

Draft
Technical Support Document for
HWC MACT Standards

Volume I:

Description of Source Categories

U.S. Environmental Protection Agency
Office of Solid Waste and Emergency Response (5305)
401 M Street, SW
Washington, D.C. 20460

February 1996

ACKNOWLEDGMENTS

This document was prepared by the U.S. EPA's Office of Solid Waste, Waste Management Division. Energy and Environmental Research Corporation (EER) provided technical support under EPA Contract No. 68-D2-0164.

ABSTRACT

EPA is revising hazardous air pollutant (HAP) emissions regulations for hazardous waste burning combustors, specifically incinerators, cement kilns, and light weight aggregate kilns. The new emissions standards are being developed using the “maximum achievable control technology” (MACT) approach defined in Title 3 of the 1990 Clean Air Act Amendments. MACT standards are set for the hazardous air pollutants (HAP) of PCDD/PCDF, mercury, semi volatile metals (cadmium and lead), low volatile metals (antimony, arsenic, beryllium, and chromium), total chlorine (considering both HCl and Cl₂), CO and HC (not strictly HAPs, but used as surrogates for toxic organic HAPs), and particulate matter (again, not itself strictly a HAP, but used as a surrogate for both condensed metals and organics). This volume provides a description of source categories. Provided are: (1) process descriptions of major design and operating features; (2) description of air pollution control devices including design principles, performance, and operating efficiency, process monitoring, and upgrade/retrofit options; and (3) major source determination for all sources including a discussion on the methodology used to estimate annual emissions, assumptions used, and an emissions summary for each source listing total HAP emissions.

TABLE OF CONTENTS

Acknowledgements	ii
Abstract	iii
List of Figure	vi
List of Tables	viii
Acronyms	ix
1.0 Introduction	1-1
2.0 Process Descriptions	2-1
Hazardous Waste Incinerators	2-1
Rotary Kiln Incinerators	2-1
Process Description	2-2
Operating Parameters	2-4
Liquid Injection Incinerators	2-5
Fluidized Bed Incinerators	2-6
Process Description	2-6
Operating Parameters	2-7
Fixed Hearth Incinerators	2-8
Process Description	2-8
Operating Parameters	2-9
Air Pollution Control Techniques	2-9
Cement Kilns	2-10
Process Components	2-10
Wet Process Kilns	2-11
Dry Process Kilns	2-11
Semi-Dry Process Kilns	2-13
Clinker Handling	2-13
Hazardous Waste Feeding Techniques	2-14
Air Pollution Control System	2-15
Lightweight Aggregate Kilns	2-16
Process Components	2-16
Operating Parameters	2-18
3.0 Air Pollution Control Techniques	3-1
Cyclones	3-2
Fabric Filters	3-3
Electrostatic Precipitators	3-8
Wet Electrostatic Precipitators	3-15
Venturi Scrubbers	3-15
Flux Force Condensation Collision	3-16
Free Jet Scrubbers	3-17
Rotary Atomizing Scrubbers	3-17
Rotor Filter Scrubbers	3-17
Electrodynamic Venturi	3-18
Wet Scrubbers 3-20	
Spray Tower	3-21
Tray Tower	3-21
Packed Tower	3-22
Ionizing Wet Scrubber	3-22
Dry Scrubbers	3-26
Spray Dryers	3-27

	Flue Gas Cooling	3-30
	Activated Carbon Adsorption	3-23
	Other Metals Control Techniques	3-35
	Activated Carbon Injection	3-36
	Earth-based Sorbents	3-40
	Selenium Coated Filter	3-41
	Sodium Sulfide Injection	3-41
	Mercury Scrubbers	3-42
	Catalytic Oxidation	3-42
	Sulfur Based Control	3-42
	Air Pollution Control Systems	3-43
	Wet	3-43
	Dry	3-44
	Hybrid Dry/Wet	3-44
4.0	Major Source Determination	4-1
	Methodology	4-1
	Incinerator Evaluation	4-2
	Kiln Evaluation	4-3
	References	R-1

LIST OF FIGURES

2-1	Typical rotary kiln incinerator	2-19
2-2	Typical liquid injection incinerator	2-20
2-3	Typical fluidized bed incinerator	2-21
2-4	Typical fixed hearth incinerator	2-22
2-5	Wet cement kiln	2-23
2-6	Typical gas (dashed line) and solids (solid line) temperature profiles for a long wet-process cement kiln	2-24
2-7	Typical gas velocities for a long wet process cement kiln	2-25
2-8	Dry kiln process material (solid line) and gas temperatures (dashed line)	2-26
2-9	Dry preheater/precalciner cement kiln schematic	2-27
2-10	Typical gas (dashed line) and solids (solid line) temperature and gas velocities for a preheater cement kiln	2-28
2-11	Typical gas velocities through a preheater cement kiln	2-29
2-12	Typical gas (dashed line) and solids (solid line) temperature for a preheater/precalciner cement kiln	2-30
2-13	Semi-dry cement kiln schematic	2-31
2-14	Semi-dry kiln material (solid line) and gas (dashed line) temperatures	2-32
2-15	Light weight aggregate kiln	2-33
3-1	Cyclone particle collector	3-45
3-2	Pulse jet cleaning baghouse	3-46
3-3	Reverse air cleaning baghouse	3-47
3-4	Shaker cleaning baghouse	3-48
3-5	Electrostatic precipitator particle collection procedure	3-49
3-6	One and two-stage electrostatic precipitator operation	3-50
3-7	Plate type ESP	3-51
3-8	Tubular type ESP	3-52
3-9	Wet ESP	3-53
3-10	Variable throat venturi scrubber with wetted elbow	3-54
3-11	Performance principles of a venturi scrubber	3-55
3-12	Non-wetted, fixed throat venturi scrubber	3-56
3-13	Force flux/condensation/collision scrubber	3-57
3-14	Free jet scrubber	3-58
3-15	Venturi scrubber with different flow control throat mechanisms	3-59
3-16a	Two-stage wet scrubbing process schematic	3-60
3-16b	Venturi and tray tower wet scrubbing system arrangement	3-61
3-18	Tray tower wet scrubber	3-62
3-19	Packed bed wet scrubber	3-63
3-20	Ionizing wet scrubber schematic	3-64
3-21	Limestone reagent preparation system	3-65
3-22	Impact of slurry pH (acidity) on SO ₂ removal efficiency	3-66
3-23	Impact of liquid to gas ratio on SO ₂ removal efficiency	3-66
3-24	Dry scrubbing sorbent injection process schematic	3-67
3-25	Semi-dry spary drier absorption process schematic	3-68
3-26	Spray dryer designs	3-69
3-27	Air dilution cooling procedure	3-70
3-28	Example of the amount of dilution air required for dilution cooling	3-71
3-29	Heat exchanger schematics (a) Gas-gas recuperator (b) Shell and tube type	3-72
3-30	Water quench cooling procedure	3-73
3-31	Example of amount of water required to cool flue gas	3-74
3-32	Hybrid wet/dry system schematic	3-75

4-1	Estimated annual HAP emissions for incinerators including HCl and Cl ₂	4-5
4-2	Estimated annual HAP emissions for incinerators excluding HCl and Cl ₂	4-6
4-3	Estimated annual HAP emissions for kilns including HCl and Cl ₂	4-7
4-4	Estimated annual HAP emissions for kilns excluding HCl and Cl ₂	4-8

LIST OF TABLES

3-1	Sorbents Used for Removal of Metals from Combustion Source Flue Gases	3-76
4-1	Major Source Determination Summary for Commercial and On-Site Incinerators .	4-9
4-2	Major Source Determination Summary for Cement and LWA Kilns	4-10

ACRONYMS

AB	Afterburner
ACS	Acid scrubber
APCD	Air pollution control device
BIF	Boiler and Industrial Furnace
C	Cyclone
CAAA	Clean Air Act Amendment
CCS	Calvert collision scrubber
CKD	Cement kiln dust
CO	Carbon monoxide
DA	Dilution air
DI	Dry injection
DM	Demister
EDV	Electrodynamic venturi
EPA	U.S. Environmental Protection Agency
ESP	Electrostatic precipitator
FF	Fabric filter
FSI	Furnace sorbent injection
GC	Gas cooler
HAP	Hazardous air pollutant
HC	Hydrocarbons
HE	Heat exchanger
HES	High energy scrubber
HF	HEPA filter
HS	Hydrogen chloride scrubber
HTHE	High temperature heat exchanger
IWS	Ionizing wet scrubber
KOV	Knock out vessel
LTHE	Low temperature heat exchanger
LWA	Light weight aggregate
LWAK	Light weight aggregate kiln
MACT	Maximum achievable control technology
PBC	Packed bed condenser
PCDD/PCDF	Polychlorinated dibenzofurans and dibenzo-p-dioxins
PIC	Product of incomplete combustion
PM	Particulate matter
Q	Quench
QC	Quench column
RCRA	Resource Conservation and Recovery Act
S	Scrubber
SCA	Specific collection area
SDA	Spray dryer absorber
VQ	Venturi quench
VS	Venturi scrubber
WHB	Waste heat boiler
WS	Wet scrubber

SECTION 1

INTRODUCTION

The U.S. Environmental Protection Agency (EPA) regulates the burning of hazardous waste in incinerators under 40 CFR Part 264/265, Subpart O and in industrial furnaces under 40 CFR Part 266, Subpart H. The Agency is proposing revised regulations applicable to these hazardous waste combustion (HWC) devices. This document provides the description of the source categories and the associated pollution control devices currently in use or applicable to the process. It is the first in a series of seven volumes of technical background documents for the rule. These include:

Technical Support Document for HWC MACT Standards, Volume I: Description of Source Categories, which provides process descriptions of major design and operating features including different process types and air pollution control devices currently in use and potentially applicable to various combustion source categories; description of air pollution control devices including design principles, performance and operating efficiency, process monitoring options, and upgrade/retrofit options; and major source determination for all sources including a discussion on the methodology used to estimate annual emissions, assumptions used, and an emissions summary for each source listing total HAP emissions.

Technical Support Document for HWC MACT Standards, Volume II: HWC Emissions Data Base, which contains a summary of the emissions information on toxic metals, particulate matter (PM), HCl and Cl₂, hydrocarbons, carbon monoxide, semi-volatile and volatile organic compounds, and dioxins/furans from HWCs. Other detailed information encompassed in the data summary include company name and location, emitting process information, combustor design and operation information, APCD design and operation information, stack conditions during testing, feed stream feed rates, and emissions rates of HAPs by test condition.

Technical Support Document for HWC MACT Standards, Volume III: Selection of Proposed MACT Standards and Technologies, which identifies the MACT floor for each HAP and source category for existing sources and new sources and discusses the approach used to define the floor and beyond-the-floor alternatives considered for the proposed rule.

