

The total capital investment is determined from direct and indirect costs. The capital cost factors for ESPs are presented in Table 6-7. Since a packaged two-stage system includes some installation costs, the total direct costs for installation for two-stage ESPs is approximately 0.20B to 0.30B (Vatavuk, 1990). The annual operating cost estimates for ESPs are given in Table 6-8. Vatavuk, 1990 contains further detailed cost analysis information for ESPs.

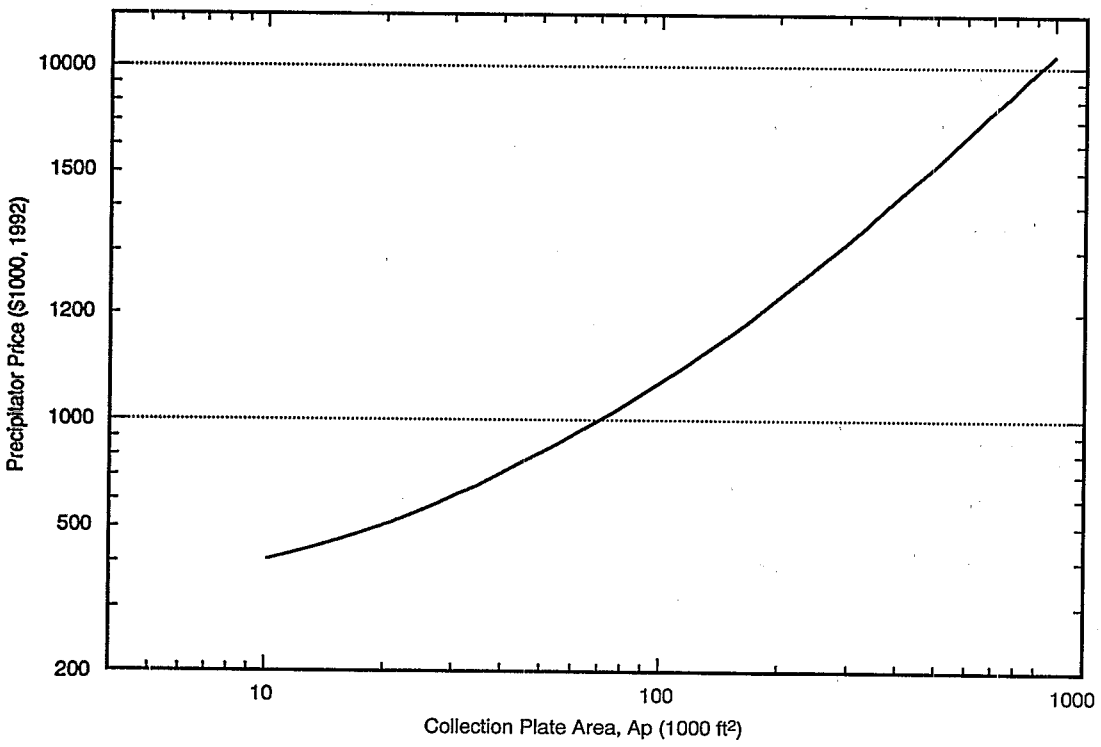


Figure 6-8. ESP equipment cost.

Table 6-6. Cost Factors for Upgrading ESP Construction Material

Material	Factor
Stainless Steel, 316	1.3
Carpenter 20 CB-3	1.9
Monel-400	2.3
Nickel-200	3.2
Titanium	4.5

Source: U.S. EPA, 1990.

6.3 Operational Controls

Operational controls are those procedures or practices inherent to the operation (and design) of control systems that can be followed to minimize the overall long-term emissions. Among these are:

- Adequate system design and installation;
- Startup testing;
- Preparation of standard operating procedures for operators;
- Control of operating variables to minimize emissions;
- Monitoring of system performance;
- Minimization of process upsets and startups; and
- Preventative and routine maintenance.

Operational controls for particulate matter and acid gas controls follow the same philosophy as those for VOC controls (see Section 5.7).

6.4 Wet Scrubbers

6.4.1 Process Description

Wet scrubbing is one of the most widely used methods of flue gas treatment for the control of acid gases, particulate matter (PM), heavy metals, and trace organics. The use of two or three different types of scrubbers in sequence can result in high removal efficiencies, particularly for acid gases. The absorption may be either physical or chemical. Physical absorption occurs if the pollutant is merely trapped by the liquid, e.g. particulate matter impingement on water. Chemical absorption occurs when a reaction takes place between the pollutant and the liquid; e.g., HCl reacting with a lime-based slurry to form $CaCl_2$. **Note**: dry scrubbing, the injection of an alkaline reagent into the gas stream

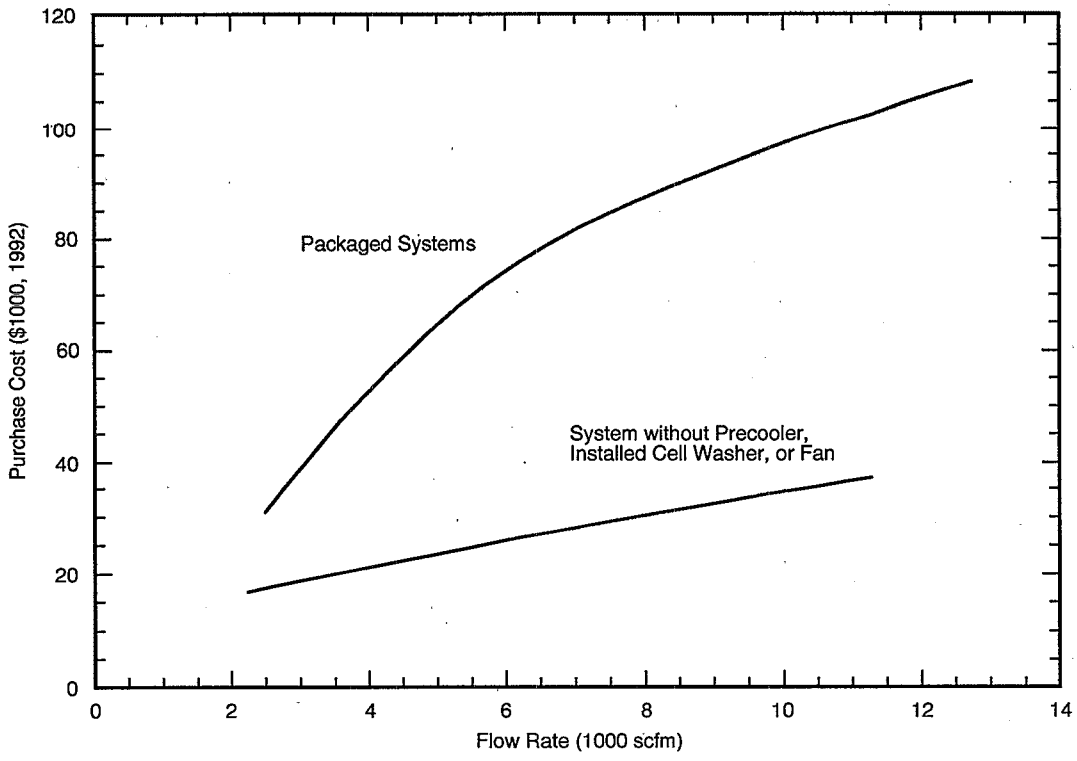


Figure 6-9. Purchase costs for two-stage precipitators.

Table 6-7. Capital Cost Factors for ESPs

Cost item	Factor
Direct Costs	
Purchased equipment costs	
ESP + auxiliary equipment	As estimated, A
Instrumentation	0.10 A
Sales taxes	0.03 A
Freight	0.05 A
Purchased equipment cost, PEC	B = 1.18 A
Direct installation costs	
Foundations and supports	0.04 B
Handling and erection	0.50 B
Electrical	0.08 B
Piping	0.01 B
Insulation for ductwork	0.02 B
Painting	0.02 B
Direct installation costs	0.67 B
Site preparation	As required, SP
Buildings	As required, Bldg.
Total Direct Costs, DC [a]	**1.67 B + SP + Bldg.**
Indirect Costs (installation)	
Engineering	0.20 B
Construction and field expenses	0.20 B
Contractor fees	0.10 B
Start-up	0.01 B
Performance test	0.01 B
Model study	0.02 B
Contingencies	0.03 B
Total Indirect Costs, IC	**0.57 B**
Total Capital Investment = DC + IC	**2.24 B + SP + Bldg.**

[a] For two-stage precipitators, total installation direct costs are more nearly 0.20 to 0.30 B + SP + Bldg.

Source: Vatavuk, 1990.

while not allowing the gas to be saturated with water vapor, is discussed in Section 6.5.

The physical concepts involved in wet scrubbing are quite simple: use of a liquid to absorb pollutants from a waste gas stream, enhanced through a large liquid/gas contact surface area. Gaseous matter is removed by diffusion and absorption of the pollutant into the liquid. Quenchers work by condensing the gases into a liquid. The absorber removal rate is a function of the concentration of the vapor, and the equilibrium concentration of the liquid phase of the pollutant with the scrubber liquid. Particulate scrubbers (venturis) capture particles by impingement and agglomeration with the liquid droplets.

The use of a scrubber, which introduces a liquid into the waste gas stream, requires a liquid separator downstream of the absorber. Separators can be cyclones, mist eliminators, or swirl vanes, and use impaction or centrifugal force to remove the liquid droplets from the exhaust stream. Mist eliminators can be either the chevron or mesh pad type.

The pH of the scrubbing liquor is an important process variable. Although even an acidic liquor can remove some HCl, HF, PM, and metals, a more neutral liquor is required for high removals of other pollutants. A pH of 5.0 or higher is required for SO_2 removal. Trace organics removal also is enhanced by an alkaline pH. The most common alkaline scrubbing reagents are lime, limestone, sodium hydroxide, and sodium carbonate.

Sodium-based scrubbing liquors have the advantage over calcium reagents of being less prone to causing scale formation on scrubber internal surfaces. Gypsum scale, which is formed in calcium-based processes, can be particularly difficult to remove. However, gypsum scale formation can be avoided through proper design and operation. Sodium reagents also have the advantage that they can provide higher removal rates, but usually they are more expensive than lime or limestone. Calcium-based scrubber waste products, however, are typically easier to dispose than sodium-based solids. The higher solubility of sodium salts makes leaching more of a problem from such waste streams. Therefore, the planned disposition of scrubber byproduct solids will be a factor in the selection of a reagent.

Wet scrubbing can be accomplished by many methods. Four such processes are illustrated in Figure 6-10. A discussion of these four and others is found below.

High Efficiency Venturi Scrubber--Venturi scrubbers often are used as a primary control device, operating at a low pH to remove particulates and hydrogen chloride. The particulate removal efficiency in a venturi is normally in the range of 80 to 95% for particles larger than 0.2 microns (Brna, 1987).

This device uses the venturi principle to scrub the waste stream: as gas enters the venturi throat, its velocity increases, and scrubber liquor is introduced as a spray perpendicular to the gas stream. The high gas velocity atomizes the liquid, creating a large surface area for absorption. The small droplets agglomerate as the gas velocity decreases downstream.

Prefabricated units can handle waste streams of up to 80,000 cfm. Although these units are considerably less expensive than ESPs or fabric filters, the savings may be offset by their high pressure drop. Removal efficiency increases with increasing particle size and increasing venturi pressure drop.

Jet Venturi Scrubber--These systems use energy from pressurized liquid to induce a draft which entrains the flue gas. The jet scrubber is capable of PM collection efficiencies of 90% or better, and will also remove acid gases. The jet scrubber can process gas directly from the combustion chamber, but it is usually preceded by a quencher.

Packed Tower Scrubber--Packed towers are primarily used for gas absorption. In this system, waste gas enters at the bottom of the unit, and the scrubber liquid is sprayed onto the top of a packed bed. As the gas passes upward, it contacts falling liquid that absorbs the pollutant. A mist eliminator above the packing removes liquid droplets from the gas stream, and cleaned gas exits the top. This type of scrubber can typically achieve higher removal efficiency than other scrubber devices, due to its high liquid/gas contact surface area.

Spray Tower Scrubber--This system is also primarily used for gas absorption. Three configurations can be used. The gas can flow upward or countercurrent to liquid spray; downward or cocurrent to spray; or, horizontally through a vessel with spray perpendicular to the gas flow direction. The main design variables affecting spray tower efficiencies are tower height, liquid to gas ratio, gas velocity, droplet size, and liquid chemistry/pH. The spray tower must operate with a higher liquid to gas flow ratio than the packed tower, to achieve equivalent removal rates.

Tray Scrubber--These units typically are in the form of a vertical cylindrical tower with many levels of trays inside. The scrubber liquor is recirculated through the absorber, with a layer of liquor being held on each tray. The flue gas bubbles up through holes in each tray, ensuring a high surface contact area. These systems can be bubble-cap, perforated-tray, or valve-tray scrubbers. Often, one or more trays can be added to enhance the mass transfer performance of open spray tower absorbers.

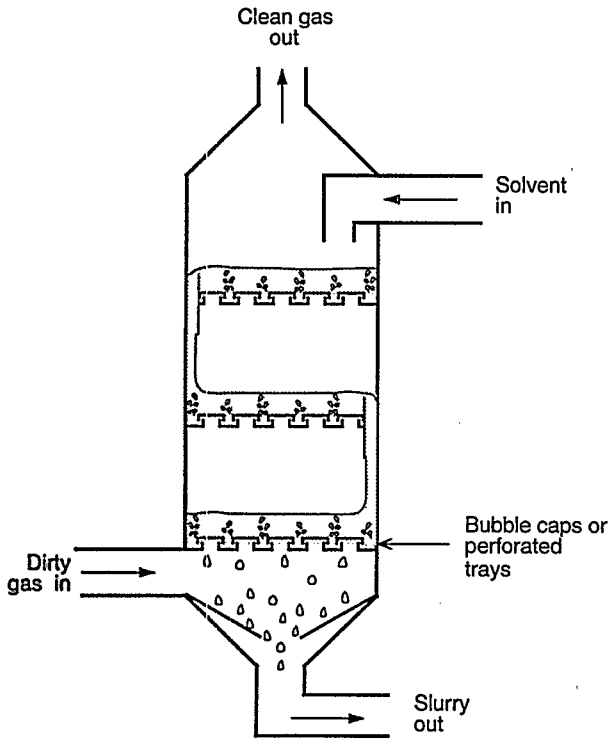
Quencher--This type of device typically is not used on its own, but instead is used as the first step in a wet off-gas treatment system. Quenchers are similar to spray tower scrubbers, but they are used for pre-treatment and they are designed for temperature control and humidification rather than pollutant removal. A quencher can cool the off-gas from incineration temperatures to saturation or near saturation temperature, increase the humidity to or near saturation, and reduce gas volume. The degree of approach to saturation temperature depends mainly on the liquid rate, droplet surface area, and gas residence time. This increased

Table 6-8. Annual Operating Maintenance Costs for ESP System

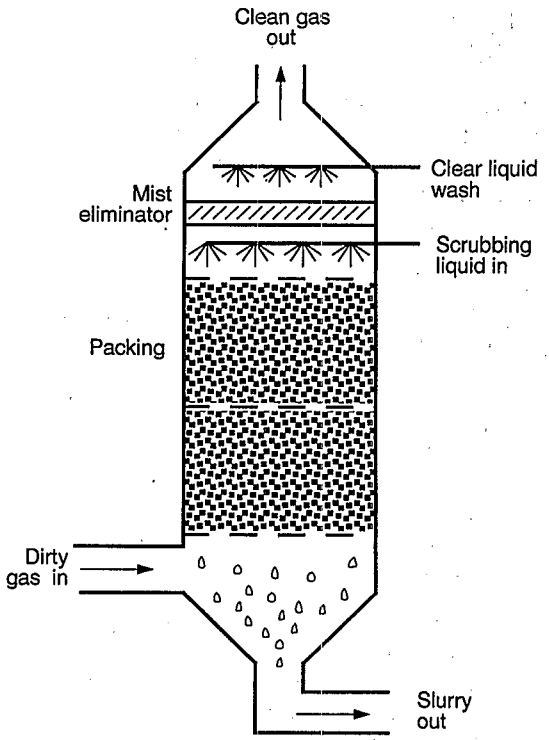
Cost item	Calculation
Direct Annual Costs, DC	
Operating labor	
Operator	3 hr/day x θ (day/yr) x hourly rate
Supervisor	15% of operator
Coordinator	1/3 of operator
Operating Materials	
Maintenance	
Labor	0.0825A (minimum of $5,265)
Material	1% of purchased equipment cost
Utilities	
Electricity-fan	0.000181 x Q x ΔP x θ x electricity cost ($/kwh)
Electricity-operating	1.94×10^{-3} x A x θ x electricity cost
Waste disposal	DD = 4.29×10^{-6} x G x θ x Q x [T + (TM x D)]
Total DC	
Indirect Annual Costs, IC	
Overhead	60% of sum of operating, supv., coord., and maint. labor and maintenance materials
Administrative charges	2% of TCI
Property Tax	1% of TCI
Insurance	1% of TCI
Total IC	
Total Annual Cost (rounded)	DC + IC

where: θ = Operating time (hr/yr);
A = ESP plate area (ft^2)
Q = Flow rate (acfm);
ΔP = System pressure drop (in H_2O);
G = ESP inlet grain loading (gr/ft^3);
T = Tipping fee ($/ton);
TM = Mileage rate ($/ton mile); and
D = Hauling distance (mile).

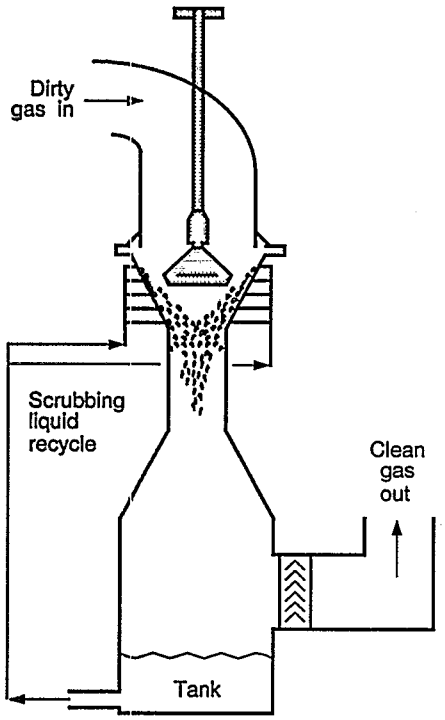
Source: Adapted from Vatavuk, 1990.



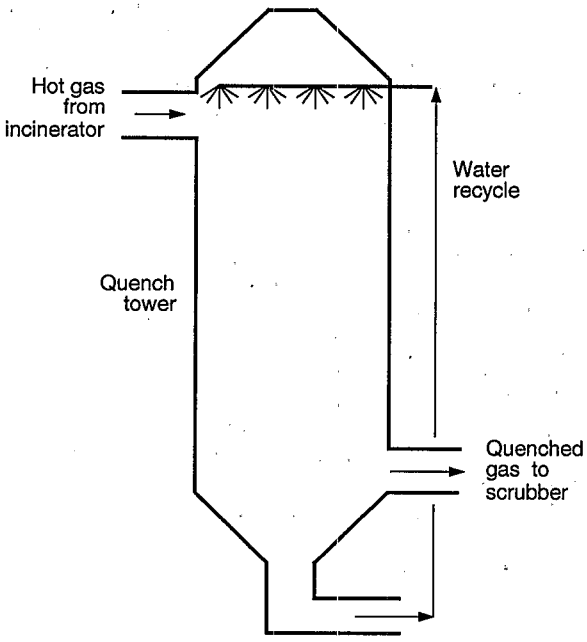
a. Tray Scrubber



b. Packed Tower



c. Venturi Scrubber



d. Quencher (spray tower)

Figure 6-10. Four common types of wet scrubbing systems.

humidity inhibits evaporation and contributes to absorption efficiency in downstream devices.

Quenchers are capable of some scrubbing, and can remove up to 50% of the acid gas present in a waste stream, (if the scrubber liquor contains an alkaline reagent). The quencher can be followed by a higher efficiency scrubber unit, such as a venturi or packed tower.

6.4.2 *Applicability to Remediation Technologies*

Incineration commonly generates the pollutants that wet scrubbers remove most cost-effectively: acid gases, heavy metals, and particulate matter. Wet scrubbing is also applicable to other thermal treatment methods such as thermal desorption. The particulate removal efficiency of a wet scrubber usually is not as high as that of a baghouse or ESP. One possible drawback to the use of wet scrubbers is that the flue gas temperature is cooled to its saturation temperature. This will lower the dispersion characteristics of the released flue gas and can result in a visible plume. Flue gas reheating may be required to eliminate the plume.

Some attributes of wet scrubbers that make them a popular choice among pollution control devices is their simplicity of operation, as compared with some other control devices. However, there are drawbacks: for VOC control, solutions other than water are usually required, since most VOCs are not water-soluble. Therefore, proprietary solvents are required, which raises the cost. Also, these devices are not efficient for low VOC concentrations, and must be used in conjunction with other controls for these applications.

Wet scrubbers achieve high efficiencies for the removal of heavy metals, since most of the volatile metals (except mercury) will condense at the temperatures reached in wet scrubbers. Mercury has a higher vapor pressure than the other heavy metals, and will not condense as readily. The collection efficiency of mercury vapors in wet scrubbers is not well known.

Physical scrubbing does not destroy pollutants, it only transfers them from the gaseous medium to a solid or liquid medium. Chemical absorption may well neutralize but will not destroy the pollutant, as when acid gases are chemically absorbed by an alkaline solution and form salts. Therefore, some waste usually is generated, which must be treated or disposed. This additional cost will affect the economics of the wet scrubber option.

Because of the relatively specialized nature of wet scrubbers, there is not one standard configuration used for all jobs; rather, the scrubber system(s) chosen will depend on the pollutants to be removed and on the physical characteristics of the waste stream. Typical wet scrubbing systems used with thermal treatment of hazardous materials and wastes are described below.

Thermal Desorption--One combination of wet scrubbers used for this application is a quench chamber followed by a venturi scrubber. This system would primarily be used to control particulate emissions, but could also control acid gases if the hazardous waste feed contains halogenated compounds.

Incineration--Wet scrubbers typically are used for cases not requiring very high total and fine (<10 micron) particulate removal or when inlet loading is not too high. All types of scrubbers may be used, depending on the waste stream parameters. Sometimes, wet scrubbers are the only controls used for removal of pollutants. Their ability to remove heavy metals, trace organics, and acid gases makes them especially well-suited to incinerator control.

One typical combination would be a quencher for cooling and condensing the hot waste gas as well as initial acid gas collection, followed by a venturi for primary particulate removal, and then a packed or spray tower for final acid gas absorption.

A wet scrubber also may be used downstream of an ESP or fabric filter, in situations that require higher PM removal than a venturi alone can achieve, to control acid gases, and to control some fraction of the heavy metals and trace organics that make it through any prior APCDs.

6.4.3 *Range of Effectiveness*

Absorption efficiency depends on many factors, including viscosity, diffusivity, density, temperature, liquid surface area, system chemistry, and flow rates. Absorption efficiency is enhanced by increasing liquid-gas interface surface area, reducing temperature, and maintaining a high liquid-gas ratio. Wet scrubbing does not remove pollutants efficiently from low volumetric flows; however, increased turbulence enhances removal rates. Typical liquids used to date include water, non-volatile organics, and alkaline solutions. The latter is especially common as the liquid in a second scrubber, since absorption of acid gases is enhanced if the pH of the solution is maintained in the range 6.5 to 9.0.

The use of common types of wet scrubbers for PM control is limited by the particle size distribution and the removal requirements. The wet scrubber systems described above may reach a maximum of about 99.5% removal. Newer hybrid types of scrubbers are being developed that combine wet scrubbing with other processes, such as ionization, increasing the equipment's range of effectiveness and improving its economics.

Wet scrubbers are often the technology of choice for high removal rates of acid gases. HCl removal efficiency will usually be greater than 99%. SO_2 is more difficult to remove than HCl, but removal rates greater than 95% can be achieved.

6.4.4 *Sizing Criteria*

Sizing wet scrubbers for remediation applications is a difficult process, requiring the determination of many design variables, including flue gas saturation temperature, tower heights, packing requirements, etc. The interested reader is referred to U.S. EPA, 1991 or Vatavuk, 1990, which asserts "...in reality, column design is so complex that nearly all towers are custom fabricated, making it extremely difficult to postulate a general costing/sizing procedure."

Some of the costing equations given in the next subsection require an estimate of the diameter of the scrubber unit. The

diameter (ft.) can be calculated from the flow rate Q (cfm) and velocity V (ft/min) using the following equation:

$$d = \sqrt{\frac{4Q}{pV}} \qquad \text{(Eq. 6-4)}$$

A typical design velocity for non-venturi scrubbers is 10 ft/sec. In a wet scrubber, the gas will be saturated with water vapor, and the gas volumetric flow rate, Q, must be based on this saturation temperature. The scrubber process should be optimized by choosing the best diameter and gas velocity.

6.4.5 Cost Estimating Procedure

Capital Costs--Equipment costs will vary with the system. A representation of some equipment costs are presented below.

A venturi system consisting of a mist eliminator, recirculation liquid pump, and sump in addition to the venturi, all in carbon steel, would cost (Vatavuk, 1990):

$P = \$9018 + 1.55\ Q$ for $600 < Q < 19{,}000$ acfm (Eq. 6-5)
$P = \$92.8\ Q^{0.612}$ for $19{,}000 < Q < 59{,}000$ acfm (Eq. 6-6)

For applications with corrosive streams, carbon steel is not appropriate. To obtain the cost of this venturi system with a rubber lining, or fabricated of fiber-reinforced plastic, multiply the above equations by 1.6. For epoxy coated carbon steel, multiply by 1.1. Instruments and controls cost approximately 10% of the equipment cost.

A costing equation was developed (Vatavuk, 1990) for impingement scrubbers of 304 stainless with 1, 2, or 3 stages (levels), internal sprays and piping. This estimate does not include fan, pumps, or other auxiliary equipment. In the presence of chlorides, type 304 stainless is not appropriate and higher grade alloys or linings are required. The following equation is valid for parameters listed in the table below:

$P = \$\ a\ Q^b$ with $900 < Q < 77{,}000$ acfm (Eq. 6-7)

The following two costing guidelines are adapted from Hesketh, 1991:

Stages	Effective height, ft.	a	b
1	8	58.9	0.570
2	16	68.8	0.586
3	24	69.5	0.610

- Purchase cost of packed tower absorbers, Pa, in 1992 dollars can be estimated by:

$$Pa = 1337\ D^{0.75} \qquad \text{(Eq. 6-8)}$$

where:
D = Column diameter, in inches, from 10 to 200.

- Packing cost per cubic foot of material Pp is:

$$Pp = \frac{32.2}{(Sp^{1.05})} \qquad \text{(Eq. 6-9)}$$

where:
Sp = Packing size from 1 to 3 in.

Hesketh's estimate for mist eliminators is \$121/ft^2 of cross-sectional area. Vatavuk, 1990, estimates mist eliminator cost for mesh pad designs by:

$$P = 86.4\ D^{1.66} \qquad \text{(Eq. 6-10)}$$

where, again, D is the diameter of the unit and typically is between 2 to 10 feet.

Installed capital costs are 2.2 times equipment costs. Installed absorber costs are in the range of \$9.1-18/scfm for systems with a flow greater than 10,000 scfm (Hesketh, 1991).

Operation and Maintenance Costs--A conservative estimate (Vatavuk, 1990) is that operation and maintenance must be performed 1/8 of the annual running time. Corrosion and scaling are the main sources of maintenance. Mist eliminators will need periodic replacement. The major operation costs are for chemical reagent, makeup water, and operating labor. Additional cost considerations include:

- Absorbers usually operate automatically, needing little labor or maintenance;
- Where venturis are used, most power is to regain pressure after scrubbing;
- Unlike fume destruction, absorbers incur fees for disposal of waste solids; and
- The wastewater may be disposable in an existing on-site treatment system or used to cool heated soil.

6.5 Dry Scrubbers

6.5.1 Process Description

There are two principal types of dry absorption systems: dry-dry and semi-dry absorption. Dry-dry systems inject the alkali absorbent as a dry powder, and semi-dry systems inject the alkali in a concentrated slurry, then evaporate the liquid. Both types of systems remove any unreacted alkali and solid wastes via ESPs or fabric filters. A dry scrubbing device includes a chemical injection zone, a reaction zone where the pollutants react with the alkali, and a particle removal device where the solids are removed from the waste stream. Figure 6-11 illustrates three commonly used dry scrubbing systems.

The most common use of this technology with remediation systems is for incinerators. Wherever halogenated compounds are thermally destroyed, some type of scrubber (wet or dry) will usually be required to remove the resulting acid gas. Dry scrubbers operate on absorption principles similar to wet scrubbers, but produce lower pressure drops and require less power. Another difference is that the waste gas is not saturated with

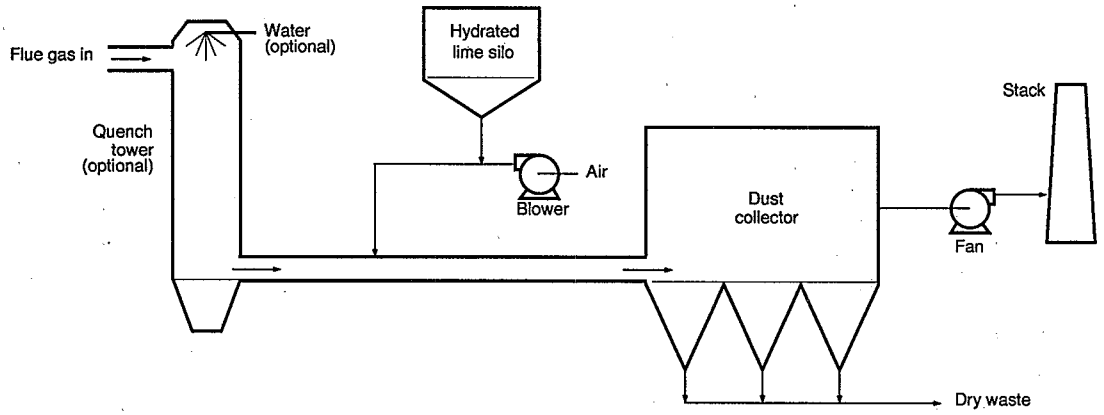


Figure 6-11a. Dry sorbent injection process.

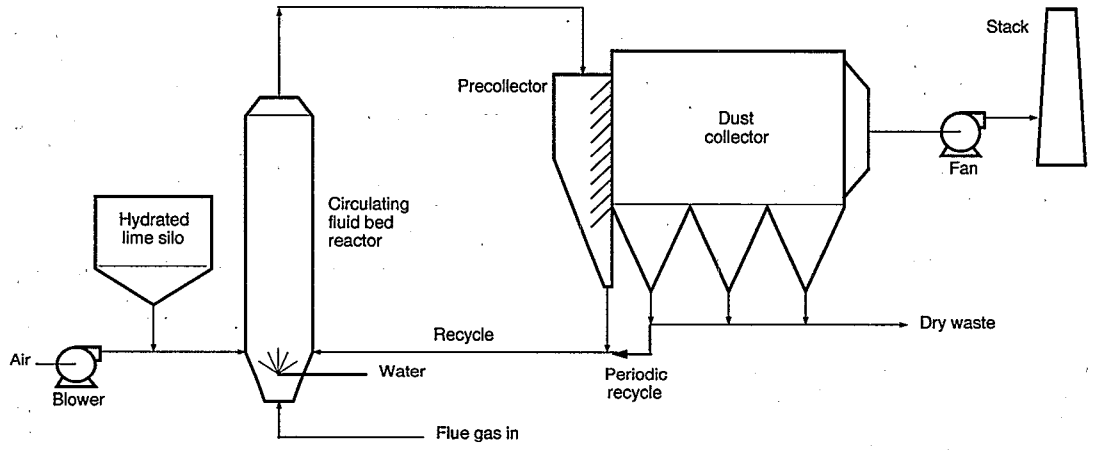


Figure 6-11b. Circulating fluid bed reactor process.

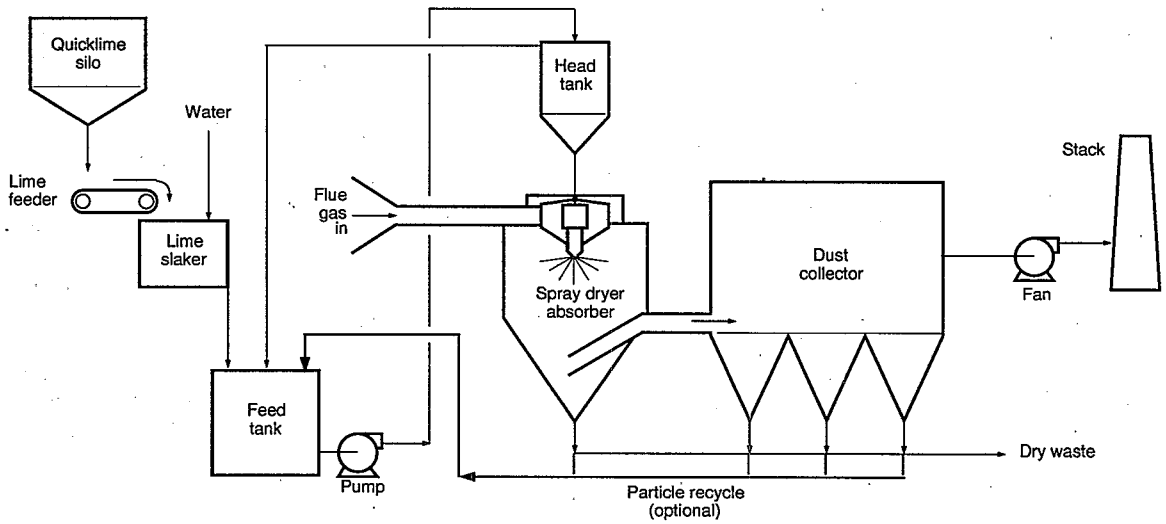


Figure 6-11c. Spray dryer absorption (semi-dry) process.

moisture, and the waste material is collected in dry form. With wet scrubbing the plume must usually be reheated, and waste is typically a slurry. A wet waste can be a liability, if a larger volume of waste is generated for disposal. These advantages of dry scrubbers are sometimes offset by their need for a separate downstream particulate collection device. High sulfur removal rates (>90%) are generally more difficult and expensive to achieve in a dry scrubber than in a wet scrubber. The stoichiometric ratio (i.e. moles of absorbent per mole of pollutant absorbed) is higher with dry scrubbers than with wet scrubbers.

Practically all dry chemical absorbers use alkalis, in particular calcium and sodium, which have good absorbent properties for many of the acid gases and for some organic pollutants. In dry scrubbers the calcium-based absorbent is usually in the form of slaked lime, $Ca(OH)_2$. The solids, including both used and unused absorbent particles, and particulate matter from the waste stream, are collected at the bottom of the absorber vessel, and in a baghouse or other particulate separator. Removal efficiency is mainly dependent on the acid-alkali ratio and the outlet gas temperature. Fabric filters and ESPs are the most common removal devices downstream of dry scrubbers. Acid gas removal efficiency is enhanced as the gas passes through the particle separator. However, a fabric filter provides greater removal of acid gases than does an ESP. The collected solids often can be recycled, to achieve greater utilization.

The use of dry scrubbers for power plant applications is relatively common, and standard design and operating parameters have been developed. The use of dry scrubbers for hazardous waste incinerators and remediation projects, however, is less well-defined. There are many control possibilities, and no single combination of scrubbers, fabric filters, ESPs, etc. is best for every application. Some typical systems are described below.

Dry-Dry Systems--Dry sorbent injection (DSI) involves injecting hydrated lime or limestone directly into the furnace or into the ductwork downstream of the furnace (see Figure 6-11a). Sulfur dioxide removal efficiencies of about 50% have been reported for this technology. The process has a high alkali requirement, and erosion of mechanical components can be a problem. Dry sorbent injection uses pneumatic equipment to introduce alkali into the hot gas stream. The gas stream may be humidified between the furnace and the particulate control equipment to improve removal efficiency. In general, SO_2 removal efficiencies increase with more alkali, greater contact time, higher pollutant concentration, higher moisture content, and lower temperature at the particulate control device inlet (to about 20-30°F above saturation temperature). On the other hand, if the gas stream is not humidified, higher temperatures may make separation of other pollutants difficult, and also may allow formation of polychlorinated dibenzo dioxins (PCDDs), polychlorinated dibenzo difurans (PCDFs), and other products of incomplete combustion (PICs). Dry-dry systems therefore are not used as the only device for control of hazardous air pollutants (HAPs).

Semi-Dry Systems--This process consists of conditioning the gas to a temperature above its saturation point by the adiabatic evaporation of water. An alkali is injected into the gas either as a slurry with the water, or separately. As with wet scrubbing, this causes cooling and a decrease in gas volume, as well as chemical reaction with the acid gases. A fabric filter or ESP then collects the particles and also may serve as a secondary reaction bed. Semi-dry systems have the advantage of no liquid waste, but by cooling the waste gas avoid the dry-dry problems with PICs discussed above. Further, the presence of liquid droplets in the semi-dry process produces higher acid gas removal rates than do dry-dry systems.

In spray dryer absorber (SDA) systems, hydrated lime is the most common alkali sorbent, and is mixed with water to form a slurry of approximately 15% $Ca(OH)_2$. The dosage of lime is regulated according to the acid gas concentration in the flue gas and the desired removal rate. This process often is used for power plants and municipal solid waste (MSW) incinerators, and as such has been well studied. The slurry can be introduced to the SDA by single or multiple rotary atomizers, or multiple dual fluid nozzles. Slurry droplet size is about 50 to 90 μm. With respect to gas flow, the SDA vessel can be downflow, upflow, or upflow with a cyclone pre-collector, and can have single- or multiple-gas inlets. Acid gas removal can be as high as 95% for SO_2, 99+% for HCl, 99+% for SO_3, and 95% for HF. The temperature of incoming gas can be up to 1000°C since the evaporating liquid will cool it back to 100 to 180°C. Flue gas residence time is 10 to 18 seconds, and up to 25% of the reaction products and ash can be collected in the SDA vessel.