Technical Support Document for HWC MACT Standards, Volume IV: Compliance with the Proposed HWC Standards, which contains detailed discussions of continuous emissions monitors and operating limits for the proposed rule.

Technical Support Document for HWC MACT Standards, Volume V: Engineering Costs,

which contains the cost estimates for APCD requirements for existing and new facilities to meet the proposed emissions standards.

Technical Support Document for HWC MACT Standards, Volume VI: Development of Comparable Fuels Specifications, which summarizes the composition including hazardous species in benchmark fossil fuels such as gasoline, #2 fuel oil, #4 fuel oil, and #6 fuel oil. This information is being used to develop specifications which EPA is considering to allow comparable fuels to be excluded from the definition of hazardous waste.

Technical Support Document for HWC MACT Standards, Volume VII: Miscellaneous Technical Issues, which provides additional information on several topics such as the treatment of measurements below analytical detection limits, the procedures for handling missing data, and the rationale for grouping metals of similar volatility. The impact of these methodologies on the proposed MACT limits, the cost estimates, and the national emissions estimates are also discussed.

Emission standards are being proposed for three types of hazardous waste incineration facilities:

- Cement Kilns
- Lightweight Aggregate Kilns
- Incinerators (On-site and Commercial)

The hazardous air pollutants for which emission standards are proposed are:

- Mercury (Hg)
- Low Volatility Metals (LVM)
- Semi-Volatile Metals (SVM)
- Particulate Matter (PM)
- Hydrogen Chloride and Chlorine as Total Chlorine (HCl/Cl₂)
- Carbon Monoxide (CO)
- Hydrocarbons (HC)
- Dioxins/Furans (PCDD/PCDF)

These emission standards are being developed through the “maximum achievable control technology” (MACT) approach defined in Title 3 of the 1990 Clean Air Act Amendments (CAAA). In this approach the MACT floor standard for existing facilities is established at the level of the average performance of the best 12% of existing sources. Depending on the additional benefits and costs, EPA may elect to set more stringent, but technically achievable, beyond-the-floor (BTF) standards for specific HAPs. In the proposed rule, BTF standards have been set for PCDD/PCDF and for Hg for all HWC source categories, and BTF standards have been proposed for HCl/Cl₂ for LWAKs only.

The proposed floor and BTF standards have been selected based on a database (described in Volume II) of trial burn and compliance test emissions measurements from 77 incinerators, 35 cement kilns, and 12 lightweight aggregate kilns using a process described in detail in Volume III.

In this volume, the three different source categories (hazardous waste incinerators, cement kilns, and light weight aggregate kilns) are described. This description includes process operating characteristics. Additionally, the air pollution control systems that are used to control the hazardous air pollutants (HAPs) are discussed. The report also describes the methodology used to determine major sources within the hazardous waste combustor community.

SECTION 2

PROCESS DESCRIPTIONS

Incineration has developed as a means of treating various types of waste materials, including hazardous wastes, municipal wastes, medical wastes, and sewage sludges. Incineration may be effective for destroying hazardous organic wastes and reducing waste volume and mass, thus aiding in safe ultimate disposal. Additionally, the heat generated from waste combustion may be used to produce electricity or process heat, or may be used to fuel industrial processes such as cement or light weight aggregate production or industrial boilers. Three important operating conditions for proper incineration are incineration temperature, gas residence time at temperature, and waste, supplemental fuel, and combustion air mixing and turbulence rates. These conditions vary with the chemical structure and physical form of the waste as well as the incinerator design. Process descriptions for equipment which burns hazardous waste are included in this section. These include hazardous waste incinerators, cement kilns, and lightweight aggregate kilns. Process components, characteristics, and operating parameters are discussed for each of the different types of units.

2.1 HAZARDOUS WASTE INCINERATORS

Hazardous waste incinerators are used at both “commercial” and “on-site” hazardous waste treatment facilities. Commercial facilities accept and treat wastes, for a tipping fee, which have been generated off-site. The sole purpose of commercial incinerators is to generate a profit from treating hazardous wastes. There are approximately 22 commercial hazardous waste incineration facility sites run by 17 companies in the United States. On-site facilities treat only wastes which have been generated at the facility to avoid the costs of off-site treatment. There are approximately 168 on-site hazardous waste incineration facilities in the United States.

Different types of technologies are used for hazardous waste incineration; the majority of which include rotary kilns, liquid injection incinerators, fluidized bed incinerators, and fixed hearth incinerators. The majority of the commercial incinerators are rotary kilns. Additionally, there are three liquid injection, one fluidized bed, and four fixed hearth facilities. The on-site facilities consist of approximately equal numbers of rotary kilns and liquid injection facilities, with a few additional fixed hearths and fluidized beds. The following incinerator designs are discussed in this section: rotary kiln, fluidized bed, liquid injection, and fixed hearth. In general, each of the systems have common exhaust gas air pollution control requirements. Air pollution control devices and systems used on hazardous waste incinerators are discussed in the Section 2.1.5. Specific design, operating, and performance characteristics of the individual air pollution control devices is discussed in detail in Section 3.

2.1.1 Rotary Kiln Incinerators

Rotary kilns are the commonly used technology for hazardous waste incineration. This is due to their ability to handle almost any conceivable waste form (e.g., bulk and containerized solids, sludges, slurries, bulk and containerized liquids, and less common wastes such as Department of Defense propellants, ammunitions, and nerve agents) as well as a variety of waste compositions (e.g., wide ranges of waste organics, halogens, heating value, and principal organic hazardous constituents).

2.1.1.1 Process Description

Rotary kiln systems used for hazardous waste incineration typically consist of two incineration chambers: the rotary kiln and an afterburner. A typical rotary kiln system is shown in Figure 2-1. The rotary kiln itself is a cylindrical refractory-lined steel shell typically with a diameter which is typically less than 15 to 20 feet (to allow for truck or rail shipment) and a length-to-diameter ratio of 2:1 to 10:1. The shell is supported by two or more steel “trundles” that ride on rollers, allowing the kiln to rotate around its horizontal axis. The refractory is typically made of an acid resistance brick. Rotary kiln incinerators are typically sized around 60 million Btu/hr, but may be as large as 150 million Btu/hr.

Usually, the inside of the kiln is lined with a smooth refractory, although recent designs have included internal vanes or paddles to encourage solids mixing along the kiln length. The kiln is oriented on a slight incline from the horizontal, known as the “rake”. The rake is less than 5° and typically ranges from 2 to 4°. The kiln rotation rate typically ranges from 0.5 to 2 rotations per minute. Mixing may be improved by increased rotation rate; however, this also acts to reduce solids residence time. Kiln rotation and incline serve to promote the mixing of wastes with combustion air, as well as to facilitate the heat transfer between the waste and hot flames and refractory, and to move the wastes through the rotary section.

Almost all hazardous waste rotary kiln incinerators are of the “co-current” design because they are better suited toward treating combustible solid wastes. In the co-current design, as shown in Figure 2-1, wastes and auxiliary fuels are fed at the same upper kiln end (i.e., the waste and flue gas travel in the same direction). Co-current designs provide for rapid ignition of the cold wastes and maximum gas residence time for the products of combustion and thus achieve the largest amount of volatile organic destruction in the rotary section.

Solid and liquid wastes are fed directly into the rotary kiln. Solids can be fed, on a continuous or semi-continuous basis, through a variety of waste feed mechanisms such as a ram feeder, auger screw feeder, or belt feeder for waste contained in drums. For batch feeding, an air lock is usually used to reduce the amount of air infiltration through the feeding chute. Liquid wastes may also be injected, with steam or air assisted atomizing nozzles, directly into the kiln through the main burner. These liquid wastes may also be injected through a waste lance, and/or mixed with the solid wastes. In most cases, rotary kilns can handle unprocessed wastes. However, waste pretreatment may include mixing of liquid and solid wastes, as well as neutralizing corrosive wastes prior to being fed to the kiln. Waste grinding and sizing may aid in smooth kiln operation.

Wastes are heated by the primary flame, bulk gases, and refractory walls. Through a series of volatilization and partial combustion reactions, combustible fractions of the wastes are gasified. The solids continue to heat and burn as they travel down the kiln. Typically, solids retention time in the kiln is 0.5 to 1.5 hours, while gas residence time through the kiln is usually around 2 seconds. Waste feed to the kiln is controlled so that the waste contributes no more than 20% of the kiln volume. Typical flame/solids temperatures in the rotary kiln range from 1200 to 3000°F.

An auxiliary gas or oil burner, located at the feeding end of the kiln, is used for start-up (bring unit up to temperature) and to maintain desired kiln temperature when sufficient heat input is not available from the waste. Wastes with an average heating value of 4500 Btu/lb are typically adequate to sustain combustion at kiln temperatures between 1600 to 1800°F. Combustion air is provided through ports on the face of the kiln, as well as through rotary seal leakage. The kiln typically operates at 50 to 200% excess air levels.

Kiln operating pressure is maintained at negative to the atmosphere, typically -0.5 to 2.0 in. H₂O gauge, through the use of an induced draft fan which is located downstream of the air pollution control system. Operation at negative pressure assures that fugitive emissions of combustion gases to the atmosphere through rotary seal leaks are avoided. Seals on ends of the rotary section provide possible kiln gas leakage points. There is potential for kiln gas fugitives to escape through leaks in rotary seals when excessive kiln pressure develops. This “over-pressure” can occur when highly combustible or explosive wastes are fed into the kiln. The resulting increase in combustion gas volume can not be handled by the downstream exhaust system, creating an over-pressure of the kiln. Also, if seals become worn or damaged, ambient air infiltration through them may make it difficult to maintain temperature at an acceptable kiln gas flow rate.

Overcharging of highly combustible or explosive wastes may also lead to kiln “puffing”. Volatiles are released quickly at high temperature thus depleting local oxygen, creating pyrolysis conditions and the formation of products of incomplete combustion. Higher rotations rates also increase the puff magnitude because devolatilization rates are enhanced by bed mixing. Puffing can be avoided by operating at a charging rate which will reduce the hydrocarbon release rate to avoid consuming available oxygen. Also, transient puffs can be minimized by operating at lower rotational speeds and lower kiln temperatures.

To avoid over-pressurization caused by feeding highly combustible wastes, a thermal emergency relief vent, typically located between the afterburner and the air pollution control system, is used to protect the equipment. Flue gases are released through this vent when overpressurizations occur. The use of the emergency relief vent is minimized to avoid the direct release of untreated flue gases to the atmosphere (i.e., flue gases which have not passed through the air pollution control system).

Inorganics, ash, slag, and other incombustible items that remain when the waste reaches the end of the kiln are removed by gravity into an ash pit. Typically, the ash is water quenched with the ash removal system normally provided with a water seal trough. Dry collection systems allow for undesirable air leakage into the kiln. Dropping of solids into the water seal trough can result in steam explosions, often resulting in positive pressure excursions.