6.5.2 Applicability to Remediation Technologies

Dry absorption has two features that make it relatively less attractive as a control for remediation purposes. First, it is difficult to achieve the very high removal efficiencies of wet scrubbers or other technologies. Second, dry absorption adds to the volume of waste to be disposed of because of the absorbent in the slurry. On the other hand, dry absorption has some aspects which are useful for some remediation applications; it is able to handle heavy metals, PM, and acid gases, as well as trace organics and some PICs. PCDD and PCDF removal rates for SDA/baghouse systems can reach 90 to 99+% (Donnelly, 1991). Dry activated carbon can be added to the SDA to increase the removal of heavy metals and trace organics. SDA systems also show promise for mercury removal. The applications where dry absorption is used are described below.

Incinerators--Dry absorption is effective for every type of pollutant in the incinerator exhaust gas streams, to varying degrees; sticky or corrosive particles are not a problem. Spray dryer absorption often is used, with a spray dryer coupled with a fabric filter. Reagent addition, flue gas humidification, and most of the absorption take place in the dryer; additional absorption occurs in the collector as dust is removed from the gas stream. The acid gases, trace metals, and trace organic compounds present in the waste stream of an incinerator are the pollutant types that SDAs control best. High electrical power costs can result from maintaining air pressure to dual fluid nozzles. Rotary atomizers consume less electrical power than dual fluid nozzles. Reagent and disposal costs are generally higher than for wet absorbers; however, the dry system itself has a lower capital investment cost.

The end product from an SDA is hygroscopic with a significant soluble fraction, stickier than fly ash and more difficult to handle.

End product constituents include fly ash, calcium compounds, trace metals, and trace organics. Due to its origin, this material must be disposed of as hazardous waste. If the fabric filter would be clogged by lime residue or unable to withstand the high temperatures, another post-SDA control, such as an ESP, can be used.

Thermal Desorption--Systems used as controls for thermal desorbers typically include an SDA for acid gases with a baghouse filter for particulate matter. This combination can meet the desired removal rates for acid gases, heavy metals, and trace organics.

6.5.3 *Range of Effectiveness*

Removal efficiencies for an SDA/baghouse system can range as high as 99%+ for most incinerator pollutants: acid gases, and heavy metals. More commonly, removal rates will be near 70 to 80%. Spray dryers with ESPs can remove 98% of dioxins and furans (PCDD/PCDF). The achievable removal efficiencies for an SDA/baghouse operating on the waste stream from an incinerator are indicated in Table 6-9.

SDA systems can accommodate input temperatures up to 1000°C. They are capable of handling a wide range of flue gas flow rates, although they are not very effective at removing low concentrations of pollutants.

6.5.4 *Sizing Criteria*

The major design variables for an SDA system are gas residence time and reagent slurry flow rate. Residence time is a function of SDA volume, flue gas flow, and gas inlet and exit temperatures. SDA volume determines the size of the vessel. Reagent slurry flow rate determines the size of slaking, pumping, and atomization equipment. The required slurry flow rate depends on many factors including gas temperatures, concentrations and types of pollutants, use of solids recycle, and type of reagent.

For both SDA and dry injection, the capital cost of a system of one size may be approximated from the known cost of a system of another size by the sizing exponent:

$$n = 0.73 \qquad \text{(Eq. 6-11)}$$

This parameter is used in the sizing equation:

$$Ib = Ia\ (Cb/Ca)^n \qquad \text{(Eq. 6-12)}$$

where Ib is the cost of a system of size Cb, and Ia, Ca are the respective cost and size of a reference system. An estimate of the installed-cost-to-purchase ratio is 2.17 (Hesketh, 1991).

6.5.5 *Cost Estimating Procedures*

As with wet scrubbers, the variety of system configurations and complexity of system design makes it difficult to provide a generic cost estimating scheme for all dry absorption systems. Further, most dry scrubber manufacturers will not typically sell only one component of the system, but will instead market an entire control system. The cost of the total system may be less if it is an off-the-shelf model rather than a custom design, but that may not always be an option.

Capital costs for dry injection on a 278,000 acfh (4633 acfm) incineration system are reported to be $66/acfm, or $38 Am^3/hr (Hesketh, 1991). This is less expensive than an SDA system but can require more alkali with less efficient acid gas control than the SDA system provides.

For SDA, the installed cost of a 2.6 million Am^3/hr lime sprayer in 1992 dollars is $48.6/acfm or $28 Am^3/hr. An SDA system on a 278,000 Am^3/hr MSW incinerator has an installed capital cost of $58.8/acfm, or $40.8 per Am^3/hr.

Table 6-9. Hazardous Waste Incinerator Emissions Estimates

	EPA* conservative estimated efficiencies	Typical actual control efficiencies	Typical range of emissions rates
Particulate matter	99+%	99.9+%	0.005-0.02 gr/dscf
Hydrogen chloride (HCl)	—	99+	10-50mg/NM^3
Sulfur dioxide (SO_2)	—	95+	30-60
Sulfuric Acid (H_2SO_4)	—	99+	2.6
Arsenic	95	99.9+	1-5 µg/Nm^3
Beryllium	99	99.9	<0.01-0.1
Cadmium	95	99.7	0.1-5
Chromium	99	99.5	2-10
Antimony	95	99.5	20-50
Barium	99	99.9	10-25
Lead	95	99.8	10-100
Mercury	85-90	40-90+	10-200
Silver	99	99.9+	1-10
Thallium	95	99+	10-100
PCDD/PCDF**	—	90-99+	1-5 ng/NM^3

* Based on spray dryer fabric filter system or 4-field electrostatic precipitator followed by a wet scrubber.

** Total all cogeners

Source: Donnelly, 1991.

6.6 HEPA Filters

6.6.1 Process Description

High efficiency particulate air (HEPA) filters are commonly used in medical, research, and manufacturing facilities requiring 99.9% or greater particulate removal. Although their use during remediation activities at Superfund sites has not been widespread, they could be used as a PM polishing step in ventilation systems for buildings undergoing asbestos removal, for enclosures, or with solidification/stabilization mixing bins.

The major components of a PM control system employing HEPA filters include the following:

- HEPA filters;
- Filter housing;
- Duct work; and
- Fan.

Such a system is shown in Figure 6-12.

The HEPA filter housing unit required is dependent on the nature of the PM collected and on the number/arrangement of filters required. For example, PM consisting of asbestos or PM laden with dioxins/furans will require a bag-out housing unit be installed. This type of housing unit is designed so that personnel removing the HEPA filters are never in direct contact with the filters. Such a unit is shown in Figure 6-13.

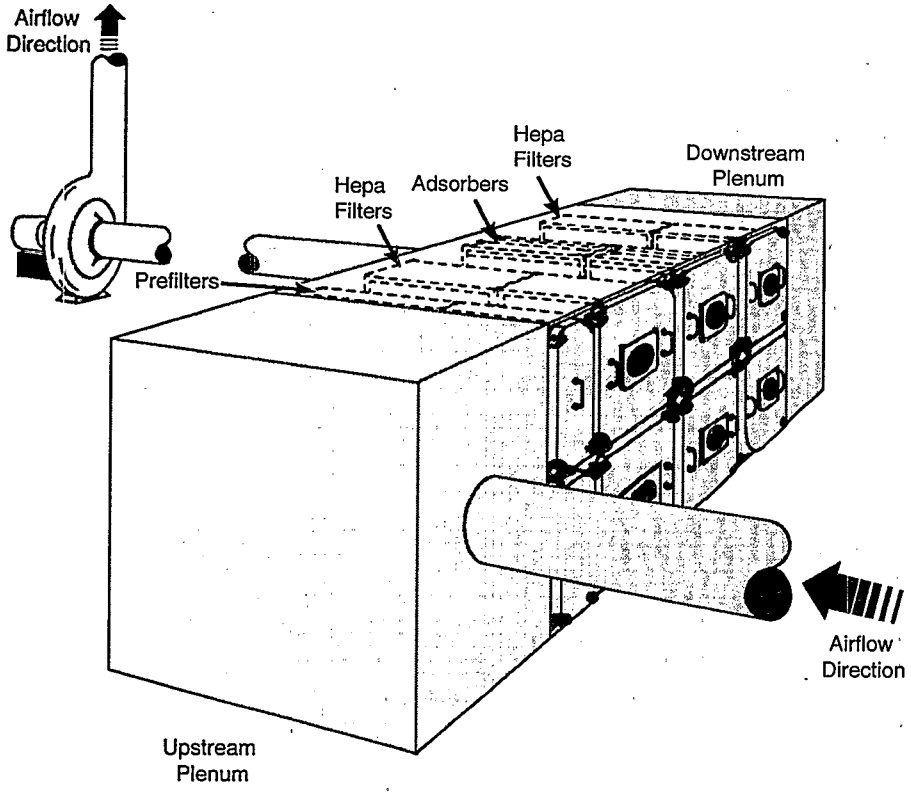
HEPA filters can be arranged in parallel, in series, or in a combination of these arrangements depending on the degree of PM control desired and the allowable pressure drop across the filters. Generally, parallel filter arrangement will lower the pressure drop across the filters, but will increase the size of the housing unit. Serial filter arrangement generally will increase the PM collection efficiency and the total pressure drop.

6.6.2 Applicability to Remediation Technology

The advantages/disadvantages of using HEPA filters to control PM emissions are given in Table 6-10. Remediation technologies with which HEPA filters are compatible are listed in Table 6-11.

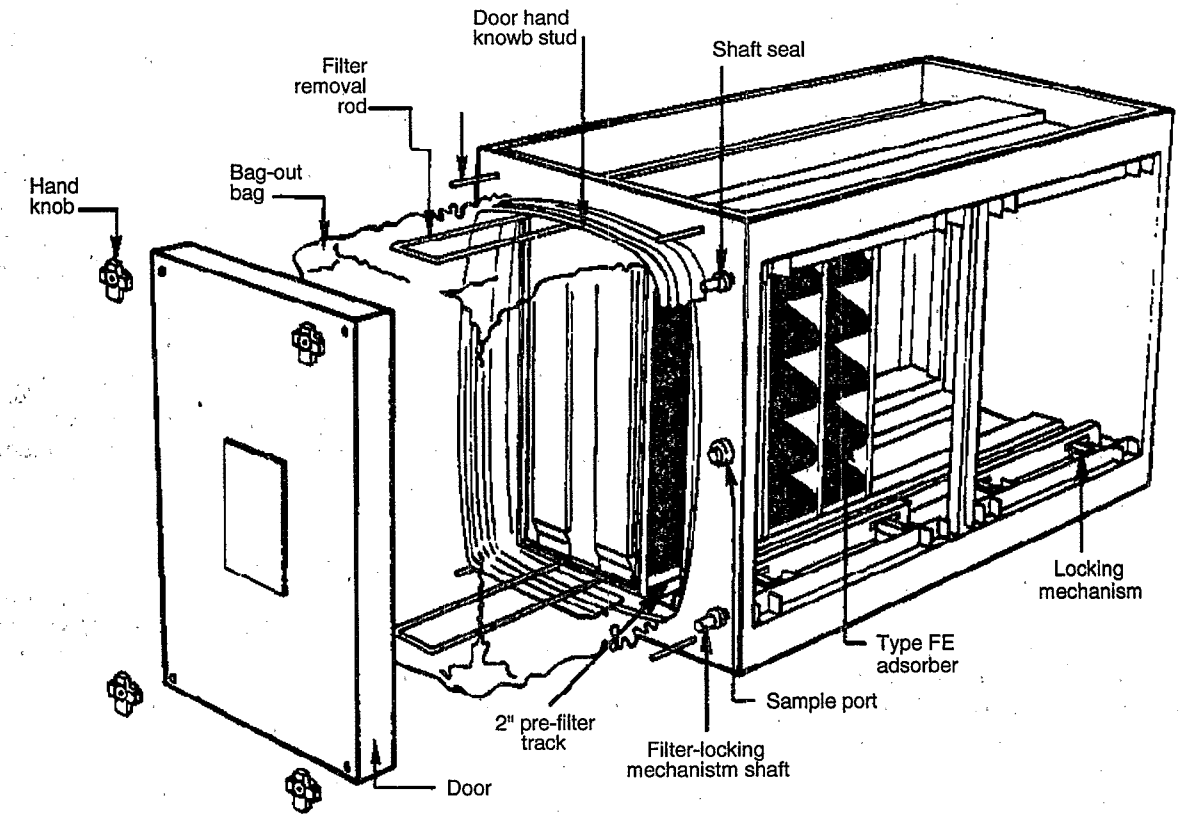
6.6.3 Range of Effectiveness

Parameters that will affect the efficiency and/or useful lifetime of HEPA filters are outlined in Table 6-12. Vendors report HEPA filter PM control efficiencies to be 99.9% and up for particulate diameters of 0.3 microns.



Source: Flanders, 1984.

Figure 6-12. PM control system employing HEPA filters.



Source: Barneby-Cheney, 1987.

Figure 6-13. Bag-out HEPA filter housing unit.

Table 6-10. Advantages/Disadvantages of HEPA Filters

Advantages	Disadvantages
• Easy to operate	• May require prefilter for exhaust with high PM concentrations
• 99.9% or greater PM removal efficiencies are achievable	• Required housing units are expensive and may be subject to corrosion • Filters are subject to fouling by high humidity exhaust gases • Filters must be replaced periodically due to plugging caused by PM • High power costs due to pressure drop across filter

Table 6-11. Remediation Technologies Compatible with HEPA Filters

Emission Source	Qualifications
Asbestos removal from buildings	HEPA filters must either be installed in building ventilation system or negative air pressure system used during asbestos removal HEPA filters will require bag-out housing units and must be disposed of properly
Enclosure ventilation system	Pre-filters may be required for high PM concentrations Depending on the nature of the PM (e.g., heavy metal or SVOCs contamination), bag-out housing units may be required High humidity within the enclosure will limit filter lifetime
Hoods or enclosures of solidification/stabilization mixing bins	HEPA housing material may be subject to corrosion due to lime Pre-filters may be required for high PM concentrations Depending on the nature of the PM (e.g., heavy metals or SVOCs) bag-out housing units may be required High humidity exhaust gases will limit filter lifetime

Table 6-12. Parameters Affecting HEPA Filter Efficiency/Lifetime

Parameter	Comments
Moisture	Moisture will bind filter resulting in increased pressure drop across filter, eventually leading to filter failure due to excessive resistance.
PM loading	Higher the PM loading the shorter the useful life of the filters. Also, the change in pressure drop across the filters will be accelerated.
	Higher the velocity, the lower the PM control efficiency, higher the pressure drop across the filter, and diminished filter life.

6.6.4 Sizing Criteria/Application Rates

Sizing of HEPA filters is based on pressure drop vs. face velocity curves which are developed by the manufacturer for each type of filter design. If the maximum allowable pressure drop across the filter and the air flow rate are specified, then the type of filter and the filter arrangement can be determined. A family of pressure drop vs face velocity curves is depicted in Figure 6-14.

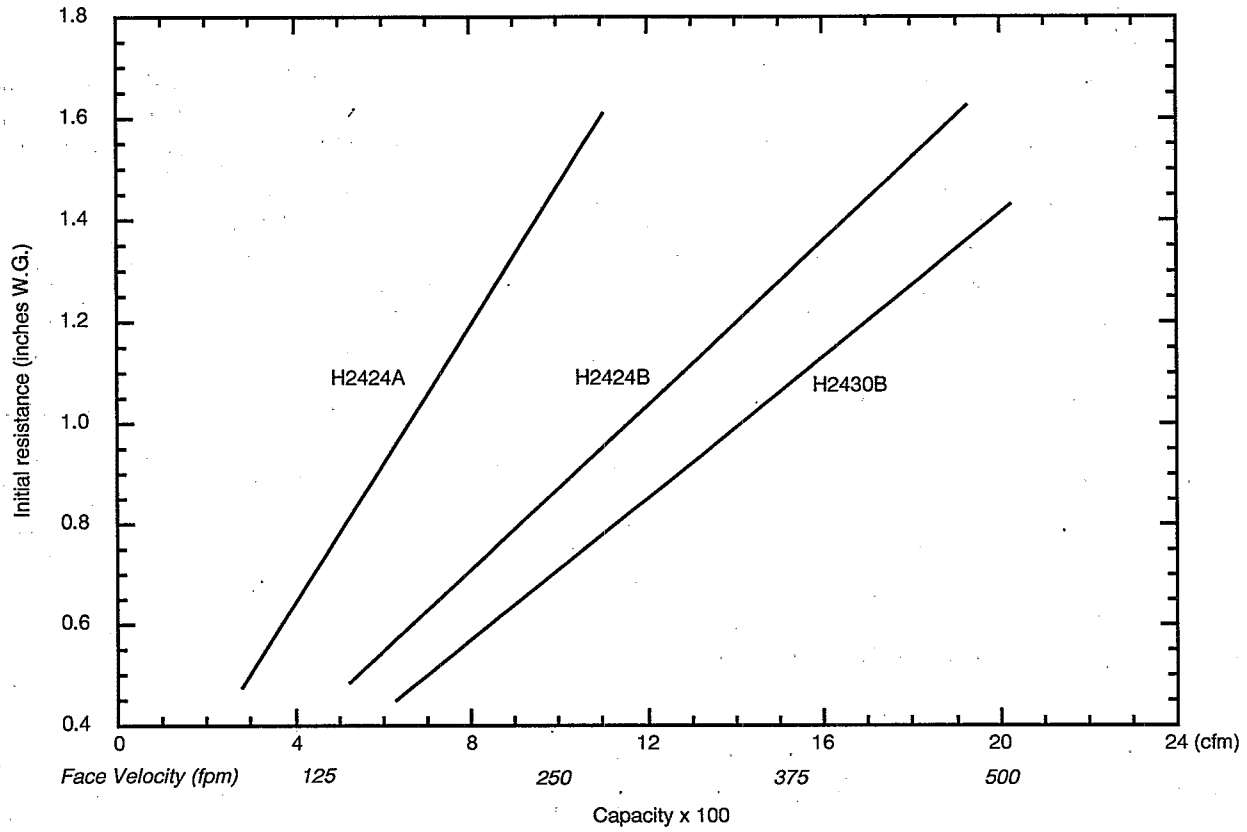
If, for example, HEPA filters are to be used to control PM emissions in an exhaust gas flowing at 9000 acfm (2250 fpm for a 2 ft x 2 ft HEPA filter) and the maximum allowable pressure drop across the filter is 0.8 inches H_2O gauge, then ten-H2424B, nine-H2430B, eighteen-H2424A HEPA filters must be used in parallel (see Figure 6-14).

6.6.5 Cost Estimating Procedure

HEPA filter costs are dependent on the specific filter characteristics:

- PM removal efficiency achievable; and
- Maximum face velocity allowable across filter.

Also, the useful filter lifetime is dependent on face velocity across the filter, PM loading rate, and the moisture loading rate onto the filter. The useful lifetime will determine the frequency of filter replacement. Generally the range of HEPA filter costs is \$20 - 100/ft^2 filter area. The costs of housing units is a function of the type of housing unit required (e.g. regular vs. bag-out) and ranges in price from \$150-500/ft^2 filter area.



Source: HEFCO, 1989.

Figure 6-14. Pressure drop vs. face velocity curves for specific HEPA filter designs.

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Chapter 7
Area Source Controls for VOCs, SVOCs, PM, and Metals

Information about various control technologies used to control emissions from area sources is presented in this chapter. The control technologies generally are applicable to the control of all classes of air contaminants, including volatile organic compounds (VOCs), semi-volatile organic compounds (SVOCs), particulate matter (PM), and metals associated with PM. The specific control technologies addressed in this section are covers and physical barriers, foams, wind barriers, water sprays, water sprays with additives, operational controls, enclosures, collection hoods, and miscellaneous controls. The discussion for each control technology includes a process description, applicability for remediation technologies, range of effectiveness, sizing criteria, and cost information.

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

Relative to point source controls, the capture efficiency and control efficiency of area source controls tends to be low. Overall control efficiencies may be only 50% or lower. Also, many of the area source controls have short-lived effects and require frequent reapplication. The controls are generally simpler in design than point source controls and do not require as highly a trained operator for their operation and maintenance. Finally, operational controls may be the single most cost-effective method of minimizing emissions from area sources; their consideration is strongly recommended.

7.1 Covers and Physical Barriers

Cover materials used to control VOC and/or particulate matter (PM) emissions include the following: soils, organic solids such as mulch, asphalt/concrete (paving), gravel/slag with road carpet, and synthetic covers (e.g. tarps). Cover materials are used extensively at controlled landfills and construction sites for vapor and dust suppression. The most common uses of covers for Superfund sites are soil covers for inactive sites; asphalt, concrete, or gravel covers for roadways; and thin polymer liners (e.g., 45 mil HDP) for storage piles of contaminated soil.

Soil material can range from top-soil to clays. However, sand generally is not used because of its porous nature and tendency to erode.

Organic solids include such materials as wood chips, sawdust, sludges, mulch, straw, corn stalks, etc. Because some of these materials are prone to wind erosion (e.g., straw, cornstalks), they must be anchored with a net. The availability of these materials may limit their use.

Synthetic liners (polymer sheeting) are relatively new and are used widely at landfills to minimize leachate migration. They also serve as a barrier to vapor transport. Liner thickness varies from 2-125 mil; however, 30-60 mil is common. Some common geomembranes are

- Polyethylene
  - High density—HDPE
  - Low density—LDPE - should not be used
  - Very low density—VLDPE
  - Linear low density—LLDPE
- Polyvinyl chloride (PVC)
- Chlorosulfonated polyethylene (CSPE)
- Ethylene interpolymer alloy (EIA)

  Note: Others will not sell to our industry due to potential liability.

Road carpets are water permeable polyester fabrics that are placed between the road bed and the coarse aggregate road ballast (e.g., gravel, slag).

The effectiveness of cover materials to control VOC and PM emissions is outlined in Table 7-1.

7.1.1 Process Description

Covers control emissions of contaminated particulate matter and VOCs by physically isolating the contaminated media from the atmosphere. Physical isolation is the primary means of controlling particulate matter emissions, while increasing the resistance to diffusion is the primary means of controlling VOC

Table 7-1. Cover Material Effectiveness for Controlling VOC and Particulate Emissions

Cover material	Contaminated media	Control effectiveness	
		VOCs	Particulates
Soil	Soil	Low [1]	High
Organic solids	Soil	Low[1]	High
Geomembranes	Soil	High[1]	High
	Sludge	High[1]	N/A
	Liquid	High[1]	N/A
Asphalt/concrete	Soil	None[2]	High
Road carpet and gravel/slag	Soil	None[2]	High

[1] *VOC emission control dependent on diffusivity coefficient of individual VOCs through cover material and on cover material depth.*
[2] *Assumes cover material is applied to unpaved roads only.*

emissions. Mass emission rates for VOCs, assuming diffusion only, can be determined from Equation 7-1:

$$ER_i = \frac{A \cdot D_i}{x}\left(C_{i,1} - C_{i,2}\right) \qquad \text{(Eq. 7-1)}$$

where:

- ER_i = Mass emission rate of species i (g/sec);
- A = Area of emitting source (cm^2);
- D_i = Diffusivity coefficient of species i through cover material (cm^2/sec);
- x = Cover thickness (cm); and
- $C_{i,1}$-$C_{i,2}$ = Concentration gradient of species i (g/cm^3).

Therefore, covers reduce VOC emission rates by:

1. Decreasing diffusivity coefficient relative to air (via chemical interactions and soil temperature reductions); and
2. Increasing required VOC diffusion path (x).

Some cover materials (e.g., sawdust, straw) are tilled into the contaminated soil as an anchoring mechanism. This practice results in a soil/cover layer with a higher porosity than the soil alone, resulting in increased VOC emission rates. The major components typically required to apply the various cover materials are listed in Table 7-2.

7.1.2 Applicability to Remediation Technologies

The applicability of the various cover materials is dependent on site characteristics (terrain, vegetation, access, and contaminated media) and on the desired PM/VOC control efficiencies required. The advantages/ disadvantages and applicable remediation technologies of various cover materials are given in Tables 7-3 and 7-4, respectively. Also, some specific characteristics of various geomembranes are given in Table 7-5.

7.1.3 Range of Effectiveness

Parameters that influence the effectiveness of cover materials to control VOC/particulate matter emissions are presented in Table 7-6. Reported PM/VOC control efficiencies for various cover materials are presented in Table 7-7. These control efficiency ranges should be used only as a guide since methods used in determining these efficiencies, site characteristics, and cover application procedures vary from site to site. Information about the permeability of various polymeric materials to specific liquid VOCs is available for gloves and other personal protective equipment (Radian, 1992); these data can be extrapolated for selecting soil covers.

7.1.4 Sizing Criteria/Application Rates

The amount (depth, thickness, etc.) of cover material required to achieve a given control efficiency is not well defined in the literature. However, there are general sizing guidelines reported in the literature that are presented in Table 7-8.

7.1.5 Cost Estimating Procedure

Cost estimates of implementing cover-based VOC/PM control measures are presented in Table 7-9. Caution should be exercised when using these cost estimates, since costs are highly dependent on the site characteristics, labor costs, weather conditions, and the availability of specific cover materials at each site.

7.2 Foams

7.2.1 Process Description

Modified fire-fighting foams are commonly used to control PM/VOC emissions during the remediation of hazardous waste sites. Suppression of PM/VOC is accomplished by blanketing the emitting source (liquid, sludge, or soil) with foam, thus forming a physical barrier to those emissions. Foams also act to insulate the emitting source from the wind and the sun, further reducing PM/VOC emissions. Some foams are "sacrificial", meaning that the chemicals compromising the foam will react with specific VOCs thus further suppressing their emissions. Rusmar and 3M are the two primary manufacturers of foams for use at Superfund sites.

Table 7-2. Major Components for Cover Material Applications

Cover material	Major components required
Soil	Front end loader Grader Water wagon (optional) Compaction equipment (optional)
Organic solids	Front end loader Grader (dependent on material) Tilling equipment (optional) Water wagon (optional) Anchoring net
Polymer sheeting	None
Asphalt/concrete (paving)	Grader Front end loader Paving application equipment Compaction equipment Base material
Road carpet and gravel/slag	Grader Front end loader Base material Compaction equipment

Table 7-3. Advantages/Disadvantages of Cover Materials

Cover material	Advantages	Disadvantages
Soils	• Inexpensive • Easy to apply • Equipment readily available	• Creates more contaminated soil • Subject to erosion • No particulate or VOC control for working face
Organic solids	• Inexpensive • Easy to apply • Equipment readily available	• Material availability location dependent • Often requires anchoring to reduce erosion • No particulate or VOC control for working face • Combustible • Creates more contaminated soil
Asphalt/concrete	• Long working life • Equipment readily available	• Expensive • High maintenance • Extensive preparation required • Limited to high traffic volume or permanent traffic pattern areas
Road carpet and gravel/slag	• Cheaper than asphalt/concrete • Long working life • Applicable to low traffic volume areas • Allows contaminated soil from spillage and "track-out" to be washed beneath road carpet	• Higher maintenance than paved roads • Extensive preparation required • Subject to erosion
Polymer sheeting	• 100% particulate emission control • No erosion potential • Carbon black addition can limit photodegradation • Conversion of area source to a point source	• Limited tear resistance • Limited chemical resistance • Photodegrades easily • Must be anchored to surface • No particulate or VOC control for working face

Table 7-4. Cover Materials vs. Applicable Remediation Technologies

Cover material	Applicable remediation technology	Qualifications
Soils	1. Materials handling - Storage piles - Unpaved roads - Inactive sites*	Daily cover may be applied to active storage piles, however soils more applicable to inactive storage piles. High erosion potential. Best to use "tight" soils (e.g., clay). Soils must be uniformly applied and deep enough to prevent erosion from exposing contaminated soil.
	2. Bioremediation	Well compacted soils may limit biological growth by limiting moisture loading.
	3. Solidification/stabilization	Increases soil to be treated.
	4. On-site incineration	Increases soil to be treated. Also decreases Btu content of contaminated soil.
Organic solids	1. Materials handling - Storage piles	Impractical for active storage piles unless "anchoring" is not required.
	- Inactive sites*	Some materials require anchoring via a net or tilling into soil to prevent erosion.
	2. Bioremediation	May add nutrients to soil (e.g., organic sludges).
	3. Solidification/stabilization	Applicable only for small grained organic solids (e.g., sawdust, sludges).
	4. On-site incineration	May increase Btu content of contaminated soil.

(continued)

Table 7-4. (continued)

Cover material	Applicable remediation technology	Qualifications
Asphalt/Concrete	1. Materials Handling - Unpaved Roads*	Applicable for permanent traffic pattern areas (>100 passes/day).
Road Carpet and Gravel/Slag	1. Materials Handling - Unpaved Roads*	Applicable to permanent and temporary traffic pattern areas.
Polymer Sheeting	1. Materials Handling - Storage Piles*	Applicable to inactive storage piles.
	- Inactive sites*	Inactive areas may require extensive pre-application procedures (i.e., grading, base material, weed control).
	2. In-Situ Thermal Treatment	May be used to convert area source to a point source if liners can withstand the heat.
	3. Soil Vapor Extraction	May be used to minimize/control infiltration of ambient air.
	4. Bioremediation	May reduce biological activity due to decreased moisture loading and oxygen transfer impairment.

* Typical use of cover materials. Other listed uses are less common.

Table 7-5. Synthetic Cover Characteristics[1]

Synthetic material	Chemical resistance		Weather resistance	Gas permeability resistance	Tear resistance
Polyethylene					
High density polyethylene (HDPE)	Inorganics Organics	Good Good	Excellent	Excellent	Good
Low density polyethylene (LDPE)	Inorganics Organics	Good Poor	Poor	Poor	Poor
Very low density polyethylene (VLDPE)	Inorganics Organics	Good Good	Excellent	Excellent	Good
Linear Low Density Polyethylene (LLDPE)	Inorganics Organics	Good Good	Excellent	Excellent	Good
Polyvinyl chloride (PVC)	Inorganics Organics	Good Poor	Poor	Good	Good
Chlorosulfonated polyethylene (CSPE)	Inorganics Organics	Good Poor	Good	Good	Good
Ethylene interpolymer alloy (EIA)	Inorganics Organics	Good Good	Good	Good	Good

[1] Source: Landreth, 1988

Foams are generally classified as either long-term (stabilized) or temporary foams. Temporary foams are effective at controlling PM/VOC emissions from 1-24 hours, at which time 25% or more of the water incorporated in the foam will have been released ("quarter drainage time"). Long-term foams either contain a stabilizing agent incorporated into a short-term foam (3M products) or are comprised entirely of proprietary agents (Rusmar Products). Long-term foams will form an elastomeric membrane upon setting (1-2 min) which is the primary mechanism of PM/VOC control. Generally the useful life of a long-term foam is from several days to several months.

Foams generally are produced by pressurizing a mixture of proprietary foam concentrate/water solution through an air-aspirated or air-injected foam nozzle; a schematic of this system for 3M products is shown in Figure 7-1. However, the long-term foams produced by Rusmar do not require dilution with water.

Two important indicators of foam quality in relation to vapor control are the "expansion ratio" and the "quarter drainage time". The expansion ratio is a dimensionless number that expresses the ratio of the volume of foam to the volume of foam concentrate that

Table 7-6. Parameters Influencing Cover Material Effectiveness

Cover material	Parameter	Comments
Soil	- Porosity	- Decreased porosity → increased VOC control.
	- Moisture content	- Increased moisture → increased VOC/PM control.
	- Depth	- Increased depth → increased VOC/PM control (to a maximum).
Organic solids	- Porosity	- Decreased porosity → increased VOC control.
	- Moisture content	- Increased moisture content → increased particulate/VOC control and decreased erosion due to wind (only for small grained solids).
	- Depth	- Increased depth → increased VOC/PM control (to a maximum).
Asphalt/gravel	- Road base	- Stable road base → decreased maintenance required.
	- Maintenance	- Well maintained road will limit spillage.
	- Surface cleaning	- Frequent cleaning will limit PM emissions due to spillage and "track-out."
Polymer sheeting	- Liner material	- Liner material influences diffusivity coefficient of various VOCs with respect to liner. Also determines susceptibility to photodegradation.
	- Liner thickness	- Thicker liner → increased resistance to VOC diffusion, puncture, and tear.

Source: Landreth, 1983.

Table 7-7. Cover Material Control Efficiency Ranges

Cover material	Pollutant	Control efficiency (%)	Notes	Source
Soils	PM	~100	Theoretical[1]	U.S. EPA, 1988a[1]
	VOCs	92-99.8	1" and 40" soil layer on an inactive site	Vogel 1985
Organic soils	PM	85[2]	Inactive storage piles[2]	U.S. EPA, 1987a
	VOCs	NR	—	-
Asphalt/concrete	PM	85-99	99% with frequent cleaning	U.S. EPA, 1987a
		90	Calculated[3]	U.S. EPA, 1987b
Road carpet	PM	45	—	U.S. EPA, 1987a
Gravel/slag	PM	30-50	Gravel/slag on unpaved roads	U.S. EPA, 1987a
Polymer sheeting	PM	100	Theoretical	-
	VOCs[4]	90	Polyethylene liner for hexachlorobenzene emission control	Vogel, 1985

NR = Not Reported
[1] Theoretical based on zero wind/water erosion of soil layer.
[2] Particulate control efficiencies for inactive storage piles/sites are equivalent (EPA, 1989).
[3] Calculated based on AP-42 emission factors for paved and unpaved roads (U.S. EPA, 1985b).
[4] Some VOC diffusivity coefficients for a 20 ml PVC liner are reported by Springer, et al., 1986.

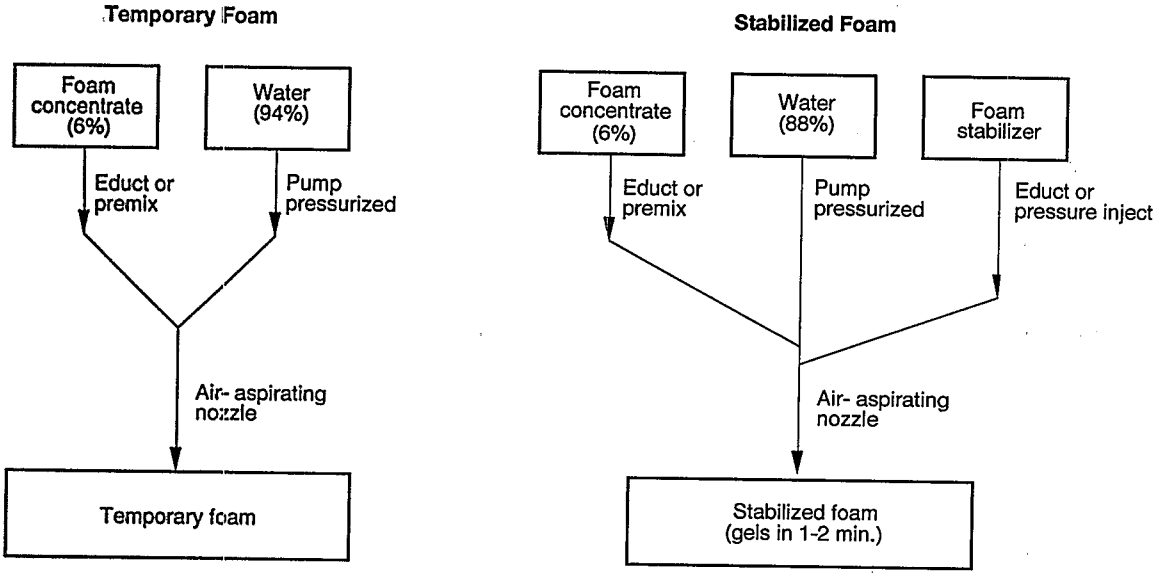
Table 7-8. Cover Material Sizing/Application Guidelines

Cover material	Pollutant	Sizing Guidelines
Soil	PM	Apply enough soil to insure even application and to prevent exposure of contaminated soil due to erosion of clean soil layer.
	VOCs	Sizing is dependent on moisture content and porosity of soil. Assume linear relationship from data presented in Table 7-7.
Organic solids	PM	Apply organic solids to the point that no emissions are measured.
	VOCs	None currently available.
Asphalt/concrete	PM	Follow accepted civil engineering guidelines for road construction using asphalt or concrete.
Road carpet and gravel/slag	PM	Follow accepted civil engineering guidelines for road construction using gravel or slag.
Polymer sheeting	PM	Surface roughness will determine liner thickness required.
	VOCs	VOCs to be controlled will determine liner material to be used. Contact manufacturer for specific information.

Table 7-9. Cost of Implementing Cover Based Area Control Measures

Cover material	Cost (1992 $) Equipment[4]	Labor/materials	Source
Backfill dirt	2.0 m^3	15/m^3	Means, 1991; Vendor
Clay	1.0 m^3	15/m^3	Means, 1991; Vendor
Road base, road carpet, and gravel[1]	3-6/m	4-10/m	Means, 1991; Vendor
Asphalt, road base[2]	6-12/m	200-300/m	Means, 1991; Vendor
Wood fibers with plastic netting[3]	0.5/m^2	0.5/m^2	Means, 1991; U.S. EPA, 1988b
Polymer sheeting	1.0/m^2	1.0/m^2	Vendor

[1] 7.5 m wide and 0.15 m gravel.
[2] 7.5 m wide and 0.10 m asphalt.
[3] Wood fiber depth not stated.
[4] Assumes material not already on site.