Exhaust gas from the kiln is usually routed to a secondary refractory lined combustion chamber, referred to as an “afterburner”. The afterburner is typically operated at 2000 to 2500°F, with 100 to 200% excess air, turbulent mixing flow, and a gas residence time from 1 to 3 seconds to ensure complete combustion of the remaining volatile gas phase unburned components in the kiln flue gas. An auxiliary fuel, and sometimes pumpable liquid hazardous wastes, are used to maintain the afterburner temperature. A hot cyclone may be positioned between the kiln and afterburner for removal of entrained solid particles that may cause slagging problems in the afterburner.

Design modifications to the rotary kiln have included: 1) a “fast” rotary kiln which rotates at a rate greater than 20 rotations per minute to provide efficient mixing, 2) starved air and oxygen assisted kilns to reduce flue gas volume and auxiliary fuel requirements, and 3) “slagging” kilns. The slagging kiln operates above the ash melting point (2600 to 2800°F) to generate a molten ash. Eutectic properties of slag are controlled using additives to the feed. Slagging kilns typically have a negative rake, permitting for the accumulation of slag in the kiln. In addition, these kilns have the ability to accept metal drums and salt laden wastes, provide better destruction efficiency and generate lower particulate emissions compared with normal rotary kilns, and produce of a slag product known as “frit” which is less leachable than non-slagging kiln ash. However, slagging kilns have increased NO_x emissions, shorter refractory lifetime, and potential for the slag to solidify in the kiln, creating operational difficulties.

2.1.1.2 Operating Parameters

Rotary kiln incinerator operating parameters include:

- Kiln and afterburner exit temperature — This is typically maintained above 1500°F. Temperature must be maintained above the minimum demonstrated for adequate destruction of POHCs and avoidance of product of incomplete combustion (PIC) formation. Monitoring limitations include errors in measurement from furnace and flame radiation. The temperature may be controlled through adjustment of waste, auxiliary fuel, and combustion air feed rates.
- Kiln pressure — Kiln pressure must be maintained at negative to atmosphere and the afterburner pressure must be below that of kiln to prevent kiln fugitive emissions through kiln rotary seals. Pressure is controlled by use of an induced draft fan and damper system downstream of the combustion chambers.
- Combustion gas velocity (flowrate) — This is controlled to ensure proper combustion gas residence time at operating temperature for complete destruction of volatile PICs. Gas flowrate is dependent on waste feed composition and feed rate, as well as auxiliary fuel and combustion air rates.
- Waste feed rate — This is adjusted to avoid over-loading, over-pressuring, and depleting kiln oxygen, which may result in kiln fugitives and excessive kiln flue gas volatiles. If kiln is fed semi-continuously, the maximum size of each batch must be controlled.

- Oxygen level at kiln and afterburner exit — Controlled to assure availability of oxygen, and thus the potential for complete combustion (i.e., lower CO, HC, and possibly PIC levels). The kiln is typically operated at 50 to 100% excess air, while the afterburner is typically operated at 100 to 200% excess air.
- CO and HC combustion gas levels — CO and HC levels are monitored to ensure satisfactory operation of kiln and afterburner and possible avoidance of PIC formation.
- Kiln solids residence time — This is typically maintained at 0.5 and 1.5 hours and is controlled by rotation rate and kiln rake to ensure that the waste spends enough time in the kiln to be thoroughly treated. Controlling residence time is important for treatment of relatively non-combustible wastes.
- Kiln solids and combustion air mixing — Assures that volatiles are thoroughly combusted.

2.1.2 Liquid Injection Incinerators

Liquid injection combustors, like rotary kiln incinerators, are commonly used for hazardous waste incineration. Liquid injection combustors can be used to dispose of virtually any combustible liquid or liquid-like waste (e.g., liquids, slurries, and sludges).

Typical liquid injection incinerator systems, which are possibly the simplest type of combustion device, include a waste burner system, an auxiliary fuel system, an air supply system, a combustion chamber, and an air pollution control system. A typical liquid injection incinerator is shown in Figure 2-2. Liquid wastes are fed and atomized into the combustion chamber through the waste burner nozzles. These nozzles atomize the waste and mix it with combustion air. Atomization is usually achieved either by mechanical methods such as a rotary cup or pressure atomization systems, or by twin-fluid nozzles which use high-pressure air or steam. With a relatively large surface area, the atomized particles vaporize quickly, forming a highly combustible mix of waste fumes and combustion air. This mixture ignites and burns in the combustion chamber. Typical combustion chamber residence time and temperature ranges are 0.5 to 2 seconds and 1300°F to 3000°F, respectively, in order to ensure complete liquid waste combustion. Typical liquid feed rates are as high as 200 cubic feet per hour. If the energy content of the waste is not high enough to maintain adequate ignition and incineration temperatures, a supplemental fuel such as fuel oil or natural gas is provided. In some cases, wastes with high solids are filtered prior to incineration to avoid nozzle plugging.

The liquid injection incinerator may dispose of aqueous or non-aqueous waste which can be atomized through a burner nozzle (i.e., a viscosity less than 10000 SSU). The waste must be atomized to small droplets of 40 μm or less. Atomization is usually accomplished mechanically using rotary cup or pressure atomization systems. Wastes with high solids are filtered prior to entering the feed tank. The liquid waste fuel system transfers the waste from drums into a feed tank.

The combustion chamber can be as simple in design as a refractory-lined cylinder, or it can be relatively complex with combustion air preheat around the chamber and firing multiple fuel streams. The incinerator can be designed using either a horizontal or vertical orientation. In either case, flame impingement on the combustion chamber wall is undesirable because it can lead to refractory corrosion and loss of heat. Thus, the burner(s) are located to prevent flame impingement on the walls.

2.1.3 Fluidized Bed Incinerators

Fluidized beds are occasionally used for hazardous waste combustion, although not nearly as frequently as rotary kilns or liquid injection types.

2.1.3.1 Process Description

A fluidized bed incinerator consists of a fluidized bed reactor, fluidizing air blower, waste feed system, auxiliary fuel feed system, and an air pollution control device system. A typical reactor is shown in Figure 2-3. The fluidized bed reactor is essentially a vertical cylinder containing a bed of granular material (typically sand or some other inert material) at the bottom. Combustion air is introduced at the bottom of the cylinder and flows up through openings in a distribution plate; the distribution plate is designed to allow sufficient air to pass upward into the bed but to prevent bed media from falling through when the bed is at rest. The air flows up through the bed material, suspending the granular particles.

Solid, liquid, and gaseous waste fuels may be injected into the bed, where they mix with the combustion air and hot bed media, and burn. The waste is put in direct contact with the bed media, causing heat transfer from the bed particles. At the proper temperature, waste ignition and combustion occur. The bed media acts to scrub the waste particles, exposing fresh surface by the abrasion process which encourages rapid combustion of the waste. Waste and auxiliary fuel are injected radially into the bed and react at temperatures from 840 to 1500°F. Further reaction occurs in the volume above the bed, known as the “freeboard”, which is maintained at temperatures up to 1800°F. An auxiliary burner is located above the bed to provide heat for start-up, reheat, and maintenance of bed temperature. Waste ash and bed materials are removed periodically from the bottom of the bed as well as entrained out of the bed with the exhaust gas.

Typical reactors have an inside diameter of 26 feet and elevation of 33 feet. Silica beds are commonly used and have a depth of 3 feet at rest and extending up to 6.5 feet in height when fluidizing air is passed through the bed.

Generally, fluidized bed incinerators have two separate waste preparation/feed systems — one for solids and one for liquids. In some cases, four feed systems are employed: wet solids, dry solids, viscous fluids, and non-viscous fluids. Solid wastes are usually fed into a coarse shredder. The coarsely shredded waste falls into a classifier which separates the light and dense particles. The lighter particles are transferred to a secondary shredder from which they are conveyed to the hopper for feeding the fluidized bed. Liquid waste is pumped into a larger holding tank. To ensure the mixture is as homogeneous as possible, the liquid waste is continuously pumped through a

recirculating loop from the bottom of the tank to the top. A metering pump draws the waste fuel to be burned from the tank to the primary reactor. Nozzles are used to atomize and distribute the liquid waste within the bed.

Due to efficient mixing, fluidized beds in general can operate at lower temperatures compared with other incineration technologies. This potentially results in lower NO_x and volatile metals emissions, as well as lower potential for ash agglomeration and lower auxiliary fuel requirements. This also allows for the treatment of low heating value wastes (below 4500 Btu/lb). The use of alkali containing bed materials such as lime or sodium allows for “in-situ” acid gas control; hence, fluidized beds may be efficient at treating high sulfur or halogenated wastes due to reduced downstream acid gas emissions control requirements.

Maintaining proper bed fluidization is important for effective waste treatment. Solid waste size reduction (shredding or grinding) may be required. Fluid beds are not well suited for irregular, bulky wastes, tarry solids, or wastes with a fusible ash content. Improper bed fluidization may lead to bubbles of gas that “short circuit” the bed, allowing for potentially unburned wastes to escape the bed. Particulate emissions in the flue gas may be high compared to other incinerator designs due to the high fluidization velocity, erosion of bed material, bed turbulence, and the small size of waste and bed particles.

2.1.3.2 Operating Parameters

Fluidized bed operating parameters include:

- Bed temperature — The fluidized bed temperature must be monitored and controlled by waste feed and auxiliary burner adjustments, as well as adjustments of the input rate of combustion air and inert fluidizing gases, to assure that the temperature remains above an established minimum. Operating temperatures are normally maintained in the 1400 to 1600°F range.
- Oxygen level — The oxygen level in the bed must be maintained to ensure the potential for complete combustion.
- CO and HC flue gas levels — Monitoring the CO and HC concentration in the flue gas is also an indication of complete combustion.
- Bed retention time — Solids retention time in the bed is a measure to the thorough treatment of the waste. Retention time is especially important for relatively non-combustible wastes.
- Bed fluidization — Uniform bed fluidization must be maintained to properly treat the waste.
- Bed gas residence time — The combustion gas residence time must be monitored to assure that the combustion gas has been exposed to volatile destruction temperature for a sufficient period of time.

2.1.4 Fixed Hearth Incinerators

Fixed hearth incinerators, which are used extensively for medical waste incineration, are less commonly used to incinerate hazardous wastes. Fixed hearths can handle bulk solids and liquids, however, this design does not have the versatility of a rotary kiln.

2.1.4.1 Process Description

Fixed hearth incinerators typically contain two furnace chambers: a primary and secondary chamber. A typical fixed hearth system is shown in Figure 2-4. Solid and liquid wastes may be charged into the primary chamber; small units are normally batch-fed, while larger units may be continuously fed with a screw feeder or moving grate, or semi-continuous fed with a raw pusher. In some designs, there may be two or three step hearths on which the ash and waste are pushed with rams through the system. In other designs, rotating rabble arms stir the solid waste material on the grate.

A controlled flow of “under-fire” combustion air is introduced, usually up through the hearth on which the waste sits. In some designs, combustion air may also be provided from the wall over the waste bed. In many fixed hearth incinerators, known as controlled air or starved air incinerators, 70 to 80% of the stoichiometric air required is provided in the primary chamber, thus the primary chamber is operated in a “starved-air” mode. In this situation the waste is pyrolyzed and partially combusted. In some cases steam injection into the primary combustor is used to enhance waste fixed carbon burnout (fixed carbon is non-volatile carbon which will burn only when exposed to combustion air). Because fixed hearth incinerators have relatively poor mixing of waste with the combustion air, they are not effective at processing waste which require turbulence for effective combustion, such as powdered carbon, pulp wastes, sludges, and viscous wastes.

Primary chamber temperature is controlled by the under-fire air supply. Temperature in the primary chamber is maintained high enough to destroy hazardous organics in the waste (typically 1000°F) but low enough to reduce the potential for slagging and refractory damage (1800°F). Waste slagging may clog the under-fire air ports. Bottom ash is removed on a continuous or semi-continuous method, depending on the unit design. The ash is usually dumped into a water bath, which provides a seal between the primary unit and the atmosphere.

For controlled air units, due to insufficient supply of air, the primary chamber flue gas will contain unburned hydrocarbons, and high levels of CO and H₂. These volatiles are burned out in a secondary or afterburner chamber. In the secondary chamber, 140 to 200% excess air is provided, as well as sufficient residence time at temperature for complete volatiles burnout. Liquid wastes may be injected either in the primary or secondary chamber. Supplementary fuel may be provided in both chambers for the maintenance of temperature. Secondary chamber temperature may be as high as 2000°F. Temperatures beyond this are avoided to prevent refractory damage, decreased gas residence time, and usage of auxiliary fuel.

2.1.4.2 Operating Parameters

Critical fixed hearth operating parameters include primary chamber and afterburner temperature. Primary chamber temperature is controlled by the under-fire air supply. Afterburner temperature can be controlled by auxiliary fuel firing and primary waste feed rate adjustments. Note that the capacity of afterburner or secondary chamber limits the primary chamber burning rate. The afterburner must have adequate volume to accept and oxidize all volatile gases generated in the primary chamber. Additionally, the afterburner must be kept operating at excess air conditions to ensure complete volatile burnout.

2.1.5 Air Pollution Control Techniques

The exhaust combustion gas leaving the primary (or secondary if used) incinerator combustion chamber will be composed primarily of CO₂, O₂, and N₂, and H₂O vapor. It may also contain undesirable constituents that are a byproduct of the combustion process such as: (1) acid gases (HCl, HF, SO₂, and NO_x), (2) entrained suspended solid particles (potentially containing condensed metals and unburned non-volatile organics), (3) inorganic vapors (e.g., volatile metals such as mercury), and (4) products of incomplete combustion such as unburned organics and CO. Levels of these combustion byproducts is highly site specific, and depends on a variety of factors such as waste composition and incinerator system design and operating parameters (e.g., temperature and exhaust gas velocity).

Most hazardous waste incinerators use air pollution control systems to remove undesirable components such as suspended solid particles (“particulate matter”) and acid gases from the exhaust gas prior to release to the atmosphere. The air pollution control system is typically made up of a series of different devices that work as a unit to clean the exhaust combustion gas. Unit operations usually include exhaust gas cooling, following by particulate matter and acid gas control.

Exhaust gas cooling can be performed many different ways including using a waste heat boiler or heat exchanger, mixing with cool ambient air, or injection water into the exhaust gas. For PM and acid gas control, many different types of air pollution control devices can be used, including wet scrubbers (such as venturi and packed bed type wet scrubbers, ionizing wet scrubbers), and electrostatic precipitators and fabric filters (sometimes used in combination with dry acid gas scrubbing). In general, the control systems can be grouped into the following three categories: “wet”, “dry”, and “hybrid wet/dry” systems.

In wet systems, a wet scrubber is used for both particulate and acid gas control. Typically, a venturi scrubber and packed bed scrubber are used in a back-to-back arrangement. Ionizing wet scrubbers, wet electrostatic precipitators, and innovative venturi-type scrubbers may be used for more efficient particulate control. Wet systems generate a wet effluent liquid waste stream (scrubber blowdown), are relatively inefficient at fine particulate control compared to dry control techniques, and have equipment corrosion concerns. However, wet scrubbers typically provide efficient control of acid gases and have lower operating temperatures (compared with dry systems) which may help control the emissions of volatile metals.

In dry systems, a fabric filter or electrostatic precipitator is used for particulate control, sometimes in combination with dry scrubbing for acid gas control. Dry scrubbing systems in comparison with wet scrubbing systems are inefficient at the control of acid gases.

In hybrid systems, a dry technique (ESP or fabric filter) is used for particulate control (and possibly acid control with use of dry scrubbing) followed by a wet technique (venturi and packed bed scrubber) for acid gas control. Hybrid systems have the advantages of both wet and dry systems (lower operating temperature for capture of volatile metals, efficient collection of fine particulate, efficient capture of acid gases), while avoiding many of the individual disadvantages. In some hybrid systems, known as “zero discharge systems”, the wet scrubber liquid is used in the dry scrubbing operation, thus minimizing the amount of liquid byproduct waste.

In a separate and unique category are facilities which do not use any air pollution control devices. Some liquid injection and fixed hearth facilities, which generate low levels of particulate when treating low ash content wastes, and/or may not generate acid gases when burning nonhalogen containing wastes, do not utilize post-combustion air pollution control devices.

2.2 CEMENT KILNS

The manufacture of cement is one of the largest mineral products in the United States. In 1990, 111 plants in the United States produced about 80 million tons of cement. There are about 34 separate sites where cement kilns are burning hazardous waste derived fuel in the United States.

2.2.1 Process Components

Cement is made from a carefully proportioned mixture of raw materials containing calcium (typically limestone, although oyster shells and chalk may also be used), silica and alumina (typically clay, shale, slate, and/or sand), and iron (typically steel mill scale or iron ore). These materials are ground to a fine power (80% passing 200 mesh), thoroughly mixed, and heated to a very high temperature to produce a cement “clinker” product. The raw feed material, known as “meal”, is heated in a kiln; a large, inclined, rotating cylindrical steel furnace lined with refractory materials. Heating of the meal as it moves through the kiln drives a number of chemical and physical processes which are necessary to form the clinker. In the first “drying and preheating zone”, occurring in a temperature range of 70 to 1100°F, residual water is evaporated from the raw meal feed, and clay materials begin to decompose and are dehydrated (removal of bound water). Next, in the “calcining zone” (with materials temperatures of from 1100 to 1650°F) the material is “calcined”; that is calcium carbonate in the limestone is dissociated producing calcium oxide (“burnt lime”) and carbon dioxide. Finally, in the “burning zone”, also known as the “clinkering” or “sintering” zone, calcium oxide reacts with silicates, iron, and aluminum to form “clinker”. The clinker is a chemically complex mixture of calcium silicates, aluminates, and alumino-ferrites. A minimum meal temperature of 2700°F is necessary in the burning zone of the kiln to produce the clinker.

Heating of the raw meal to produce cement clinker can take place in three different types of arrangements: “wet”, “dry”, or “semi-dry” processes. The hardware used to dry, calcine, and clinker the raw meal is different between the three set-ups; the physical and chemical processes to produce the cement are similar. A rotary kiln is the common element in all systems, and always contains the

burning zone and all or part of the calcining zone.

2.2.1.1 Wet Process Kilns

A schematic of the wet cement making process is shown in Figure 2-5. In wet process kilns, ground raw materials are mixed with water (about 30% by weight) to form a slurried meal. The slurry is ground in wet mills to required size and pump fed to the elevated end of the rotary cement kiln. The slurry is fed to the kiln through a flow metered pump. The kiln is a long (450 to 750 ft. in length with a length-to-diameter ratio of about 30:1 to 40:1), inclined rotating cylindrical steel furnace. Refractory material internally lines the kiln to protect the steel shell from the high temperature and to retain heat within the kiln. The kiln slope (3 to 6°) and rotation (50 to 70 revolutions per hour) cause the meal to move toward the “hot” lower end of the kiln. The kiln is fired at the hot end, usually with coal or petroleum coke as the primary fuel; natural gas, fuel oil, or hazardous waste derived fuel may also be used as a supplemental energy source. This energy is required to heat the raw materials to clinker formation temperature. As the raw meal moves down the kiln it is heated by hot fuel combustion gases moving in a “counter-current” direction. This configuration (exhaust gases and solids flowing in opposite directions through the kiln) provides for more efficient heat transfer compared with “co-current” operations. Kiln rotational speed, raw meal feed, and fuel firing rates are adjusted to maintain clinker quality and heat transfer and to limit the raw meal from occupying more than 15 to 20% of the internal kiln volume. To improve the energy efficiency of the process, steel chains are typically attached to the inside of the kiln shell in the upper kiln drying zone. The chains act as a heat transfer mechanism. As the kiln rotates, the chains hang by gravity and pick up heat from the kiln flue gases. When the hot chains settle back into the meal after further rotation, heat is transferred from the chains to the meal.

The wet cement making process is the older traditional process, characterized in part by handling, mixing, and blending of the raw materials in the slurry form, and lower emissions of kiln dust. However, because all water must be evaporated out of the slurry mixture, wet process kilns require greater energy input than other types of cement kilns; typically, from 5 to 7 million Btu/ton of clinker product is required. Although, because some raw materials are quarried in a wet form, the wet process may be preferred.

A typical solids and gas temperature profile of a wet kiln is shown in Figure 2-6. The feed does not begin to heat up until all of the water in the raw meal slurry is evaporated. The gas temperature in the burning zone approaches 4000°F, while the clinker reaches a maximum temperature of approximately 2700°F, which is required for the formation of clinker. Flue gas velocity is also shown in Figure 2-7 as a function of kiln axial location. This relates to a kiln gas residence time of over 10 seconds. Typical solids residence time in the kiln is from 2 to 3 hours.

2.2.1.2 Dry Process Kilns

Due to higher energy efficiency compared with wet kilns (3.4 to 4.5 million Btu/ton clinker), and improvements in dry grinding and blending technology, dry processes have become popular. In the dry process, the ground raw material is dried and pneumatically transported to the kiln, or preheater if used. Kiln exhaust flue gases or hot clinker cooler air are typically used for drying the raw materials. There are three different dry process configurations: long, preheater, or preheater/

precalciner.