Source: Alm, et al., 1987

Figure 7-1. Production of temporary and long-term 3M foams.

produced the foam. Expansion ratios are generally defined as follows:

- High-expansion: greater than 250:1;
- Medium-expansion: between than 20-250:1; and
- Low-expansion: less than 20:1.

High-expansion foams can be generated only by using high-expansion surfactant foam concentrates in combination with special foam-generating equipment. However, low- and medium-expansion foams can be generated using various combinations of foam types and foam nozzles. For example, a given brand of foam concentrate may produce a medium-expansion foam with one nozzle and a low-expansion foam using a different nozzle. Another brand of foam may produce a medium-expansion foam with both nozzles.

The term "quarter drainage time" refers to the time it takes for a foam to release 25 percent of the total liquid incorporated into the foam. Long quarter drainage times are indicative of stable foams, which are capable of suppressing vapors for long time periods before reapplication is necessary. High-expansion foams exhibit the longest quarter drainage times, often exceeding one hour. However, these foams may be blown away easily under windy conditions. Medium-expansion foams exhibit quarter drainage times exceeding 15 minutes, but usually less than 30

minutes. Quarter drainage times for low-expansion foams generally range between 3 and 12 minutes.

The major components of a foam PM/VOC suppression system are as follows:

- Foam concentrate;
- Water (subject to foam requirements);
- Foam concentrate bulk storage tank; and
- Foam generating/distributing unit
- Manifold distribution
- Hand-line distribution.

A list of foams by type, brand name, manufacturer, and useful lifetime is presented in Table 7-10.

7.2.2 *Applicability to Remediation Technology*

The advantages and disadvantages of using foams to control PM/VOC emissions are outlined in Table 7-11. Remediation technologies compatible with foam PM/VOC suppression systems are listed in Table 7-12. Foams are most commonly used as temporary covers to control emissions during excavation, dredging, and other materials handling operations.

7.2.3 *Range of Effectiveness*

Several parameters that influence the effectiveness of foam systems to control PM/VOC emissions are given in Table 7-13. Reported control efficiencies for foam based systems as a function of time, foam type, and contaminant to be controlled (PM or VOC) are given in Table 7-14.

7.2.4 *Application Rates*

Prior to applying foam, the concentrate must be diluted with water. Dilution ratios (water:concentrate) can range from 0 to 16:1. The manufacturer should be contacted to determine the appropriate dilution ratio required.

Long-term foams are generally applied to depths of one-two inches, while temporary foams are generally applied to depths of two to three inches. The method of application, hand-line or manifold distribution systems, will depend on the topography and media characteristics (i.e. liquid, solid, sludge). Hand-line systems are capable of shooting foam 30 to 200 feet. Manifold distribution systems are capable of delivering foam at a rate of roughly 100 m^3/min.

Currently, no empirical relationships exist to predict the PM/VOC control efficiency of foam suppression systems. Therefore it is suggested to either use the data presented in Table 7-14 or conduct pilot scale testing at the site to be treated.

Table 7-10. Commercially Available Foams for PM/VOC Emissions Control

Foam type	Brand name	Manufacturer	Useful lifetime
Temporary	FX9162	3M	0.5-1.0 hours
	AC645	Rusmar	12-24 hours
Long-term	FX9161/9162 mixture	3M	1-7 days
	AC900 series	Rusmar	up to 5 months

Table 7-11. Advantages/Disadvantages of Foam Systems to Control PM/VOC Emissions

Advantages	Disadvantages
100% Control of PM emissions achievable	Ca and Mg hardness of dilution water will adversely affect useful lifetime
Effective control of VOC emissions	May not work well on steep slopes
Easy to apply	Temporary foams are easily blown/washed away by wind/water.
Specialized foam application units available	Materials handling problems due to water in foam
Allow control of working face - temporary foams	Possible that foams will react adversely with VOC's to be controlled
Applicable to liquid, sludge, and solid media	Difficult to apply on windy days
Reduced amount of material to be decontaminated relative to soil covers	Foam itself may off-gas
Long-term foams forming elastomeric membrane reduce water infiltration-hence minimize leaching	Moderately expensive
	Reapplication required to maintain PM/VOC suppression

Table 7-12. Applicable Uses of Foams by Remediation Technology

Remediation technology	Foam type	Qualifications
- Inactive sites/storage piles	Long-term	Foam must be compatible with VOCs to be controlled. May use manifold distribution systems on open, flat, and solid terrain, otherwise must use hand-line distribution systems
- Active storage piles	Temporary	Slope of storage piles must be gradual so foam will not run off.
- Dump cycle	Temporary	Place foam in truck to be loaded then add contaminated material. Because operators can't see foam level, they must know how much material they can add before foam overflows.
- Excavation	Temporary	To maintain continuous control of PM/VOC emissions, foam must be reapplied to areas as it is removed during excavation.
- Incineration	Both	Water content of foam may preclude incineration of contaminated material.
- Solidification/stabilization	Both	Foam may be incompatible with process.
- Bioremediation	Both	Possible limits on biological activity due to impairment of water and oxygen transfer to active biological zone.

Table 7-13. Parameters Influencing Effectiveness of Foam-based PM/VOC Suppression Systems

Parameter	Comment
Quarter drainage time	The longer the quarter drainage time the longer the foam will be useful.
Wind Speed	Wind speeds greater than 10 mph preclude the application of foams (U.S. EPA, 1986a). High wind speeds will blow away foams already applied, except for long-term foams which have formed an elastomeric membrane.
Precipitation	Rain will tend to wash foams away, except for long-term foams which have formed an elastomeric membrane.
Surface roughness	For some surfaces (i.e., areas covered with shrubs), foams can not be applied evenly.
Expansion ratio	The higher the foam expansion ratio the longer the quarter drainage time. Also the higher the foam expansion ratio, the more susceptible it is to being blown away.
Temperature	Increased temperatures result in decreased quarter drainage times (U.S. EPA, 1989).
Surface activity	Increased surface activity (i.e. travel) will decrease effectiveness of foam systems.
Contaminant VOC characteristics	VOCs that are reactive with chemicals comprising foam material will degrade foam effectiveness and may produce undesirable compounds.

Table 7-14. Reported PM/VOC Control Efficiencies Using Foam Suppression Systems

Foam type	Contaminant	Control efficiency (%)	Time since application	Comments	Source
NR	PM	92	Continuous	10.5 ft^3 /ton material	U.S. EPA, 1989
NR	PM	74	Continuous	8.4 ft^3 /ton material	U.S. EPA, 1989
Long-term	VOC	—	—	6:1 Expansion ratio 1 inch foam	Alm, 1987
	Paraffins	100	24 hours		
	Olefins	100	24 hours		
	Aromatics	99	24 hours		
Temporary	VOC	—	—	6:1 Expansion ratio 1 inch foam	Alm, 1987
	Paraffins	95	20 minutes		
		73	2 hours		
	Olefins	90	20 minutes		
		64	2 hours		
	Aromatics	99	20 minutes		
		79	2 hours		
Long-term	VOC	99	7 days	—	Radian, 1991
	VOC	91-97	7 days	2-3 inches	Schmidt, 1992
	VOC	100	7 days	2-3 inches	Schmidt, 1992
	VOC	100	7 days	1 inch	U.S. EPA, 1991

NR = Not reported.

7.2.5 *Cost Estimating Procedure*

Costs for various foam types are given in Table 7-15. These costs are a function of the area to be treated at the application depths recommended by the manufacturer.

Table 7-15. Foam Costs

Foam type	Brand name	Costs ($/m²)	Source
Temporary	FX9162	1.10	Vendor (3M)
	AC645	0.54-0.86	Vendor (Rusmar)
Long-term	FX9162/9161	3.80	Vendor (3M)
	AC904	1;.30-1.94	Vendor (Rusmar)
	AC912	1.94-2.70	Vendor (Rusmar)
	AC918	2.70-3.77	Vendor (Rusmar)
	AC930	3.77-5.28	Vendor (Rusmar)

Costs for foam application units range from $8,000 to $12,000 per month for manifold application units (including bulk storage tanks) and $3,250 to $7,750 for hand-line application units (Rusmar, 1992). Small 3M application units can be rented for about $660 per week; about $500 of ancillary equipment is also required.

7.3 Wind Screens

7.3.1 *Process Description*

Wind screens can be used to reduce PM emissions from storage piles, excavation sites, and other area sources. The principle is to provide an area of reduced wind velocity that allows settling of the large particles and reduces the particle flux from the exposed surfaces on the leeward side of the screen. Wind screens also provide limited control of VOC emissions by increasing the thickness of the laminar film layer (stagnant boundary layer) on the leeward side of the screen. In addition, wind screens reduce soil moisture loss due to the wind, resulting in decreased VOC and particulate matter emissions.

Generally wind screens are porous and constructed of plastic materials. Solid wind screens are not as effective, and are thus rarely used, because they create a turbulent zone immediately behind the fence which increases PM/VOC emissions in this area. A diagram of the effect of wind screens on wind speeds is provided in Figure 7-2.

7.3.2 *Applicability to Remediation Technology*

The advantages and disadvantages of wind screen systems to reduce PM/VOC emissions are presented in Table 7-16.

Wind screens are compatible with all remediation technologies involving contaminated materials handling operations (e.g., excavation, storage piles, and inactive sites). The qualifications for using wind screens with specific materials handling operations are outlined in Table 7-17.

7.3.3 *Range of Effectiveness*

Parameters influencing the effectiveness of wind screens to control particulate/VOC emissions are listed in Table 7-18. Reported PM/VOC control efficiencies achieved with wind screens are given in Table 7-19. In general, wind screens provide approximately 15% control of total suspended particulates (TSP) than PM_{10} (U.S. EPA, 1987b). Also, particulate matter control efficiency for relatively flat active surfaces is expected to be similar to that observed for active storage piles.

7.3.4 *Sizing Criteria/Application Rates*

Wind screen sizing for various materials handling operations is outlined in Table 7-20. In addition, crude empirical models have been developed to describe particulate and VOC emissions reductions. To predict VOC control efficiency, the following equation applies:

$$\text{Efficiency (\%)} = \left(1 - \sqrt{\frac{SR}{SH}}\right) \times 100 \qquad \text{(Eq. 7-2)}$$

where:

SR = Surface Roughness (m); and
SH = Screen Height (m).

To predict PM control efficiency, use the following model:

$$\text{Efficiency (\%)} = \left(1 - (1 - WSR)^{1.3}\right) \times 100 \qquad \text{(Eq. 7-3)}$$

where:

WSR = Mean wind speed reduction due to wind screen (fraction).

Unfortunately this model requires that the mean wind speed reduction due to the wind screen be known. This can either be measured or based on estimates provided by the vendor.

7.3.5 *Cost Estimating Procedure*

Capital costs for wind screens vary with the type of control desired (VOC or PM) and the operation requiring control (e.g., inactive sites, excavation, etc.). Costs as a function of pollutant to be controlled and operation requiring control are outlined in Table 7-21.

7.4 Water Sprays

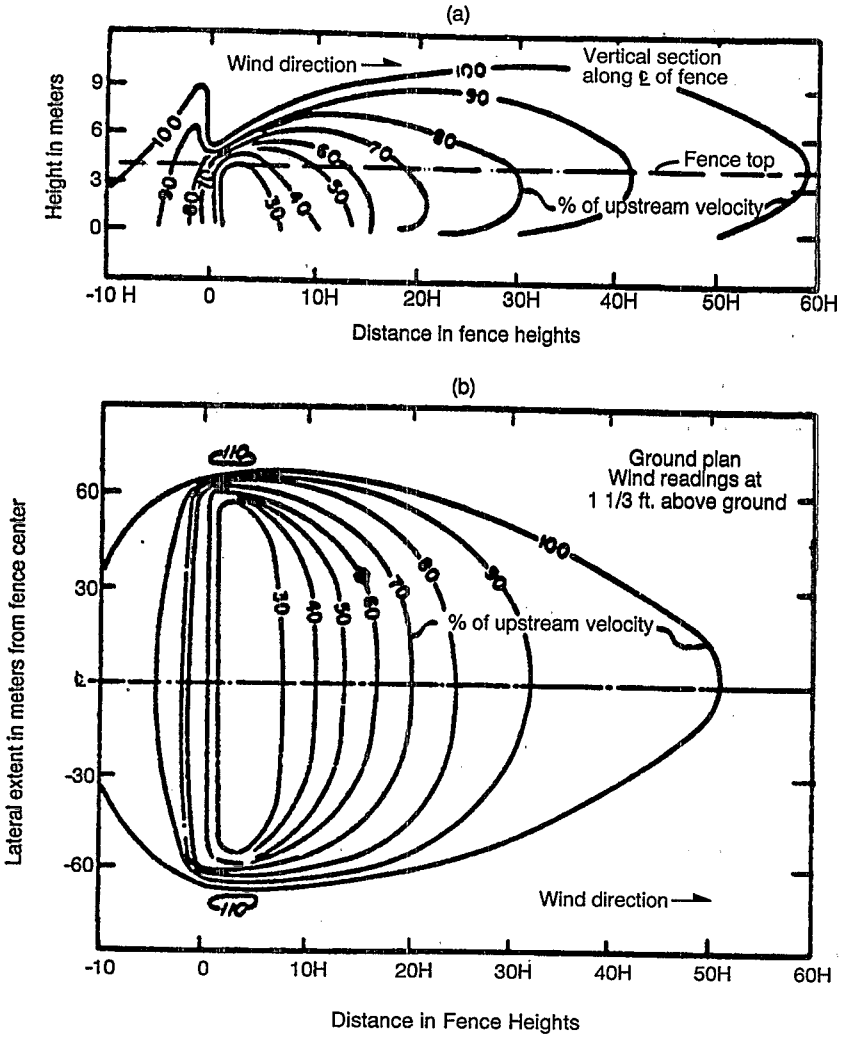
7.4.1 *Process Description*

Water sprays are used primarily to control PM emissions. The control mechanism is the agglomeration of small particles with larger particles or with water droplets. Also, water added to the soil will cool the surface soil and will decrease the air-filled porosity of the soil. These actions result in an initial displacement of VOCs followed by a decrease in VOC emissions until the water evaporates.

Typically, water is applied with mobile water wagons; however, it also may be applied via fixed perforated pipes. Fixed systems for water application are limited to long-term fixed emission sources (e.g. conveyor belts, long-term storage piles, fixed loading areas, "track-out" elimination sites). The major components of water spray systems are listed in Table 7-22.

7.4.2 *Applicability to Remediation Technology*

The advantages/disadvantages of using water as a particulate control technique are outlined in Table 7-23. The applicability of water spray systems to control area sources of particulate matter emissions for various remediation technologies is outlined in Table 7-24.



Source: U.S. EPA, 1986b.

Figure 7-2. Wind velocity pattern above a mown field during a 17 m/sec wind blowing at right angles to a 4.9 m high wood fence 122 m long of 50% porosity. (a) Side view profile. (b) Plan view profile.

7.4.3 Range of Effectiveness

Water spray systems are an effective control measure for particulate matter emissions. However, they are not recommended for VOC emissions control, unless they are applied with soil cover materials followed by compaction.

Parameters that influence the performance of water spray systems are outlined in Table 7-25. Particulate matter control efficiencies for various water application rates and intensities reported in the literature are presented in Table 7-26. Particulate matter control efficiencies for relatively flat active surfaces are expected to be similar to that observed for active storage piles.

7.4.4 Sizing Criteria/Application Rates

In general, the water loading and application rates presented in Table 7-26 can be used to obtain the reported particulate matter control efficiencies. However, predictive equations have been developed to estimate particulate matter control efficiencies obtainable for water spray systems applied to unpaved roads.

Table 7-16. Advantages/Disadvantages of Wind Screen Systems

Advantages	Disadvantages
Inexpensive	Limited VOC control.
Easy to install	Limited effective control area.
Limits site access	Limited practical screen height due to construction and stability problems.
Obstructs view of site	Easily damaged.
Easy to relocate	Maximum achievable particulate control efficiency, approximately 90%.

Table 7-17. Applicable Remediation Technologies

Materials handling operation	Qualifications
• Storage piles	Pile height must be controlled. Can completely enclose inactive piles, while active piles can only be surrounded on three sides, one side open for vehicle access.
• Inactive sites	Large inactive areas require either taller wind screens or many parallel wind screens to control emissions effectively.
• Excavation areas	Can only enclose three sides, one side open for excavation equipment. Screens must be moved as excavation site moves. VOC control not possible.
• Dump cycles	Screen height must be greater than dump height. VOC control not possible.

Table 7-18. Parameters Influencing Wind Screen Effectiveness

Parameter	Influence
Wind screen porosity	Solid wind screens form turbulent boundary layer on leeward side thus increasing emissions. Most effective wind screens have 50% porosity.
Wind direction with respect to wind screen	Wind direction influences the size of the protected area. Area of protection is greatest for perpendicular winds to the screen length and least for parallel winds.
Wind screen height	Zone of wind velocity reduction is directly proportional to wind screen height.
Soil silt content	As soil silt content increases, wind screen particulate control efficiencies decrease.

Table 7-19. Reported PM/VOC Control Efficiencies Using Wind Screens

	Control efficiencies			
Area source	VOCs	Particulates	Comments	Source
Storage pile	80	—	Theoretical	Vogel, 1985
		48-97	Measured	U.S. EPA, 1989
		75-80	Theoretical	U.S. EPA, 1987b
		30-80	Measured	U.S. EPA 1987b
		75 (TSP)	Measured	U.S. EPA, 1987b
		60 (IP)	Measured	U.S. EPA, 1987b
		0-92 (TP)	Measured	U.S. EPA 1986b
		64-88	Measured	U.S. EPA, 1988a
Inactive sites	80	—	Measured	Springer et al., 1986

TSP = Total suspended particulates (<39 μm);
IP = Inhalable particulates (<15 μm); and
TP = Total particulates.

Table 7-20. Wind Screen Sizing

Materials handling operation	Wind screen sizing
Storage Piles	Screen length = five times pile diameter. Screen/pile distance = two times pile height. Screen height = pile height.
Dump cycles	Screen height > 1 ft. above bucket drop height.
Excavation	Screen/site distance = two times screen height.
Inactive sites	Wind screen should be placed perpendicular to prevailing wind direction. Distance between parallel wind screens = four to ten times screen height.

Table 7-21. Wind Screen System Costs

Type of control	Operation requiring Control	Cost	Source
VOC	Inactive surface impoundment	0.7-1.4$/m ² impoundment area	U.S. EPA, 1991
Particulate matter	Inactive sites [1]	0.6-13 $/m ² of inactive area	Vendor data/sizing guidelines
	Storage piles [2]	721 $/m ² of pile area	Vendor data/sizing guidelines
	Excavation [3]	11 $/m ² of excavation area	Vendor data/sizing guidelines

[1] Minimum price assumes chain link fence is available to secure wind screen against (valid for small areas). Cost per linear meter for wind screen is about $40, not including support structure.
[2] Assumes conically-shaped storage pile of roughly 10m diameter.
[3] Assumes 60m diameter excavation site and 1.8m high wind screen around 2/3 of site.

$$C_{AVG} = 100 - \frac{0.8\ pdt}{i} \qquad \text{(Eq. 7-4)}$$

where:

- C_{AVG} = Average control efficiency (%);
- p = Potential average hourly daytime evaporation rate (mm/hr); also
- p = 0.0049 x (value in Fig. 7-3) for annual conditions; or
- p = 0.0065 x (value in Fig. 7-3) for summer conditions;
- d = Average hourly daytime traffic rate (hr^{-1});
- i = Water loading rate (L/m^2); and
- t = Time between applications (hr).