Long Dry Process Kilns — A long dry process kiln has a same configuration as the wet type; the only difference is that raw meal is fed in a dry form. Long dry kilns have typical length-to-diameter ratios of about 30:1; they are typically shorter than wet kilns since slurried meal water evaporation is not required, allowing for the meal to be heated more rapidly. A typical long dry kiln solid/gas temperature profile is shown in Figure 2-8. Kiln gas and solids residence times are similar to those of wet kilns (on the order of 10 seconds and 2 to 3 hours respectively). Internal chains are also used in dry process long kilns (similar to wet kilns) to increase process energy efficiency.

Preheater Dry Process Kiln — The preheater arrangement process is shown in Figure 2-9. Preheaters are used to further increase the thermal efficiency of the cement making process. In the preheater system, kiln exhaust gas is used to increase meal temperature and partially calcine the meal before feeding it to the rotary kiln. The preheater accomplishes the same tasks as the back end of a long kiln, but more energy efficiently compared with the rotary kiln. There are two types of preheater arrangements: the traveling grate type, and more commonly, the suspension type. A suspension preheater (“Humboldt” Design) consists of a vertical tower containing a series of cyclone-type vessels (typically containing four stages). Raw meal is introduced at the top of the tower. Hot kiln exhaust flue gases pass counter-current through the downward moving meal to heat the meal prior to introduction into the kiln. The cyclones are used to separate the meal from the kiln flue gases; collected meal in the cyclones is sequentially dropped into the next lower stages. Because the meal enters the kiln at a higher temperature than that of the conventional long dry kilns, the length of the pre-heater kiln is shorter; kilns with preheaters typically have length-to-diameter ratios of about 15:1.

A typical solid/gas temperature profile is shown in Figure 2-10. The preheater kiln typically has a gas residence time of about 6 seconds and a solids residence time of about 30 minutes. The gas residence time through the preheater cyclones (typically four stages) is usually about 5 seconds (Figure 2-11 shows typical gas velocities through the preheater kiln system).

With preheater systems, it is often necessary to utilize an “alkali” bypass, in which a portion of the kiln flue gases are routed away from the preheater tower at a location between the feed end of the rotary kiln and the preheater tower. The bypass is used to remove undesirable components, such as certain alkali constituents, that may accumulate in the kiln due to an internal circulation loop caused by volatilization at high temperatures in the kiln and condensation in the lower temperatures of the preheater. Accumulated alkali salts may cause preheater operating problems such as clogging of the cyclones, and an increase in fine NaCl or KCl fume in the emissions gases. Typically 10 to 15% of the flue gas is routed through the bypass. Systems without bypasses are limited with respect to raw meal and waste concentrations of alkali metals, chloride (greater than 0.015% Cl by weight), and sulfur that can be tolerated in the raw materials.

The internal circulation of alkali components is greater in systems with preheaters compared to systems without preheaters due to the filtering effect of feed material flow in the preheater cyclones. Systems without preheaters have a kiln dust with a high content of alkali salts, which can be removed from the internal cycle when caught in the air pollution control device. However, for the preheater arrangement, to reduce the alkali buildup, a bypass is required.

Preheater/Precalciner Dry Process Kiln — A preheater/precalciner process is also shown in Figure 2-9. A preheater/precalciner is similar to the preheater arrangement described above with the addition of an auxiliary firing system to further increase the raw materials temperature prior to introduction into the kiln. An additional precalciner combustion vessel is added to bottom of preheater tower, immediately upstream of the kiln. Typical systems use 30 to 60% of the kiln fuel in the precalciner to release up to 95% of the CO₂ from the raw material. Precalciner air can be supplied either directly with the precalciner fuel, or else supplied at hot end of the kiln. In another arrangement, the kiln flue gas may be routed around the calciner directly to the preheater. Kilns with preheater/precalciner can be even shorter than those with preheaters only (length-to-diameter ratio of 10:1).

The primary advantage of using the precalciner is to increase the production capacity of the kiln, since only the clinker burning is performed in the kiln. The use of the precalciner also increases the kiln refractory lifetime due to reduced thermal load on burning zone. These configurations also require a bypass system for alkali control.

A typical solid/gas temperature profile of a kiln with a preheater and precalciner is shown in Figure 2-12. It is similar to that of the preheater kiln; however, the time at which the gas temperature is above 1650°F is slightly less in a precalciner type kiln.

2.2.1.3 Semi-Dry Process Kilns

In the semi-dry process, the ground feed material is pelletized with 12 to 14% water. The pellets are put on a moving “Lepol” grate on which they are dried and partially calcined by hot kiln exhaust gases before being fed to the rotary kiln. A semi-dry process schematic is shown in Figure 2-13. A typical solids/gas temperature diagram is given in Figure 2-14.

2.2.2 Clinker Handling

In all arrangements, the clinker is removed from the kiln at the hot end. After it passes through the burning zone and by the kiln flame, it enters a short cooling area where the clinker melt begins to solidify; the cooling rate from the burning zone to the kiln exit is important since it determines the microstructure of the clinker. The clinker leaves the kiln at about 2000°F and falls into a clinker cooler. The cooler is typically a moving grate onto which the clinker sits. Cooling air is blown through the clinker bed. The cooled clinker consists of grey colored nodules of variable diameters, typically up to two inches. The clinker is blended with gypsum and ground in a ball mill to produce the final product, cement. Hot exhaust air produced from the clinker cooler is either directed to the kiln where it is used as combustion air or used to pre-dry the raw feed material in the case of dry process kilns.

2.2.3 Hazardous Waste Feeding Techniques

The feeding of the hazardous waste into the kiln is a primary factor in determining the destruction of the waste which is dependent on temperature and residence time. The method of introducing the waste also depends on its physical state, as discussed in the following sections.

Liquid wastes are either blended directly with the conventional fuels which are provided at the hot end of the kiln, or they are injected separately through a separate burner/atomizer into the primary kiln flame. Extreme combustion conditions of high temperature (greater than 3000°F), turbulent mixing, and long as phase residence time (from 4 to as high as 16 seconds in long kilns) have been demonstrated to overcome any possible deficiencies in local oxygen availability and potential atomization problems.

In the past, solid wastes were fed at the cold end of the kiln with the raw meal. However, the addition of wastes at cold end is no longer practiced because as the wastes move down the kiln and get hotter, volatile components are driven off at temperatures below those required for complete oxidation and destruction (note that the current Boiler and Industrial Furnaces Rule no longer allows this, requiring that at the location of solid waste feeding, the combustion gas temperature must exceed 1800°F and that adequate oxygen must be present to ensure complete combustion of organic constituents in the waste). Thus, significant emissions of unburned volatiles may occur without the use of an afterburner or other add-on volatile emissions control techniques.

Alternatively, solid wastes are not usually charged directly into the hot end burning zone for a variety of reasons. If introduced too close to the end of the kiln, the solid wastes may leave the kiln with the clinker in an unburned state due to insufficient time in the hot conditions. Their presence can create local reducing conditions which adversely effect clinker quality such as strength, stability, set-up time, and color. Oxidizing conditions must be maintained in the burning zone. If insufficient oxygen is present, a key component of cement clinker, tetra calcium aluminoferrite does not form; instead Fe_2O_3 is reduced to FeO . This leads to a clinker product that produces a quick setting cement with decreased final strength. Additionally, the presence of unburned carbon in the burning region produces a clinker with an undesirable brown color. To overcome these feeding location limitations, a variety of techniques are used for the introduction of solid wastes into cement kilns. The choice depends on the solid waste type (composition and physical attributes) and kiln configuration (dry long, dry with preheater, wet, etc.).

Methods which are used rely on the introduction of the solid waste into the calcining zone. For long kilns, this means that the waste is introduced mid-kiln, while for preheater/precalciner kilns, it is introduced onto the feed shelf. Introduction in the calcining zone allows the solids to have sufficient residence time for the organics to be driven off so that the presence of waste combustibles do not reach the burning zone creating reducing conditions which are detrimental to clinker quality, and yet far enough away from the cold end to provide sufficient temperature and residence time for complete destruction of volatile gaseous organics. These methods include:

- For long type wet and dry kilns, and dry kilns with preheaters, a method has been developed for charging solid wastes directly through a hatch on the rotating kiln wall at an intermediate

location within the calcining zone. At each rotation, the hatch is opened, and containerized waste solids are fed down a drop tube that is inserted through the hatch and into the rotating kiln. The drop tube prevents hot mineral material from escaping through the port or contacting the enclosure. It is important that the volume of the volatile components does not exceed the capacity for their complete combustion in the gas stream. Thus, wastes are containerized to minimizing the potential for overloading the combustion capacity (create local reducing conditions).

- As mentioned, for preheater or precalcining kilns, the solid waste may be injected directly into the precalciner vessel or preheater inlet.
- Containerized solid wastes may also be injected at the hot end of the kiln at high enough velocity so that they are projected into the calcining zone. An “air cannon”, which is mounted to the kiln hood, is used to propel the waste containers.

Other methods used for solid waste treatment in cement kilns can be used. If the waste is in powdered form, it may be injected directly into the primary burning zone coal flame of the cement kiln. In another set up, solid waste is burned in a separate kiln or combustor; the flue gas is routed to the hot end of the cement kiln, which is used as an afterburner and for acid gas control.

2.2.4 Air Pollution Control System

Kiln combustion gases are drawn through the system with an induced draft fan; this maintains kiln pressure under atmospheric to prevent fugitive emissions. Kiln (or preheater if used) exhaust gases contain large amounts of suspended fine solid particles, known as “cement kiln dust” (CKD), contain significant amounts of entrained particulate matter due to the turbulence in the kiln from the rotary action and from the use of finely ground feed material. The CKD is composed of fuel and waste ash and meal raw materials. The CKD is removed from the exhaust gas in either ESPs or FFs. ESPs have been the more common choice due to their reliability and low maintenance requirements. Recently though, with increasingly strict particulate control standards, FF have also become common. Typically, fabric filters are more efficient at collection of submicron particulate and provide lower guaranteed particulate matter emissions levels. ESPs are more common on wet kilns since the higher exhaust gas moisture content is difficult for FFs to handle. FF more common at dry process kilns. Depending on the facility, the kiln exit gas may need to be cooled prior to being introduced into the air pollution control device. Air dilution or water spray may be used for this purpose. In another arrangement, hot gases leaving the kiln are cooled in a waste heat boiler which produces steam; the steam is converted to electricity this is used on-site. Many plants return a portion of the CKD to the raw feed materials or directly into the hot end flame (known as “insufflation”). However, some must be removed to lower the buildup of alkali salts. CKD can be used in other industries as neutralizers or additives, however, usually the excess CKD is land disposed.

Due to the nature of the cement process, add-on acid gas air pollution control devices, such as wet or dry scrubbers, are not used. The cement feed raw materials are high in alkaline content (limestone in particular), which provides for “in-situ” absorption of chlorine and other halogens and sulfur, which may originate in either the coal or the hazardous waste), preventing the formation and release of acid gases.