For storage piles and inactive sites, the particulate matter control efficiency achieved can be determined from the soil moisture content before and after water application as shown in Equation 7-5.

$$C_I = \left[1 - \left(\frac{SM_B}{SM_A}\right)^2\right] x\ 100 \qquad \text{(Eq. 7-5)}$$

where:

- C_I = Instantaneous control efficiency (%);
- SM = Soil moisture content (weight %); and
- A,B = After, before water application, respectively.

7.4.5 Cost Estimating Procedure

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

7.5 Water Sprays with Additives

7.5.1 Process Description

Water additives can be classified as hygroscopic salts, bitumens, adhesives, or surfactants and are primarily used to reduce particulate matter emissions. The processes by which these additives act to reduce particulate matter emissions are outlined in Table 7-27. Some common water additives and their classification are listed in Table 7-28.

Water additives generally are applied topically; however, some additives can also be tilled into the soil. Components required for topical application include those used for water spray systems (see Section 7.4) and a storage tank for the undiluted chemical. Tilling of the water additives into the soil also requires tilling equipment.

7.5.2 *Applicability to Remediation Technology*

The advantages/disadvantages of using water additives as a particulate matter control technique are outlined in Table 7-29. Remediation technologies that are compatible with water additives are listed in Table 7-30.

7.5.3 *Range of Effectiveness*

Parameters that influence the performance of water additives are presented in Table 7-31. Particulate matter control efficiencies for various water/additive mixtures reported in the literature are reproduced in Table 7-32. Particulate matter control efficiencies for relatively flat active surfaces are expected to be similar to those observed for active storage piles.

7.5.4 *Application Rates*

In general, the water/additive dilution, application intensities, and frequencies presented in Table 7-32 can be used to obtain the reported particulate matter control efficiencies. Particulate matter control efficiencies for hygroscopic salt/water mixtures can be estimated from the predictive equations presented earlier for water spray systems (Section 7.4).

For bitumens and adhesives, time averaged PM_{10} control efficiencies as a function of additive "ground inventory" can be determined directly from Figure 7-4. The term "ground inventory" is a measure of residual effects from previous applications. Ground inventory is found by adding together the total volume of additive concentrate (not solution) since the start of additive application per surface area treated. Also, AP-42 emission factors for paved roads can be used to conservatively estimate PM emissions (1.5 to 2 times actual emissions) from unpaved road surfaces treated with bitumens/adhesives.

Typical dilution ratios and application rates (bitumens and adhesives) used in the iron/steel industry for treatment of unpaved roads are applicable and are presented below.

Paved road "housekeeping" techniques can be used on roads treated with bitumens/adhesives after the ground inventory exceeds approximately 0.9 L/m^2 (U.S. EPA, 1989). These "housekeeping" techniques will limit emissions due to spillage and "track-out" and will reduce required application frequencies.

Tilling of bitumens/adhesives into the top 7.6 cm (3 in.) of the soil followed by compaction resulted in particulate matter control efficiencies of 33 to 95% five months after application (U.S. EPA, 1987b).

7.5.5 *Cost Estimating Procedure*

Water additives costs include the costs associated with water spray systems (Section 7.4.5) and also include the cost of additives and storage tanks for the additives. Storage tank costs will vary depending on the size of the operation, the water/additive application rate and the time between deliveries of additive. Some additive costs by product name and classification are presented in Table 7-33. The dilution ratio, application rate and frequency must be determined to predict the cost/ft^2.

7.6 Operational Controls

7.6.1 *Process Description*

Operational controls are those procedures/practices inherent to most site remediation projects that can be instituted to reduce VOC/particulate matter emissions. These procedures/practices include:

Table 7-22. Major Components of Water Spray Systems

Capital equipment	Comment
Water spray system	
• Supply pumps, nozzles, and plumbing	Primarily used for fixed spray systems.
• Flat spray	Used for water screens that control particulate emissions from dump cycle.
• Hollow cone	Used for all other particulate emission sources.
• Water wagon	Used for mobile spray systems.
• Plumbing (plus winterization)	Used for stationary spray systems.
• Control system	Controls water application rate.
• Filtering units	Prevents fouling of spray nozzles.

Table 7-23. Advantages/Disadvantages of Using Water to Control PM Emissions

Advantages	Disadvantages
Inexpensive	Frequent application is required.
Easy to apply	May create groundwater contamination via mobilization of contaminant.
Well defined models for determining particulate control efficiency	Creates material handling problems.
Equipment availability.	Increases "track-out".
	Results in VOC emission spikes.
	Availability of water at some sites may preclude its use.
	Possible runoff of contaminated water.

Table 7-24. Remediation Technologies Compatible with Water Spray PM Control Systems

Remediation technology	Water spray system	Qualifications
1. Materials handling		
• Storage piles		
- Active	Mobile	Water application rate must be adjusted for exposed area and to prevent erosion.
- Inactive	Fixed	
• Excavation	Mobile	Use of hoses. Fixing hoses to excavation equipment is impractical. Water application rate must be adjusted to present materials handling problems.
• Inactive sites	Mobile	Use of water wagons. Water application must be uniform and controlled to insure a given application rate.
• Conveyor belt systems	Fixed	Water should be applied to underside of conveyor belt.
• Unpaved roads	Fixed	Unpaved roads should be well graded to insure uniform water application. Water applied to unpaved roads will increase "track-out".
• Fixed loading areas	Fixed	Water spray system designed to apply a flat spray, forming a water curtain around loading area which is two to three feet above material drop height.
• "Track-out" elimination sites	Fixed	Vehicles pass over sump covered with a metal grate located at site exit. Water spray directed upwards to wash vehicle undercarriage and wheels of contaminated soil.
2. Bioremediation	All	Water may dissolve organic compounds to be biodegraded and transport them past biological area. Water may also limit oxygen transport from atmosphere into the soil.
3. Solidification/stabilization	All	Water spray system should be compatible with waste or stabilization process used unless soil moisture is >95%.
4. On-site incineration	All	Water may lower Btu content of soil to the point that incineration is not possible.
5. Thermal desorption	All	Water may lower Btu content of soil. However, soils having 10-15% moisture exhibit enhanced VOC removal.

Table 7-25. Parameters Influencing Water Spray Systems Performance

Parameter	Influence
Application rate	For fixed meteorological conditions and traffic rates the particulate matter emissions are inversely proportional to the square of the soil moisture content (U.S. EPA, 1988a).
Application frequency	Particulate matter emissions are minimum after water application and rise steadily thereafter, until the next application of water.
Meteorological conditions	Wind, temperature, and humidity influence evaporation rate of water, hence particulate matter control efficiencies.
Traffic rate	Higher traffic volumes results in higher particulate matter emissions due to increased fines produced.

- Road cleaning practices;
- Seasonal scheduling;
- Vehicle speed control;
- Storage pile geometry/orientation;
- Excavation practices;
- Dumping practices; and
- Soil handling practices.

Of the above procedures/practices, only road cleaning requires additional equipment (i.e., broom sweepers, vacuum sweepers, or water wagons). Road cleaning practices are aimed at reducing particulate matter emissions from spillage and "track-out," and can be applied to paved roads and some chemically treated unpaved roads (see Section 7.5).

Planning site remediations according to the time of year can reduce overall PM/VOC emissions by taking advantage of lower temperatures and wind speeds and avoiding excessively dry weather. However, since site remediation is generally a relatively continual process, seasonal scheduling is only advantageous for sites which can be remediated within a season or two.

For unpaved roads, particulate matter emissions increase as the speed of the vehicle increases, all other factors remaining con-

Table 7-26. Reported Particulate Matter Emission Control Efficiencies for Watering Systems

Area source	Application intensity (L/m^2)	Time since application (hr)	Particle size[1]	Control efficiency (%)	Source
Unpaved roads	NR	0.5-4.5	TP	96-55	U.S. EPA, 1985a
			IP	98-50	
			FP	98-61	
	NR	0-1.0	TP	69-59	U.S. EPA, 1985a
			IP	73-61	
			FP	58-54	
	NR	0-0.5	TSP	88	U.S. EPA, 1985a
	NR	0-0.25	TSP	97	U.S. EPA, 1985a
	NR	0.3-1.0	TSP	75-25	U.S. EPA, 1985a
	NR	1.0-4.8	TP	98-61	U.S. EPA, 1985a
			IP	98-78	
			PM_{10}	98-79	
			FP	96-67	
	NR	0.5-2.0	TSP	77-12	U.S. EPA, 1985a
	NR	1.0-2.0	TSP	66-31	U.S. EPA, 1985a
	NR	0.5-2.0	TSP	60-15	U.S. EPA, 1985a
	2.3	4.0	NR	50-30	U.S. EPA, 1985b
	0.2	1.8	TSP/FP	59	U.S. EPA, 1987a
	0.2	2.0	TSP/FP	69	U.S. EPA, 1987a
	0.6	4.5	TSP/FP	77	U.S. EPA, 1987a
	1.9	2.8	TSP/FP	88	U.S. EPA, 1987a
Storage piles	NR	NR	NR	25-50	U.S. EPA, 1987b
Loading operations	NR	NR	NR	70-90	U.S. EPA, 1987b
Above conveyor belt operations	9.51/min	Continuous	IP	56	U.S. EPA, 1989a
			TP	59	U.S. EPA, 1989a
Below conveyor belt operations	9.51/min	Continuous	IP	81	U.S. EPA, 1989a
			TP	87	
Excavation	4.1	NR	FP	64	U.S. EPA, 1985a
			TSP	42	
Dump cycle (area spray)	4.1	NR	FP	66	U.S. EPA, 1985a
			TSP	69	

NR = Not reported;
TP = Total particulates;
TSP = Total suspended particulates (<39μm);
IP = Inhalable particulates (<15Mm);
PM_{10} = Particulate matter (<10 μm); and
FP = Fine particulates (<2.5μm).

stant. Speed reduction reduces the turbulence and energy imparted to fine particles, which reduces particulate matter entrainment.

PM and VOC emissions from storage piles can be minimized by controlling the placement and shape of piles. When feasible, the piles should be placed in areas shielded from the prevailing winds at the site. The pile surface area can be minimized for the given volume of soil by shaping the pile. The orientation of the pile will affect the wind velocity across the pile, hence PM/VOC emissions will be affected.

Since PM/VOC emissions are proportional to the surface area exposed, a reduced surface area/volume ratio will minimize emissions per unit volume of soil excavated. This reduction can be accomplished by utilizing larger excavation equipment (i.e., larger bucket volumes for front end loaders, bulldozers, and backhoes).

Dumping practices which can be employed to reduce particulate matter emissions include drop height reduction and loading/unloading of material on the leeward side of storage piles. By minimizing the soil drop height, the energy and turbulence caused by the falling soil are reduced thus reducing particulate matter entrainment. VOC emissions will also be reduced.

Table 7-27. Additive Processes

Additive	Process description
Hygroscopic salts	These compounds adsorb moisture from the air, thereby increasing the soil moisture content.
Bitumens/Adhesives	Act to agglomerate surface soil particles to form a surface "crust".
Surfactant	Act to reduce water surface tension, thereby increasing "wetting" capacity of the water.

Table 7-28. Common Water Additives

Product	Manufacturer
	A. Hygroscopic salts
Calcium chloride	Allied Chemical Corporation
Dowflake, Liquid Dow®	Dow Chemical
DP-10®	Wen-Don Corporation
Dust Ban 8806®	Nalco Chemical Company
Dustgard®	G.S.L. Minerals and Chemicals Corporation
Sodium silicate	The PQ Corporation
	B. Bitumens
AMS 2200, 2300®	Arco Mine Sciences
Coherex®	Witco Chemical
Docal 1002®	Douglas Oil Company
Peneprime®	Utah Emulsions
Petro Tac P®	Syntech Products Corporation
Resinex®	Neyra Industries, Inc.
Retain®	Dubois Chemical Company
	C. Adhesives
Acrylic DLR-MS®	Rohm and Haas Company
Bio Cat 300-1®	Applied Natural Systems, Inc.
CPB-12®	Wen-Don Corporation
Curasol AK®	American Hoechst Corporation
DCL-40A, 1801,1803®	Calgon Corporation
DC-859, 873®	Betz Laboratoires, Inc.
Dust Ban®	Nalco Chemical Company
Flambinder®	Flambeau Paper Company
Lignosite®	Georgia Pacific Corporation
Norlig A, 12®	Reed Lignin, Inc.
Orzan Series®	Crown Zellerbach Corporation
Soil Gard®	Walsh Chemical
	D. Surfactants
M 070 E	Mona Industries Inc.
Sterox	Monsanto Company

Source: Page 45 of U.S. EPA, 1987b.

Table 7-29. Advantages/Disadvantages of Using Water Additives to Control Particulate Matter Emissions

Advantages	Disadvantages
Easy to apply	Additives may be washed away by rain, thus negating their effects (e.g., salt).
Equipment availability.	Additives may react with contaminants present in the soil.
Surfactants reduce water required by 75% for same level of control (U.S.. EPA, 1989)	Additives often contain organic compounds which may vaporize, leading to ozone production (U.S. EPA, 1988a).
Less frequent reapplication required than water spray systems.	Not applicable to unpaved roads that require frequent grading. Expensive. Application of chemical additives in cool weather may be inadvisable for traffic safety reasons (U.S. EPA, 1988a). Additives may contribute to water contamination (surface water and groundwater). Some salts (e.g., $CaCL_2$) are corrosive to vehicles.

Table 7-30. Remediation Technologies Compatible with Water Additives

Remediation technology	Qualifications
1. Materials handling	
• Storage piles (inactive	Same as water spray (see Section 7.4).
• Inactive sites	Same as water spray systems.
• Unpaved Roads	Same as water spray systems. Also can use paved road cleaning techniques for unpaved roads treated with adhesives and bitumens. This practice reduces particulate matter emissions due to spillage and "track-out".
2. Bioremediation	Same as water spray systems. Also additives may inhibit biological activity.
3. Solidification/stabilization	Same as water spray systems. Additives may be incompatible with waste or stabilization process used.
4. On-site incineration	Water may lower Btu content of soil to be treated. However, certain additives may increase Btu content of soil to be teated (e.g., bitumens and adhesives).

Table 7-31. Parameters Influencing Performance of Water Additives

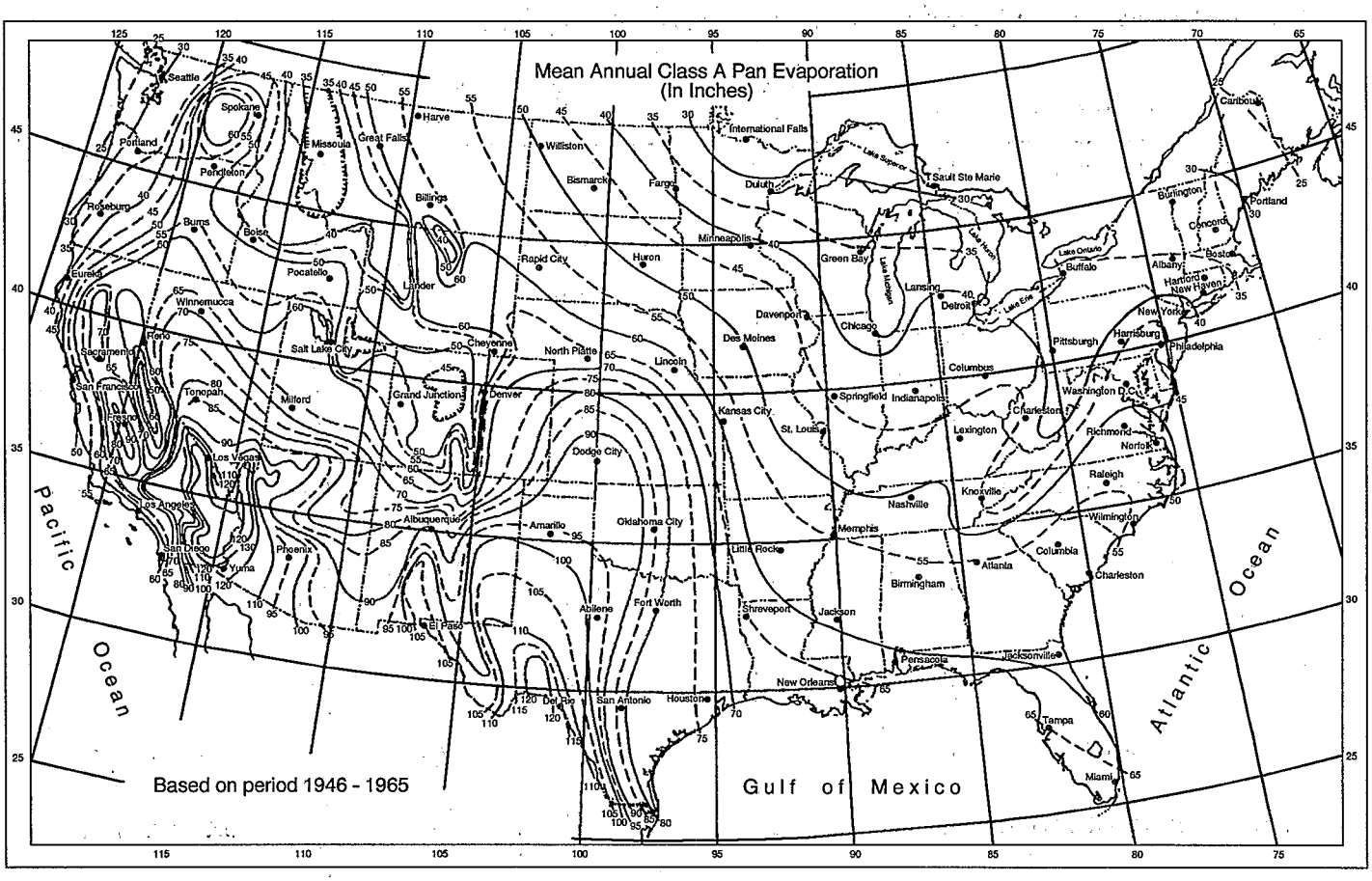
Parameter	Influence
Dilution ratio	Higher dilution ratio results in decreased additive applied for a given water/additive loading rate. This decreases long-term control efficiency (e.g., 2-3 weeks after application).
Application rate	Higher loading rate results in higher particulate matter control. However, this relationship applies only to a point, because too intense an application will produce run-off.
Application frequency	Same as for water spray systems.
Meteorological conditions	Affect required application frequency for a given control efficiency. For example, freeze-thaw cycles break up crust formed by chemical binding agents; heavy precipitation washes away water soluble additives like hygroscopic salts; and intense solar radiation dries out treated surfaces. However, light precipitation or high humidity might improve the efficiency of hygroscopic salts.
Vehicle weight, speed, and passes	Acts to break up crust formed by chemical binding agents.
Unpaved roads base and subgrade bearing strength	Low base and subgrade bearing strength will result in road deformation which will destroy crust formed by chemical binding agents.

Table 7-32. Reported Particulate Matter Emission Control Efficiencies for Water Additives

Area source	Additive classification	Dilution ratio	Application Intensity (L/m [2])	Time since application (days)	Particle size [2]	Control efficiency (5)	Source
Unpaved Roads	Hygroscopic salts	NR	2.3	3-60	TSP	48	U.S. EPA, 1987a
					IP	24	
		1:2	2.7	90	TSP	95	
					IP	95	
					FP	95	
		1:1	0.9	30-270	TSP	46	
					RP	42	
		NR	NR	93	TSP	95	
					IP	98	
					FP	88	
		NR	NR	1-49	TSP	0-83	
					IP	0-74	
					FP	0-80	
	Bitumens/adhesives	NR	NR	14	TP	47-96	U.S. EPA, 1987a
					PM_{10}	60-96	
				30	TP	47-90	
					PM_{10}	60-94	
		1:8	NR	<7	TSP	91	
		1:6	0.9	1-2	TP	92-98	
					TSP	91-96	
					FP	90-97	
		1:5	NR	14	TP	99	
		1:0	16.0	30-270	TSP	96	
					IP	57	
	Surfactant	NR	NR	1-42	TSP	0-87	U.S. EPA, 1987c
					IP	0-68	
					FP	0-85	
Storage piles	Bitumens/adhesives	1:5	3.4	60	TP	90	U.S. EPA, 1987a
					IP	62	
					FP	62	
		1:35	6.8	4	TP	44	
					IP	50	
Inactive sites	Bitumens/adhesives	1:2	0.81	1	TP	94	U.S. EPA, 1989
		1:2	0.41	1	TP	68	
		1:2	0.20	1	TP	36	
		1:12	0.31	1	TP	99	
		1:4	1.13	1	TP	99	
		1:4	0.57	1	TP	96	
		1:4	0.28	1	TP	84	
		1:19	1.13	1	TP	99	
		1:1	1.13	1	TP	99	
		1:1	0.57	1	TP	93	
		1:1	0.28	1	TP	85	
		1:7	1.13	1	TP	100	
		1:3	1.12	1	TP	99	
		1:3	0.75	1	TP	98	
		1:3	0.37	1	TP	87	
		1:11	1.12	1	TP	100	
Excavation	Surfactant	1:1000	3.4	Continuous	TSP	63	U.S. EPA, 1987b
					FP	70	
Dump cycle	Surfactant	1:1000	4.1	Continuous	TSP	77	U.S. EPA, 1985a
					FP	62	

[1] Additive concentrate: Water

[2] TP = Total particulate matter
TSP = Total suspended particulate matter (<38μm);
IP = Inhalable particulate matter (<15Mm);
FP = Fine particulate matter(<2.5μm)
PM_{10} = Particulate matter (<10 μm)
NR = Not reported



Source: Buonicore, et al., 1992.

Figure 7-3. Annual evaporation data for the contiguous United States.

Spillage of soil during transport is a consequence of loading practices and is a primary cause of particulate matter emissions from paved roads. Minimizing spillage can be accomplished by covering or enclosing tracks transporting soils increasing freeboard requirements, and repairing trucks exhibiting spillage due to leaks.

7.6.2 Applicability to Remediation Technology

The relative advantages/disadvantages of each operational practice/procedure are outlined in Table 7-34. Road cleaning practices, seasonal scheduling, and vehicle speed control are applicable to all remediation technologies, while the other practices/procedures are applicable to materials handling operations.

7.6.3 Range of Effectiveness

Reported control efficiencies for some operational practices/procedures are given in Table 7-35.

7.6.4 Sizing Criteria/Application Rates

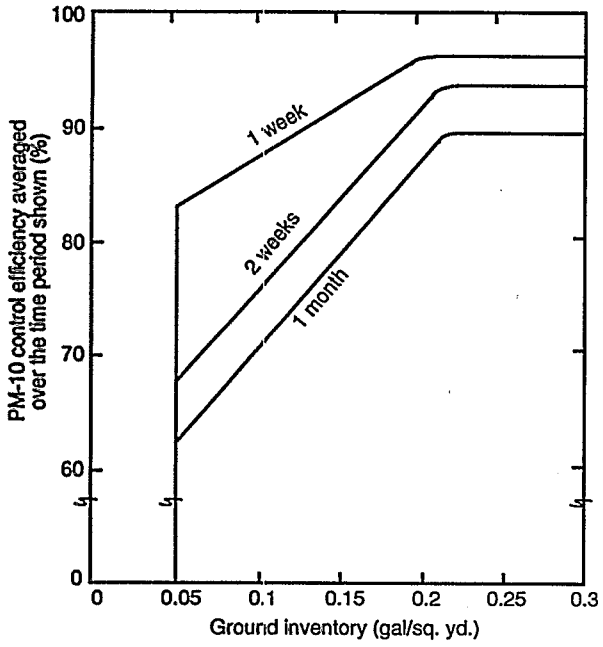
For a target control efficiency, the operational practices/procedures required can generally be determined by using AP-42 emission factors presented in U.S. EPA, 1985b. Operational practices/procedures which are amenable to this approach are:

- Road cleaning practices;
- Seasonal scheduling;
- Vehicle speed control;
- Excavation practices; and
- Dumping practices.

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

7.6.5 Cost Estimating Procedure

For the majority of the operational control measures presented in this section, the cost is negligible with the exception of road cleaning equipment and possibly seasonal scheduling. The cost of seasonal scheduling will vary with season primarily due to labor costs and equipment availability. Cost for street cleaning practices are estimated to be $140 per day per street cleaner and $66 per day per crew (Means, 1991). The use of larger excavation equipment to minimize emissions will increase costs to some extent (Means, 1991).



Source: U.S. EPA, 1987c.

Figure 7-4. Average PM_{10} control efficiency for bitumen/adhesive additives.

7.7 Enclosures

7.7.1 Process Description

Enclosures are used to provide near 100% PM/VOC emission control for area sources undergoing excavation and PM/VOC emissions control for storage piles. Enclosures used during excavation are either self-supported or air-supported structures, while those used for storage piles are self-supported structures similar to the "beehives" used to store road salt.

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

Self-supported structures consist of a rigid frame covered with an all-weather outer skin. The frame is generally constructed of light weight aluminum which may require concrete footings, depending on the size of the structure. The outer skin generally is constructed of corrugated steel or textile materials. Since self-supported structures do not rely on interior air pressure for support, they usually are operated under negative pressure. Negative interior pressure prevents PM/VOC emissions via entrances/exits and leaks in the structure.

Air-supported structures consist of an all weather membrane that is supported by positive pressure within the enclosure. Because the enclosure is under positive pressure any leaks or openings will result in PM/VOC emissions. To counter this, air-supported structures often are equipped with air lock systems.

Table 7-33. Additive Costs

Additive classification	Typical material cost ($/ft²)
Hygroscopic salt	0.02-0.10 [1]
Bitumens/adhesives	0.15-0.32 [1]
Surfactant	0.002 [2]

[1] Source: U.S. EPA, 1988a.
[2] Vendor data at recommended dilution and application rates.

7.7.2 Applicability to Remediation Technology

The advantages/disadvantages of using enclosures to control PM/VOC emissions are outlined in Table 7-36.

Because enclosures do not alter the physical properties of the material to be treated, their compatibility with various remediation technologies is only a function of the enclosure properties (size and materials of construction) and the chemical properties of the VOCs to be controlled (i.e., reactivity with enclosure materials). In general, all materials handling processes (e.g., excavation, loading, storage piles, stabilization processes) emitting PM/VOC can be controlled using enclosures. The key consideration as to whether or not enclosures are appropriate for a given site is how expensive will it be to maintain the temperature and air quality within the dome at acceptable levels for workers.

7.7.3 Range of Effectiveness

The effectiveness of enclosures to limit PM/VOC emissions is a function of the enclosure "capture" efficiency and the point source control system efficiency. Capture efficiency is a measure of the ability of the enclosure to capture the emitting PM/VOC. For example, if an air supported structure has a leak due to an incomplete seal between the structure and the surface or if the skin is torn, then PM/VOC will be emitted to the atmosphere, thus lowering the capture efficiency. Point source control system efficiency is dependent on the particular control system but generally is in the range of 95-100%. Reported enclosure control efficiencies are presented in Table 7-37.

7.7.4 Sizing Criteria/Application Rates

Enclosures range in size from 30 feet in diameter to 130 feet wide x 62 feet tall x unlimited length. For self-supported structures wider than 60 feet, footings may be required. Prior to erecting an enclosure, the site may require grading so that the slope is less than three percent (Sprung Instant Structures, Inc., 1992).

7.7.5 Cost Estimating Procedure

The costs of air supported and self-supported enclosures are given in Table 7-38. **Note**: The costs presented in Table 7-38 do not include the costs of gas collection/treatment systems.

7.8 Collection Hoods

7.8.1 Process Description

Hoods are commonly used to capture PM/VOC emitted from small area sources (e.g., waste stabilization/solidification mixing silos, bioremediation reactors) and route those emissions to appropriate air pollution control devices. In practice, hoods are

designed using the capture velocity principle which involves the creation of an air flow after the emitting source that is sufficient to remove the contaminated air.

Three hood designs that are commonly used are depicted in Figure 7-5. The selection of hood type will be dependent on the emitting source characteristics (e.g., source area and accessibility, emitting air velocity, surrounding air currents) and the required capture efficiency. Major components of a hood exhaust system are depicted in Figure 7-6.

7.8.2 *Applicability to Remediation Technology*

Hoods can be used to capture PM/VOC emissions from ex-situ waste stabilization/solidification mixing silos and bioremediation reactors. The use of a hood will be contingent upon access to the emitting source and upon the area of the emitting source. As the distance between a source and hood increases, so does the required total volumetric flow rate of air into the hood to maintain a given capture efficiency. Since the cost of most air pollution control equipment is proportional to the volumetric flow rate, a point is reached where it is not economically feasible to use a hood. The emitting source area will impact the hood size required and for canopy and capturing hoods will impact the air flow rate required to maintain a given capture efficiency. The advantages/disadvantages of using a hood to capture PM/VOC emissions are outlined in Table 7-39.

7.8.3 *Range of Effectiveness*

Parameters which influence the capture efficiency of hood exhaust systems are given in Table 7-40.

Hood PM/VOC capturing efficiencies can be as high as 90 to 100%. However, PM/VOC control efficiencies will be a function of both the hood capture efficiency and the air pollution control equipment removal efficiency.

7.8.4 *Application Rates*

Hood exhaust systems designs are based on the hood aspect ratio (width/length of hood), the required capture velocity (v), and the distance of the furthest point of the emitting source from the hood centerline (x). Ranges of capture velocities required as a function of surrounding air turbulence and the emitting source are listed in Table 7-41. The velocities obtained from Table 7-41 can then be used in the design equations presented in Table 7-42. For a more thorough presentation on hood designs, see "Industrial Ventilation" (ACGIH, 1980).

7.8.5 *Cost Estimating Procedure*

The costs of hood exhaust systems are highly dependent on the volumetric flow rate, the length of ducting required, the hood/ducting materials of construction required (e.g., carbon steel, stainless steel), hood size, and fan size required to move the air. An example of a hood exhaust system cost breakdown is presented in Table 7-43.

Table 7-34. Advantages/Disadvantages of Operational Practices/Procedures

Operational practices/procedures	Advantage	Disadvantage
Road cleaning practices	Equipment readily available Easy to operate	Requires additional equipment. Broom sweeping may increase particulate matter emissions.
Seasonal scheduling	No equipment required Potentially high control of PM/VOC emissions Inexpensive	Stagnant wind conditions may lead to unacceptable ambient air concentrations at the work site. Rigorous timing constraints.
Vehicle speed control	Easy to implement Reduces road maintenance required Decreases incidence of accidents Inexpensive	Increases haul time. May require more vehicles.
Storage pile geometry/orientation	Easy to implement Inexpensive	Difficult to maintain optimum pile geometry. Optimum pile geometry may not be possible due to space limitations.
Excavation practices	Easy to implement Decreases time to excavate a given volume	Requires larger equipment which may increase excavation cost. Increased equipment size may not be practical due to site size constraints. Increased equipment size may damage paved roads and increase particulate matter emissions from unpaved roads.
Dumping practices	Easy to implement Inexpensive	May increase unloading time.
Soil loading practices	Easy to implement Inexpensive	May decrease volume of soil per haul.

Table 7-35. Reported PM/VOC Control Efficiencies for Operational Practices/Procedures

Operational practice/procedure	Pollutant	Reported control efficiency (%)	Comments	Source
Road cleaning practice				
• Vacuum sweeping	PM	0-58	Measured	U.S. EPA, 1989
• Water flushing	PM	0-69	Measured	
• Water flushing/broom sweeping	PM	0-96	Measured	
Vehicle speed control	PM	0-80	Estimated	U.S. EPA, 1987b
Storage pile geometry/orientation	PM [4]	0-80/60 [1]	Estimated	U.S. EPA, 1991/Vogel, 1985
Excavation practices	PM [4]	20 [2]	Theoretical	U.S. EPA, 1985a
Dumping practice	PM [4]	50 [3]	Theoretical	U.S. EPA, 1985a

[1] Pile length is perpendicular to prevailing wind direction.
[2] Calculated from AP-42 Emission Factors, assuming doubling of bucket capacity.
[3] Calculated from AP-42 Emission Factors, assuming a 50% reduction in material drop height.
[4] Some VOC control would also occur, but no control efficiency data are available.

For further guidance in obtaining cost estimates for hood exhaust systems, consult Vatavuk, 1990.

7.9 Miscellaneous Controls

A number of miscellaneous controls for area sources could theoretically be used at Superfund sites. VOC emissions from lagoons could be controlled using floating solid objects such as hollow plastic spheres or rafts, or a floating layer of immiscible oil (Springer, et al., 1986). Blankets of nitrogen or other inert gases are another option. The use of these types of controls at Superfund sites has not been documented and feasibility testing certainly would be advisable prior to any full-scale use.

Table 7-36. Advantages/Disadvantages of Enclosures to Control PM/VOC Emissions

Advantages	Disadvantages
Near 100% control of PM/VOC emissions	Expensive.
Conversion of area source into point source for easier control of PM/VOC emissions.	Increased temperatures and PM/VOC concentrations limit the ability to work inside enclosure to short-time periods and may require workers to use protective apparel. Also specific VOC concentrations must not exceed OSHA prescribed IDLH values.
Limits access to working area.	Air supported structures can be damaged by wind.
Compatible with remediation of soils, sludges, and liquids.	Some VOCs may damage polymeric skin materials.
Does not create additional material to be treated.	Building permits may be required by local municipalities.
Reduces groundwater and surface water contamination due to precipitation.	Limits to structure size may require structure relocation as excavation site moves.
Assist thermal treatment of solids by excluding moisture loading rate onto soil.	Requires point source PM/VOC controls.
	Enclosure may require decontamination following its use.

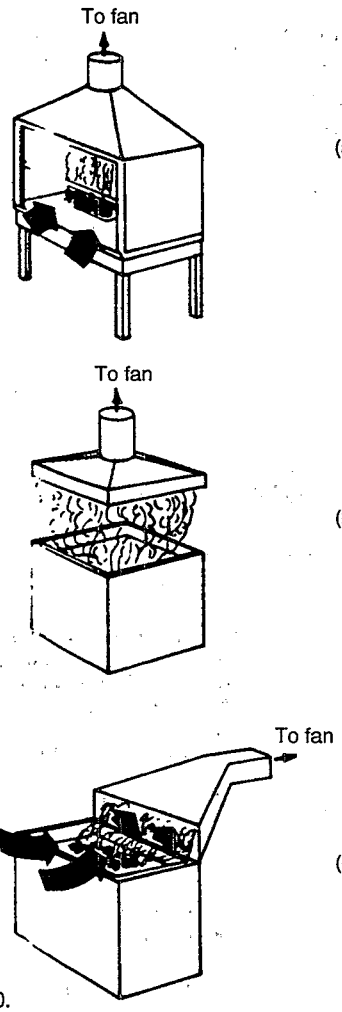
Table 7-37. Reported Enclosure PM/VOC Control Efficiencies

Contaminant	Reported control efficiency (%)	Comment	Source
PM/VOC	up to 100	Material handling operations	U.S. EPA, 1991
PM	70-99	Active storage piles	U.S. EPA, 1987b

Table 7-38. Enclosure Costs

Type of enclosure	Enclosure rental cost [a,b] ($/month-m ^{2})	O&M cost ($/m ^{2}) [c]	Source
Air-supported	5.5	NR	U.S. EPA, 1988b
Self-supported	19	48	Aul, 1992
Self-supported	4.4-8.5	1.2-6.5	Sprung Instant Structures, 1992

[a] The cost of grading and footings are not included.
[b] If the structure is needed for more than 2 years, purchase of the structure may be more economical than renting.
[c] O&M costs include the cost of erecting/dismantling the enclosure.



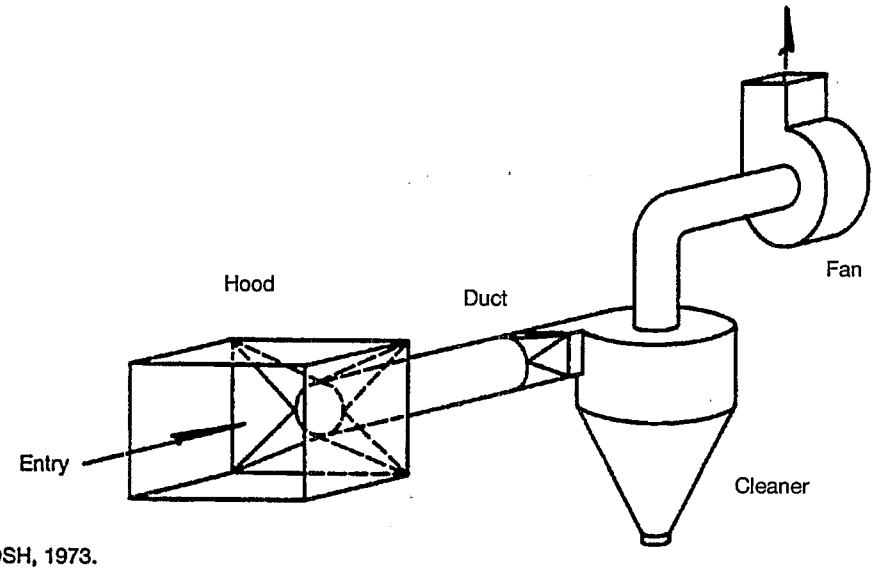
(a) Enclosures—contain contaminants released inside the hood

(b) Canopy hoods—catch contaminants that rise into them

(c) Capturing hoods—reach out to draw in contaminants

Source: Cooper and Alley, 1990.

Figure 7-5. Three commonly used hood designs.