CO and HC main stack gas emissions levels from cement kilns are typically higher than those encountered in hazardous waste incinerators. CO is believed to be high due to the limestone calcination process and the decomposition of CO₂ into CO due to elevated temperatures and moisture and metal catalysts in the cement kiln. HCs are volatilized from the raw meal at the cold end of the kiln at temperatures below those necessary for complete destruction and oxidation. Additionally, although excess oxygen conditions (oxidization atmosphere) are required for quality cement production, low kiln levels (1 to 4% in cement kilns, compared with 5 to 10% in hazardous waste incinerators) are desired for high temperature, energy efficient operation. Low oxygen levels may lead to local oxygen deficient regions and incomplete destruction of volatiles.

2.3 LIGHTWEIGHT AGGREGATE KILNS

“Light weight aggregate” (LWA) is a high strength, light weight material, with a density much less than ordinary aggregates such as gravel, sand, or stone. Its primary use is in concrete, made by combining LWA with cement. LWA concrete blocks and structural concrete are frequently used in the construction of roads, bridges, and buildings. There are over 36 LWA producing facilities in the United States. Of these, there are six which are burning hazardous waste derived fuel.

2.3.1 Process Components

A lightweight aggregate plant is composed of a quarry, a raw material preparation area, a kiln, a cooler, and a product storage area. The material flows from the quarry to the raw material preparation area. From there, the material is fed into the rotary kiln.

LWA is made by heating raw materials such as clay, shale, and slate to high temperature in a rotating light weight aggregate kiln (LWAK), as shown in Figure 2-15. When the highly siliceous raw material is heated, it bloats and expands forming a strong light weight material when cooled. The kiln is a long steel cylinder (typically 120 to 300 feet in length with a 7 to 10 foot diameter), lined internally with refractory bricks. It rotates about its axis at 3 to 5 revolutions per minute, and is inclined at an angle of 3 to 5° from the horizontal. It operates in a manner similar to previously described for cement kilns. Crushed raw material is continuously fed to the kiln at the upper “cold” end. Gravity and kiln rotation cause the material to travel downward through the kiln toward its bottom end. At the bottom “hot” end, fuels such as coal, petroleum coke, natural gas, fuel oil, and/or hazardous waste are burned with air to provide energy to heat the raw materials. Combustion air is provided in an excess (80 to 100% of minimum requirements) to aid in “expanding” the raw materials. The raw material travelling down the kiln (from the upper to lower end) is heated by hot fuel combustion gases moving in an opposite direction (from the lower to upper end). This “counter-current” operation provides for efficient heat transfer between the hot gases and raw material, leading to a minimization of fuel energy requirements. Energy requirements are typically 3 to 6 million Btu/ton of LWA product.

The raw material goes through various temperature regimes as it is heated in the kiln which cause the transformation of the material into the LWA product. In the first preheating stage, raw material moisture is driven off. As the temperature increases, the material becomes soft and pliable and decomposes. Formation of internal gases (such as SO₂, SO₃, CO₂, and O₂) also begins. These

gases cause the material to expand. When the material temperature approaches the “expanding” zone temperature of 1900 to 2100°F, it becomes sufficiently viscous to internally trap the expanding gases. This bloating action produces small unconnected gas cells, which the material retains after it cools and solidifies; these internal gas cells give the aggregate its characteristic light weight property. Maintaining the proper temperature is critical for making LWA. If the temperature is too low, the clay will not expand to form the desired structure. However, if the temperature is too high, the material fuses, leading to the formation of a heavy coating on the kiln interior that must be removed after shutting down and cooling the kiln. Kiln temperature is controlled by adjusting fuel and raw material feed rates, kiln rotation rate, and the amount of combustion air. The hot LWA product is removed at the bottom of the kiln, and cooled. The LWA may be graded and crushed after cooling. LWAK production rates typically range from 200 to 1000 tons of LWA/day.

An induced draft fan is used to pull combustion gases up through the kiln and to maintain a negative kiln pressure with respect to the atmosphere to prevent fugitive gas emissions from leaking through the rotary kiln seals. Kiln exhaust gases leave the cold upper end of the kiln at a temperature from 400 to 1000°F. The kiln exhaust gas contains suspended dust particles (consisting potentially of raw material, waste ash, and fuel ash) and may also contain volatile inorganics such as acid gases (including HCl and SO₂ produced as a byproduct of the combustion of chlorine and sulfur containing wastes and fuels) and certain volatile metals. The LWAK exhaust gas may also contain elevated levels of unburned organics and CO compared with hazardous waste incinerators due to “counter-current” operation; at the upper kiln end, as the raw material is heated, organics may be vaporized at temperatures below those required for their complete oxidation and destruction.

LWAKs historically have used both wet scrubbers and dry systems such as fabric filters and ESPs for exhaust gas dust emissions control. All hazardous waste burning LWAKs currently use fabric filters for the removal and collection of dust contained in the exhaust gas. The exhaust gas may require cooling (with either a water spray, heat exchanger, or cold air dilution) prior to the fabric filter due to fabric operating temperature limitations. The collected dust can be recycled back into the kiln (at the hot or cold end) or mixed into the final LWA product. Some LWAKs also use dry scrubbing (by the addition of an acid gas absorbing alkali upstream of the fabric filter) or wet scrubbing techniques for acid gas emissions control.

In currently operating hazardous waste burning LWAKs, only liquid hazardous wastes are treated. Liquid wastes are either blended directly with conventional fuels provided at the hot end of the kiln, or they are injected separately through a lance or atomizer into the hot end flame. The high combustion gas flame temperature (greater than 3000°F) and kiln gas residence time (greater than 2 seconds) is used to destroy hazardous organics; waste in-organics are either incorporated into the LWA product or leave the kiln with the exhaust gas (in the form of either vapors or solids). Similar to that discussed for cement kilns, LWAKs may potentially be used to treat solid wastes. Fine powder combustible solids may be injected similar to liquids directly into the hot end flame. Bulk solids may be introduced at mid-kiln through mid-kiln hatches or with air-cannon injection from the hot end.

2.3.2 Operating Parameters

Kiln operating parameters such as flame temperature, excess air level, feed size, material flow, gas and solids residence time, and speed of rotation vary from plant to plant and are determined by the characteristics of the raw material. Raw materials include clay, shale, or slate which have varying properties linked to their geological formation. As mentioned, maximum temperature in the rotary kiln varies from 2050 to 2300°F, depending on the type of raw material being processed and its moisture content. Kiln exit gas temperatures may range from 300 to 1200°F, again depending on the raw material and on the kiln's internal design. Approximately 80 to 100% excess air is forced into the kiln to aid in expanding the raw material. A typical lightweight aggregate rotary kiln has a combustion gas residence time of greater than 4 seconds, based on a kiln gas temperature at the hot end of 2100°F and a temperature at the cold end of 700°F.

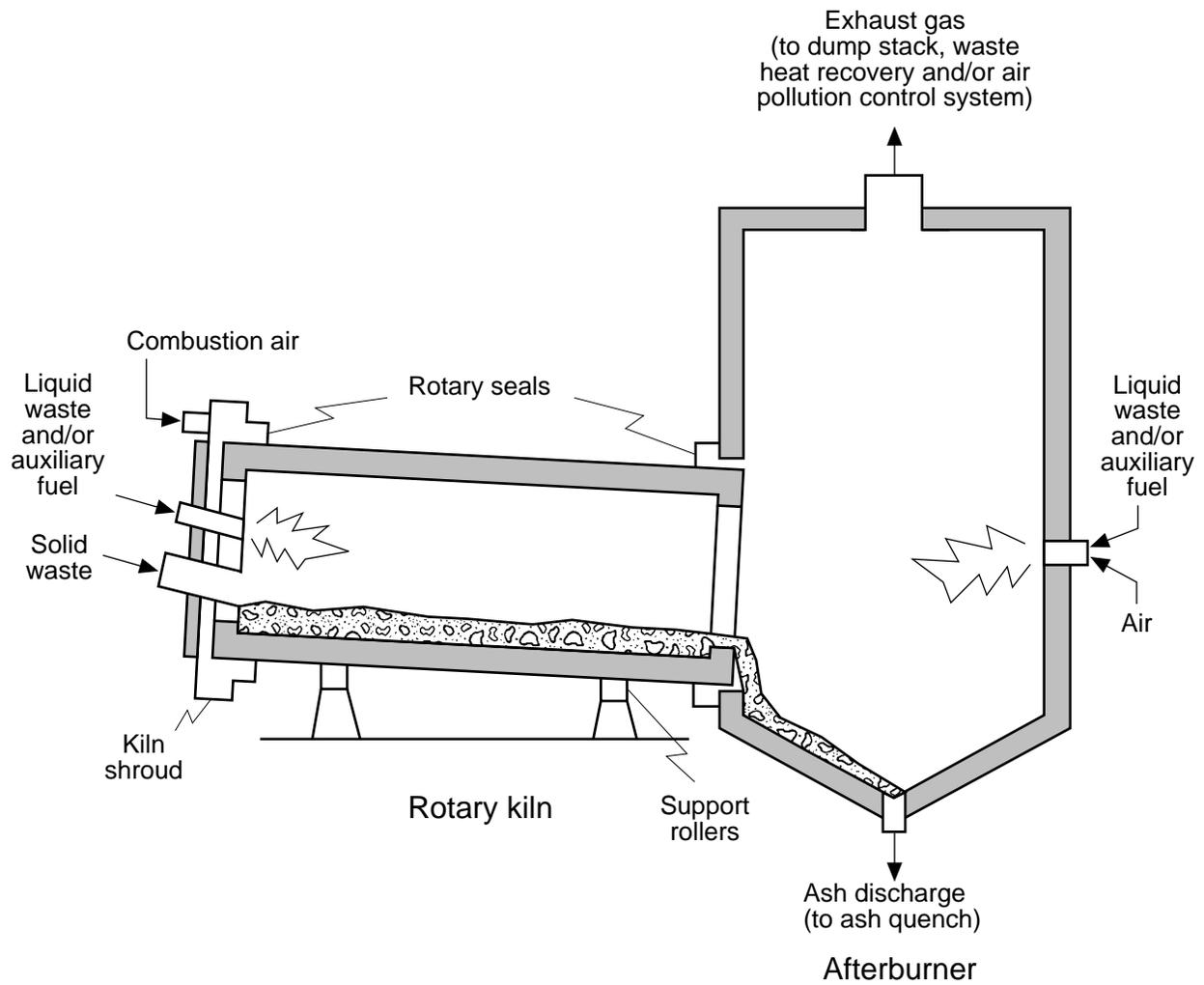


Figure 2-1. Typical rotary kiln incinerator.

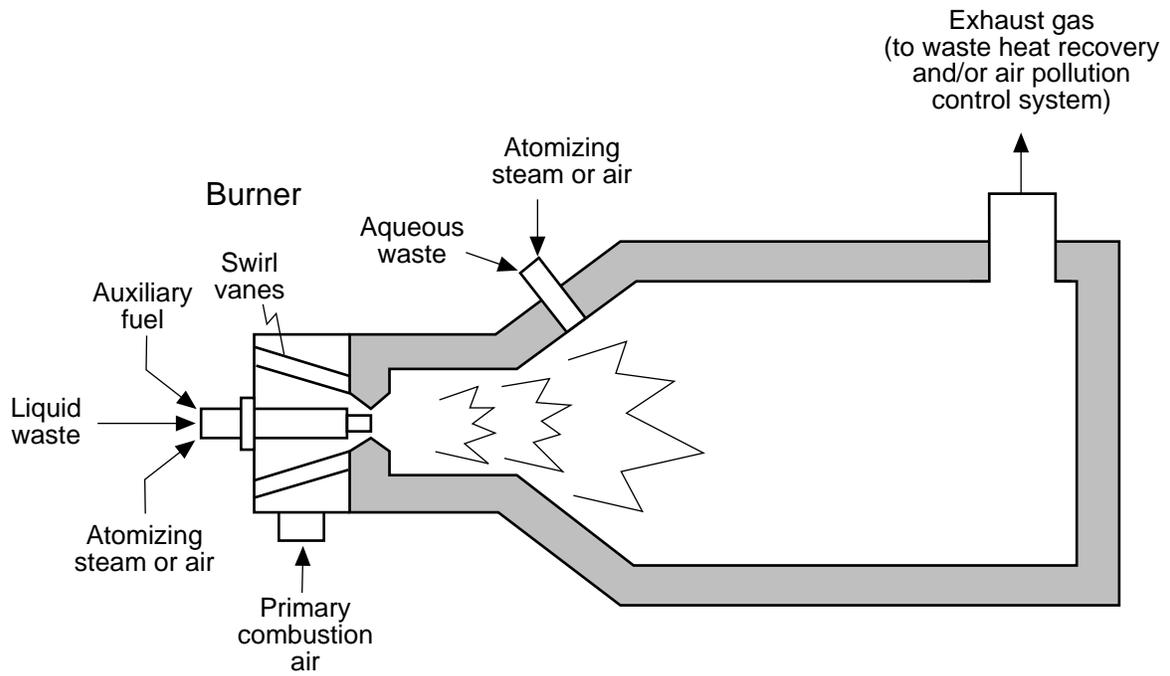


Figure 2-2. Typical liquid injection incinerator.

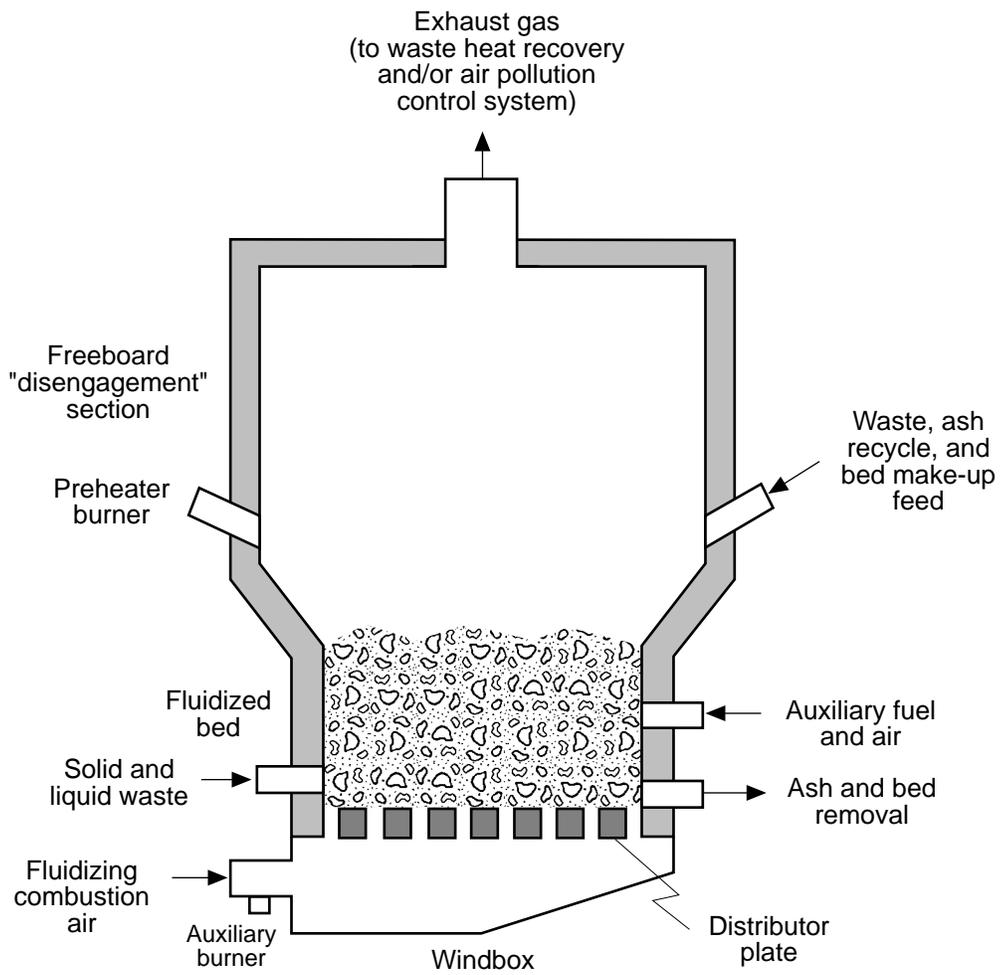


Figure 2-3. Typical fluidized bed incinerator.

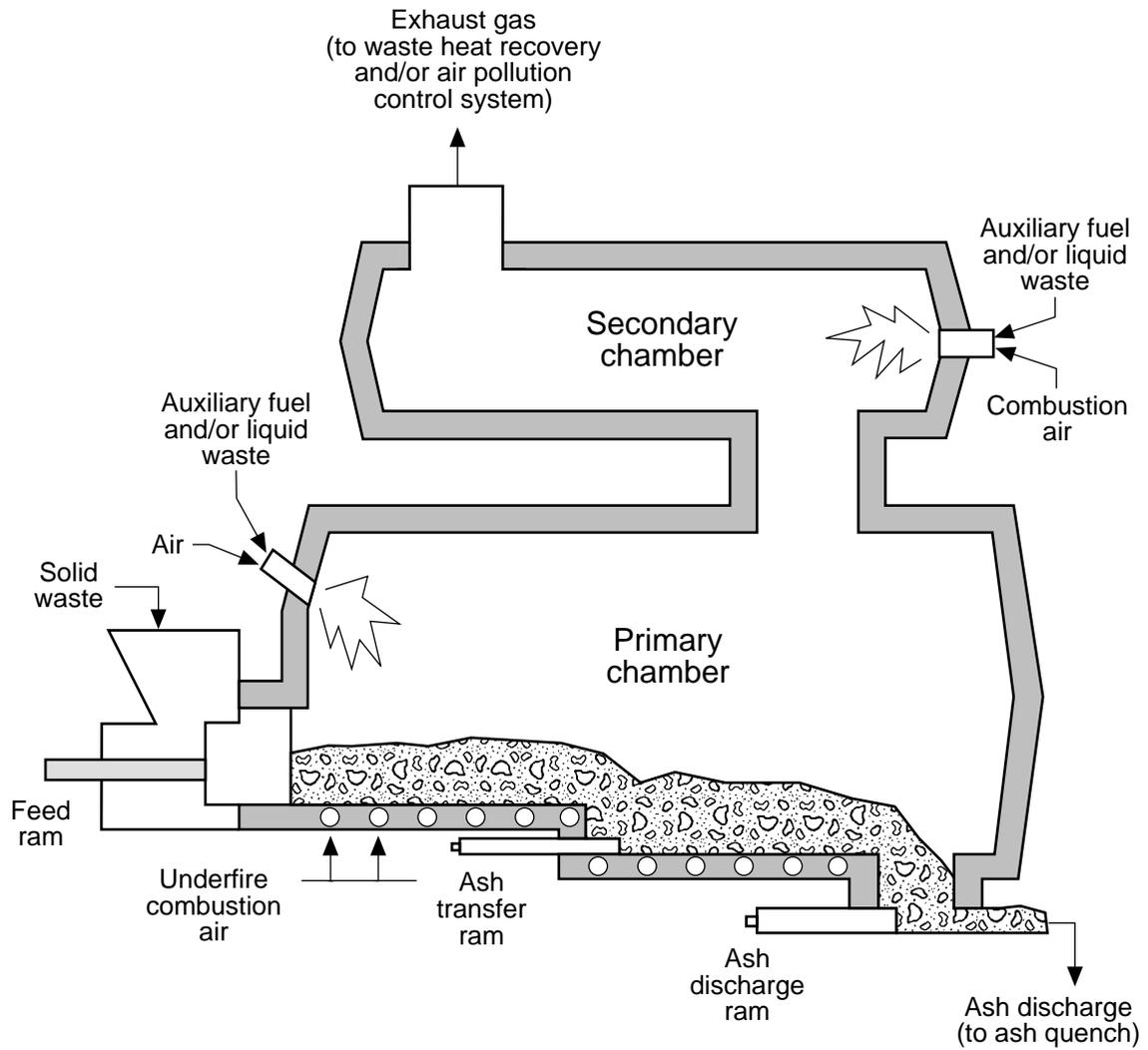


Figure 2-4. Typical fixed hearth incinerator.