Source: NIOSH, 1973.

Figure 7-6. Components of a hood exhaust system.

Table 7-39. Advantages/Disadvantages of Hoods to Capture PM/VOC Emissions

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

Table 7-40. Parameters That Affect Hood Capture Efficiencies

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

Table 7-41. Range of Capture Velocities

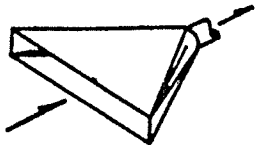
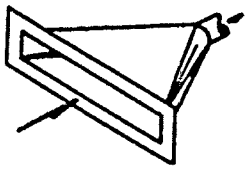
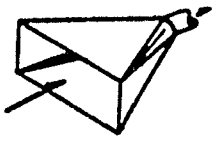
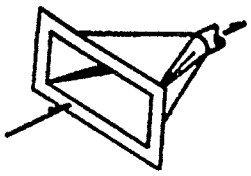
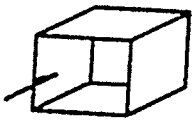
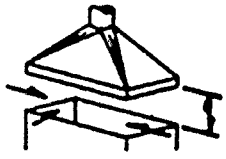
Condition of dispersion of contaminant	Examples	Capture velocity (fpm)
Released with practically no velocity into quiet air	Evaporation from tanks; degreasing, etc.	50-100
Released at low velocity into moderately still air	Spray booths; intermittent container filling; low speed conveyor transfers; welding;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

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

Lower end of range
1. Room air currents minimal or favorable to capture
2. Contaminants of low toxicity or of nuisance value only.
3. Intermittent, low production.
4. Large hood, large air mass in motion.

Upper end of range
1. Disturbing room air current.
2. Contaminants of high toxicity.
3. High production, heavy use.
4. Small hood—local control only.

Table 7-42. Hood Design Equations

	Description	Aspect ratio (W/L)	Air volume
	Slot	0.2 or less	$Q = 3.7\ LVX$
	Flanged slot	0.2 or less	$Q = 2.8\ LVX$
	Plain opening	0.2 or greater and round	$Q = V(10X^2 + A)$
	Flanged opening	0.2 or greater and round	$Q = 0.75V\ (10X^2 + A)$
	Booth	To suit work	$Q = VA = VWH$
	Canopy	To suit work	$Q = 1.4\ PVD$

Key:
X = Centerline distance to point x in emissions plume (ft)
L = Length (ft)
W = Width (ft)
H = Height (ft)
D = Distance between hood and source (ft)
A = Area (sq. ft.)
Q = Flowrate (ft^3/min)
P = Perimeter of hood (ft)
V = Velocity at point x (ft/min)

Source: NIOSH, 1973.

Table 7-43. Hood Exhaust System Cost Estimate

Equipment item	Applicable dimensions	Cost ($)
Canopy hood	3/16 in. thick carbon steel 10 ft. diameter.	$2,400
Ductwork	100 ft. of 1-foot diameter, 16-gauge carbon steel straight duct.	1,300
	Four 1-foot diameter 16 gauge carbon steel 90° elbows.	1,750
Radial tip fan	Moves 11,000 acfm at 10 in. H_2O with a 45 1/2 in. wheel diameter.	7,700
	Total cost:	$13,150

7.10 References

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Appendix A
Remediation Control Vendors

The names of remediation control vendors that appear in this appendix were obtained from the March 1991 Journal of Air and Waste Management Association Buyer's Guide, the Thomas Register, the Pollution Engineering Yellow Pages, and various references in the literature. Many of these vendors assisted in the preparation of this document by providing technical and costing information. These vendors are identified by an "*."

This list does not represent endorsement of any of the following companies by the U.S. EPA. Furthermore, while the list is as complete as possible, it does not necessarily include all vendors of all control devices that could be used at Superfund sites.

Carbon Adsorption

Amcec Corp., Solvent Recovery Div.*
Oakbrook, IL
(708)954-1515

American Environmental Int'l Inc.*
Northbrook, IL
(708)272-8635

Barnebey & Sutcliff Corp.*
Columbia, MD
(301)381-5870

Calgon Carbon Corp.*
Pittsburgh, PA
(412)787-6700

Cameron-Yakima*
Yakima, WA
(509)452-6609

DCI Corp.*
Indianapolis, IN
(317)872-6743

Dedert Corporation
Olympia Fields, IL
(708) 747-7000

Environmental Instruments, Inc.
Concord, CA
(800) 648-9355

Envirotrol, Inc.*
Sewickley, PA
(412)741-2030

Extraction Systems, Inc.
Woonsocket, RI
(401) 769-1113

RaySolv, Inc.
Piscataway, NJ
(908)981-0500

Vic Manufacturing Co.*
Minneapolis, MN
(612)781-6601

Zink Co., John*
Tulsa, OK
(918)747-1371

Catalytic Oxidation

Advanced Catalyst Systems Inc.*
South Plainfield, NJ
(908)753-9670

The Air Preheater Co. Inc.*
Wellsville, NY
(800)828-0444

Allied Signal*
Tulsa, OK
(708)450-3900

American Environmental International, Inc.
Northbrook, IL
(708) 272-8635

Anguil Environmental Systems*
Milwaukee, WI
(414)332-0230

Branch Environmental Corp.*
Somerville, NJ
(908)526-1114

Camet Co.
Hiram, OH
(216)569-3245

Dedert Corporation
Olympia Fields, IL
(708) 747-7000

EPCON Industrial Systems Inc.*
The Woodlands, TX
(409)273-1774

Johnson Matthey*
Wayne, PA
(215)971-3000

ORS Environmental Equipment*
Chadds Ford, PA
(215)558-1750

Saxton Air Systems Inc.
Harrisburg, PA
(717)545-3784

Condensers
Airco Industrial Gases
Murray Hill, NJ
(908) 464-8100

Amcec Corp.*
Oak Brook, IL
(708)954-1515

American Environmental Int'l, Inc.*
Northbrook, IL
(708)272-8635

Internal Combustion Engines
Remediation Services Int'l
Oxnard, CA
(805)644-5892

VR Systems Inc.
Anaheim, CA
(714)826-0483

Environmental Techniques Inc.
Huntington Beach, CA
(714)962-5025

Soil Beds/Biofilters
Ambient Engineering Inc.
Matawan, NJ
(908) 566-7722

Fabric Filters
AirPol, Inc.
Teterboro, NJ
(201)288-7070

American Air Filter
Louisville, KY
(502)637-0011

Ducon Environmental Technology, Inc.
Mineola, NY
(516)420-4900

Dustex Corp.
Charlotte, NC
(704)588-2030

Farr Co.
Los Angeles, CA
(800)333-7320

George A. Rolfes Co.*
Boone, IA
(515)432-3300

Lodge-Cottrell Systems*
Houston, TX
(713)297-2092

MIDWESCO Inc.*
Winchester, VA
(800)336-7300

MiKroPul Environmental Systems*
Morris Plains, NJ
(201)606-5900

Ogden Environmental Services, Inc*
San Diego, CA
(619)455-3045

P & S Filtration*
Skaneateles Falls, NY
(315)685-3466

Sealed Air Technologies*
Fort Thomas, KY
(606)7881-4330

Steelcraft Corp.*
Memphis, TN
(901)452-5200

Wheelabrator Air Pollution Control
Pittsburgh, PA
(412)562-7300

Electrostatic Precipitators
American Air Filter
Louisville, KY
(502)637-0011

Beltran Associates Inc.
Brooklyn, NY
(718)338-3311

CE Environmental Systems Div.*
Birmingham, AL
(205)991-2832

Ducon Environmental Technology, Inc.
Mineola, NY
(516)420-4900

Flakt Inc. Environmental Systems Div.
Vancouver, BC
(615)693-7550

Fuller Co.
Bethlehem, PA
(215)264-6011

Lodge-Cottrell Systems*
Houston, TX
(713)297-2092

MiKroPul Environmental Systems*
Morris Plains, NJ
(201)606-5900

Niro Atomizer Inc.
Columbia, MD
(301)997-8700

Sealed Air Technologies*
Fort Thomas, KY
(606)7881-4330

Smidth, F.L. & Co.
Cresskill, NJ
(201)871-3300

United McGill
Columbus, OH
(614)443-0192

Wheelabrator Air Pollution Control
Pittsburgh, PA
(412)562-7300

Scrubbers
Advanced Air Technology*
Arlington Heights, IL
(703) 394-9553

AirPol Inc.*
Teterboro, NJ
(201)288-7070

American Air Filter
Louisville, KY
(502)637-0011

Anderson 2000
Peachtree City, GA
(414)332-0230

Astec Industries*
Chattanooga, TN
(615)867-4210

BACT Engineering, Inc.
Arlington Heights, IL
(708)577-0950

Bayco Industries of California*
San Leandro, CA
(415)562-6700

Branch Environmental Corp.*
Somerville, NJ
(908)526-1114

The Ceilicote Co.
Berea, OH
(216)243-0700

Croll-Reynolds Co., Inc.
Westfield, NJ
(908)232-4200

Dow Chemical Gas Spec Div.*
Houston, TX
(713)978-3894

Ducon Environmental Technology, Inc.
Mineola, NY
(516)420-4900

Environmental Elements Corp.*
Baltimore, MD
(301)368-7000

Fisher-Klosterman*
Louisville, KY
(502)776-1505

Lodge-Cottrell Systems*
Houston, TX
(713)297-2092

MetPro Corp. Duall Div.*
Owosso, MI
(517)725-8184

NaTec Environmental Systems Div.*
Houston, TX
(214)824-2910

Niro Atomizer Inc.
Columbia, MD
(301)997-8700

Ogden Environmental Services, Inc*
San Diego, CA
(619)455-3045

Quad Environmental Technologies Corp.*
Northbrook, IL
(708)564-5070

Wheelabrator Air Pollution Control
Pittsburgh, PA
(412)562-7300

Zink Co., John*
Tulsa, OK
(918)747-1371

Thermal Oxidation
The Air Preheater Co. Inc.*
Wellsville, NY
(800)828-0444

Amcec Corp.*
Oakbrook, IL
(708)954-1515

American Environmental Int'l Inc.*
Northbrook, IL
(708)272-8635

Astec Industries*
Chattanooga, TN
(615)867-4210

Bayco Industries of California*
San Leandro, CA
(415)562-6700

Branch Environmental Corp. PCT Div.*
Somerville, NJ
(908)526-1114

Brule Incinerators*
Blue Island, IL
(708)388-7900

CIL Incinerator System Inc.*
Collegeville, PA
(215)287-8037

Conversion Technology, Inc.*
Norcross, GA
(404)263-6330

Dedert Corp.*
Olympia Fields, IL
(708)747-7000

EPCON Industrial Systems Inc.*
The Woodlands, TX
(409)273-1774

Eutherengy Systems, Inc.
Sanford, MI
(512) 687-2899

FECO Engineered Systems Inc., Environmental Div.*
Cleveland, OH
(216)441-2400

In-Process Technology*
Sunnyvale, CA
(408)745-1066

Johnson Matthey*
Wayne, PA
(215)971-3000

M & S Engineering and Manufacturing Co. Inc.*
Broad Brook, CT
(203)627-9396

MetPro Corp. Duall Div.*
Owassa, MI
(517)725-8184

NAO Inc.*
Philadelphia, PA
(215)743-5300

Precision Quincy Corp.
Woodstock, IL
(815)338-2675

REECO Inc.*
Morris Plain, NJ
(201)538-8585

Salem Industries*
South Lyon, MI
(313)437-4188

Saxton Air Systems Inc.
Harrisburg, PA
(717)545-3784

Somerset Technologies Inc. Ross-Waldron Div.
New Brunswick, NJ
(908)356-6000

Smith Engineering Co.*
Duarte, CA
(714)923-3331

Surface Combustion
Toledo, OH
(800)537-8980

Vulcan Iron Works Inc.*
Wilkes-Barre, PA
(717)822-2161

WBR Engineering Inc.
Cherry Hill, NJ
(609)354-9372

Williams Environmental*
Stone Mountain, GA
(800)247-4030

Zink Co., John*
Tulsa, OK
(918)747-1371

Venturi Scrubbers
Croll-Reynolds Co., Inc.
Westfield, NJ
(908)232-4200

Fairchild Int'l
Glen Lyn, VA
(703)726-2380

Miscellaneous (HEPA Filters)

Covers/Barriers
see local contractors

Foams
3M: Industrial Chemicals Div.: Environmental Protection Group
St. Paul, MN
(612)733-3493

Rusmar
West Chester, PA
(215)436-4314

Water Sprays
see local contractors

Enclosures
Sprung Instant Structures Inc.
Allentown, PA
(800)677-7864

Houston, TX
(713)520-6888

see also local contractors

Wind Barriers
see local contractors

Appendix B
Regional Air/Superfund Coordinators
(as of September 1992)

Region	Name	Telephone number
I	Rose Toscano	(617)565-3280
II	Alison Devine	(212)264-9893
III	Patricia Flores	(215)597-9134
IV	Lee Page	(404)347-2864
V	Charles Hall	(312)886-6043
VI	Mark Hansen	(214)655-7223
VII	Wayne Kaiser	(913)551-7603
VIII	Norm Huey	(303)293-0969
IX	Kathy Diehl	(415)744-1133
X	Chris Hall	(206)553-1949

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AS-23 Eklund, B., S. Smith, and A. Hendler. Estimation of Air Impacts For the Excavation of Contaminated Soil. EPA 450/1-92-004 (NTIS PB92-171925), March 1992.

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United States Environmental Protection Agency

Office of Air Quality Planning and Standards

September 1992

AIR/SUPERFUND COORDINATION PROGRAM

PURPOSE

The purpose of the Air/Superfund Coordination program is to assist EPA Regional Superfund offices to:

- Evaluate the impact of air emissions from Superfund sites prior to and during remediation and
- Develop and implement site cleanup measures to mitigate these impacts to ensure protection of public health and the environment.

REGIONAL ACTIVITIES

An Air/Superfund Coordinator in each Regional Air office is responsible for ensuring that air program support is provided to Superfund. Air offices provide routine site support services such as consultation and review of proposals, plans, and studies. They participate in decisions related to preremedial, remedial, and removal actions that may have significant air impacts. They help to ensure that Superfund site decisions involving air pollution issues are consistent with Federal, State, and local air regulations and policies. They also may perform special field evaluations during removal and preremedial actions and assist Superfund contractors by consulting in areas such as air modeling, monitoring, and the use and effectiveness of air pollution control devices.

PROGRAM SUPPORT ACTIVITIES

The program includes four types of activities to support the Regional Offices. They are:

- Coordination
- Technical assistance
- Training
- National Technical Guidance Studies

Coordination:

Coordination program facilities the exchange of information on Air/Superfund issues, procedures, and data among Regional Air Offices and between Regions and EPA Headquarters offices; and provides updated technical information and periodic reports to these offices on ongoing studies. Coordination

meetings are held at four month intervals to exchange information, coordinate the overall program, participate in miniworkshops, and receive briefings on pertinent technical and administrative subjects.

Training:

Training involves briefing Regional Air office staff on Superfund program issues, priorities, methods, and procedures; and briefing Regional Superfund staff and contractor personal on air issues, and guidance for analyzing and resolving them.

Technical Assistance:

Technical assistance is offered to Regional Air offices to assist them in analyzing air issues associated with specific sites, reviewing analyses prepared by Superfund contractors, and preparing recommendations on remedial actions proposed to minimize air impacts.

National Technical Guidance Studies:

National Technical Guidance Studies (NTGS) provide Regional Air and Superfund staffs and State and local agency staffs with technical support, data, and guidance to improve the quality of the data base and the analysis of air issues associates with Superfund sites.

AIR/SUPERFUND COORDINATORS

o	Region I	Abdi Mohamoud (617) 565-4044	o	Region VI	Mark Hansen (214) 655-6582
o	Region II	Alison Devine (212) 264-9868	o	Region VII	Wayne Kaiser (913) 551-7603
o	Region III	Patricia Flores (215) 597-9134	o	Region VIII	Norm Huey (303) 293-0969
o	Region IV	Lee Page (404) 347-2864	o	Region IX	Kathy Diehl (415) 744-1133
o	Region V	Dan Meyer (312) 886-9401	o	Region X	Chris Hall (206) 553-1949

WHERE CAN I OBTAIN INFORMATION ON THE AIR/SUPERFUND PROGRAM

Regional Air/Superfund Coordinators
or
Office of Air Quality Planning and Standards
Joseph Padgett
(919)541-5589

Appendix C
Bibliography

VOC and PM Emission Controls

Point Sources

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Appendix D
Categorization of Commonly Encountered Compounds

Class of Compounds	Example Compounds
Aromatic Hydrocarbons	Benzene
	Toluene
	Xylenes
	Ethylbenzene
Aliphatic Hydrocarbons	Hexane
	Heptane
Halogenated Hydrocarbons	Methylene chloride
	Chloroform
	Carbon tetrachloride
	1,1-dichloroethane
	Trichloroethylene
	1,1,1-trichloroethane
	Tetrachloroethylene
	Chlorobenzene
Ketones/Aldehydes	Acetone
	Methyl ethyl ketone
	Methyl isobutyl ketone
	Cyclohexanone
	Formaldehyde
	Acetaldehyde
Other Oxygenated Hydrocarbons	Methanol
	Ethylene glycol
	Cellulose
	Ethers
	Phenols
	Epoxides
Inorganic Gases	Hydrogen sulfide
	Hydrogen chloride
	Sulfur dioxide
	Nitrogen oxide
	Nitrogen dioxide

Class of Compounds	Example Compounds
Metals	Mercury Lead Chromium Arsenic Cadmium Zinc Beryllium Copper
Polynuclear Aromatics	Polychlorinated biphenyls (PCBs) Benzo(a)pyrene Naphthalene Anthracene Chrysene
Pesticides/Herbicides	Chlordane Lindane Parathion
Miscellaneous	Asbestos Cyanides Radionuclides

Potential Air Contaminants by Generic Type of Contaminant

Volatiles (>1 mm Mercury vapor pressure at 25°C)

- All monochlorinated solvents; also trichloroethylene, trichloroethane, tetrachloroethane.
- Most simple aromatic solvents: e.g., benzene, xylene, toluene, and ethylbenzene.
- Most alkanes up to decane (C_{10}).
- Inorganic gases: e.g., hydrogen sulfide, chlorine, and sulfur dioxide.

Semi-Volatiles (1-10^{-7} mm Mercury vapor pressure at 25°C)

- Most polychlorinated biphenyls, dichlorobenzenes, aniline, nitroaniline, and phthalates.
- Most pesticides: e.g., dieldrin, toxaphene, and parathion.
- Most complex alkanes: dodecane and octadecane.
- Most polynuclear aromatic's: e.g., naphthalene, phenanthrene, and benz(a)anthracene.
- Mercury

Non-Volatiles or Particulate Matter (<10^{-7} mm Mercury vapor pressure at 25°C)

- Larger polynuclear aromatics: e.g., chrysene.
- Metals: e.g., lead and chromium.
- Other inorganics: e.g., asbestos, arsenic, and cyanides.

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