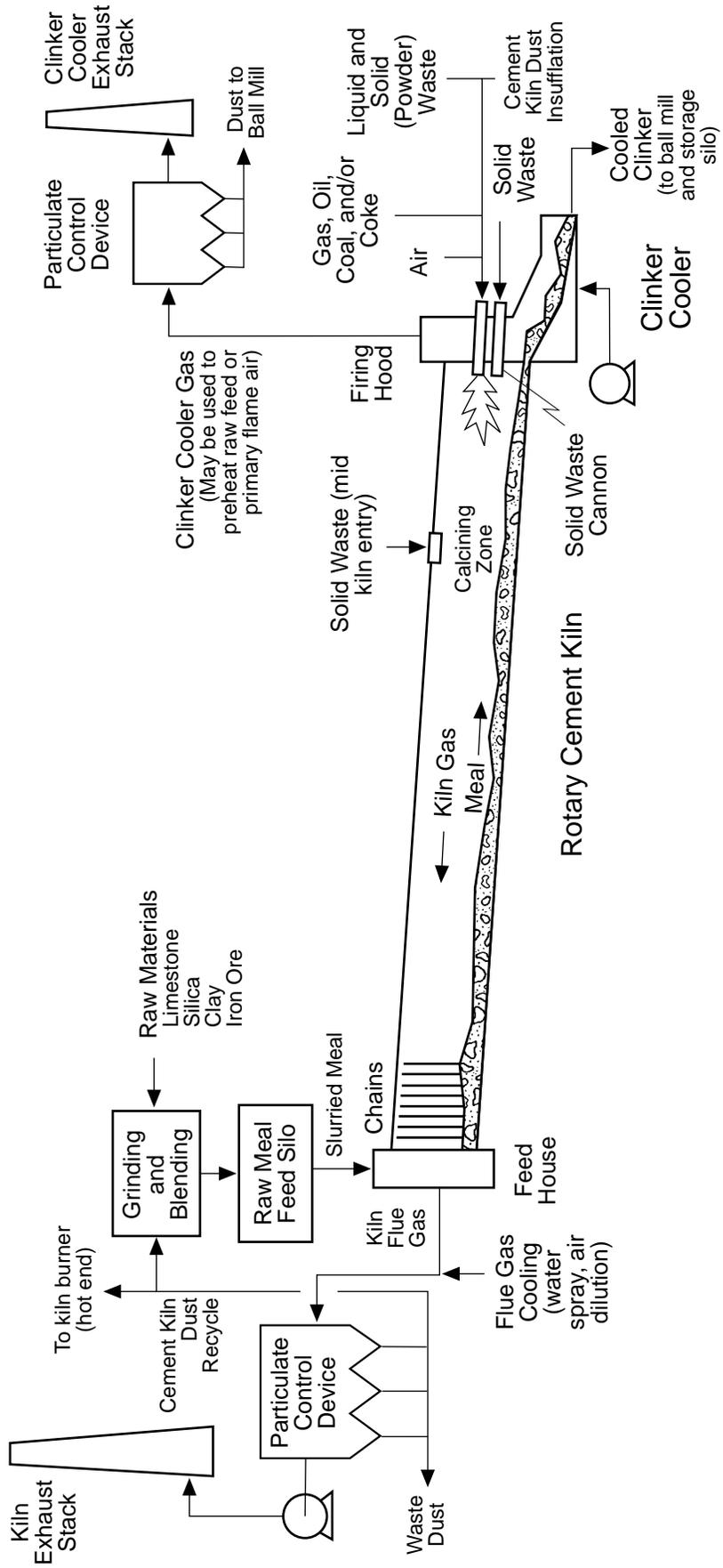


Figure 2-5. Wet cement kiln.

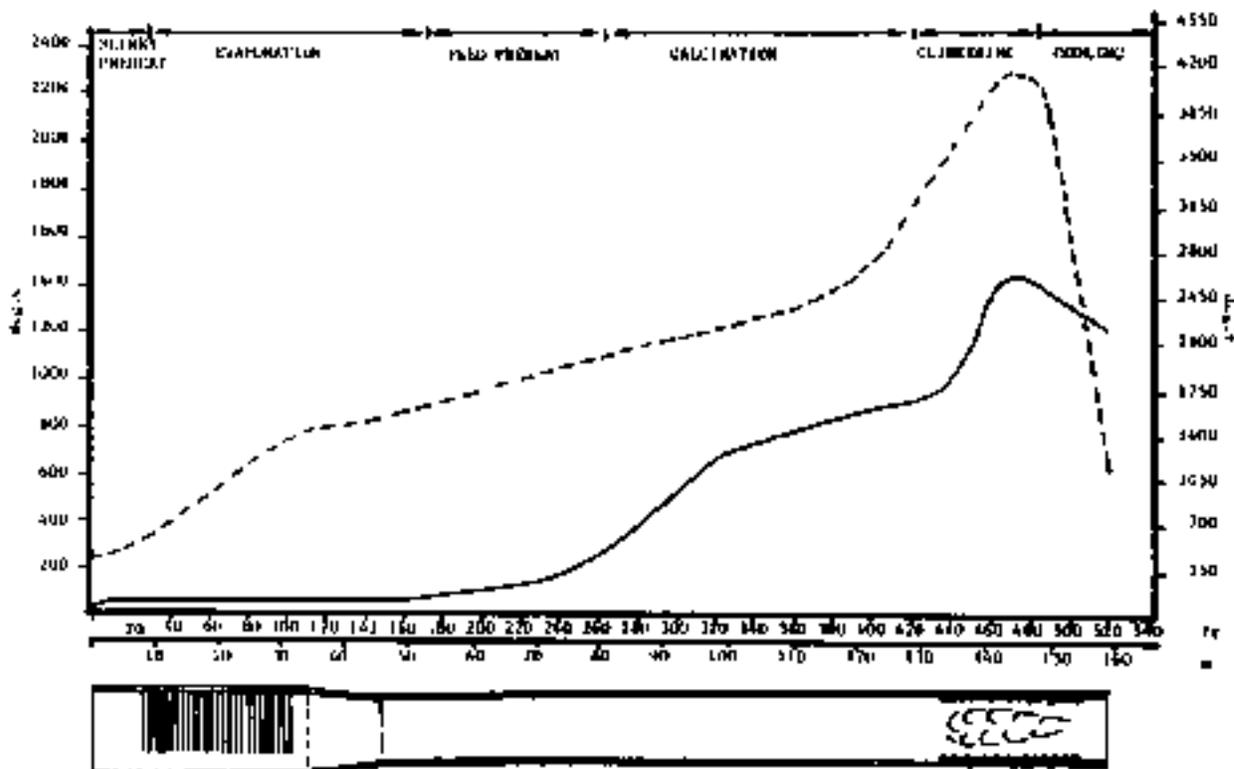


Figure 2-6. Typical gas (dashed line) and solids (solid line) temperature profiles for a long wet-process cement kiln.

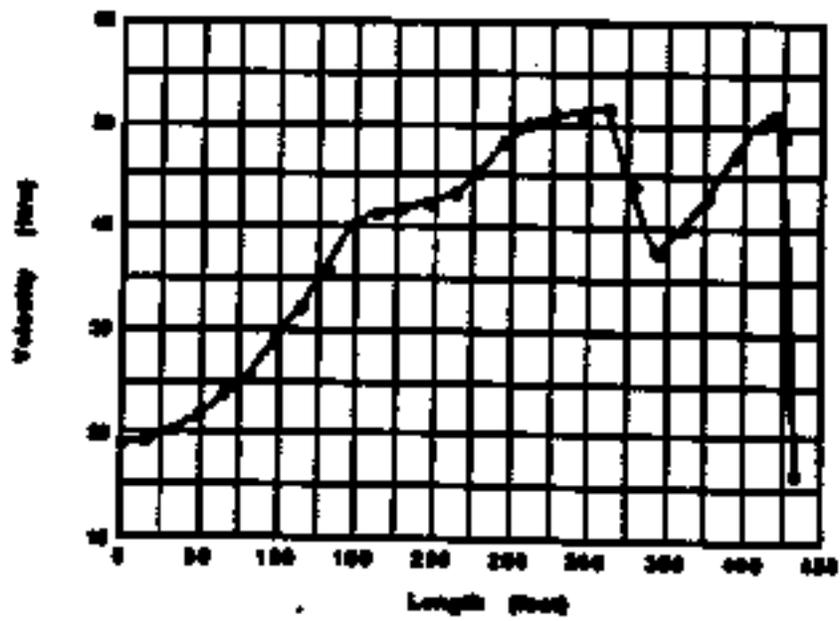


Figure 2-7. Typical gas velocities for a long wet-process cement kiln.

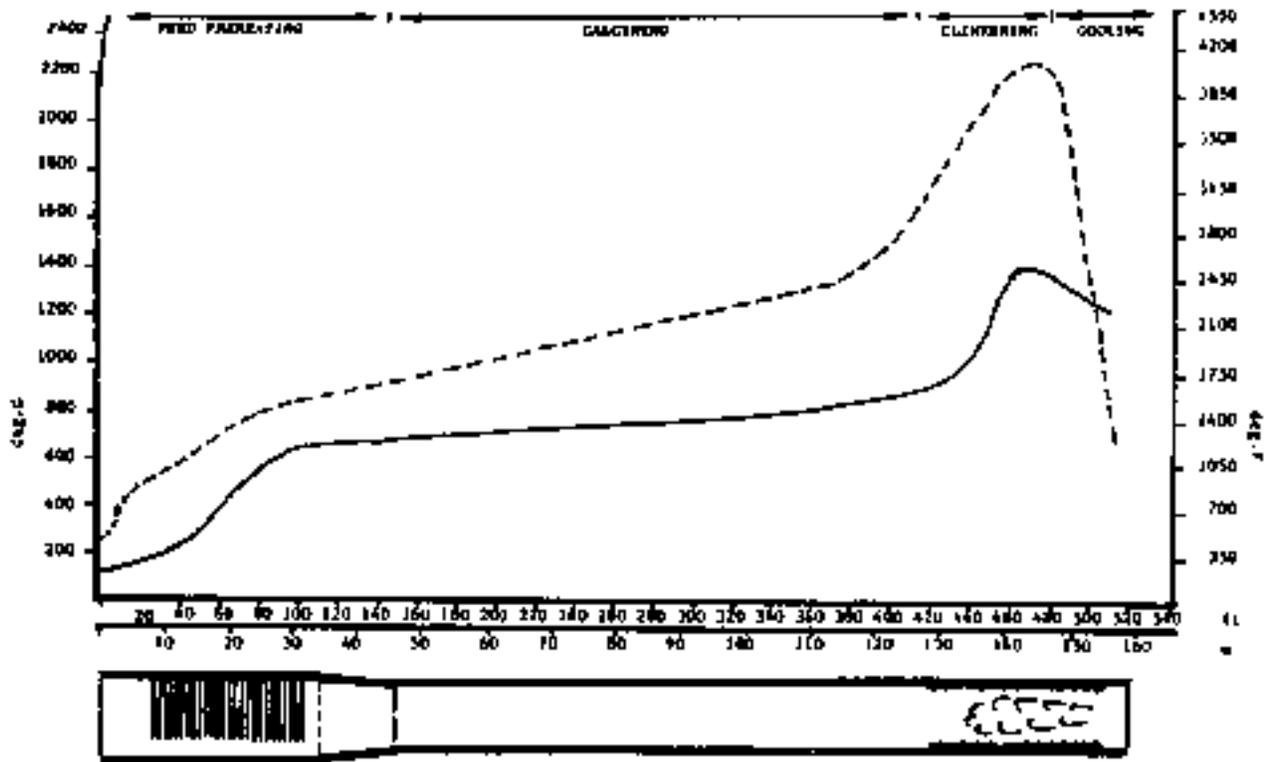


Figure 2-8. Dry kiln process material (solid line) and gas temperatures (dashed line).

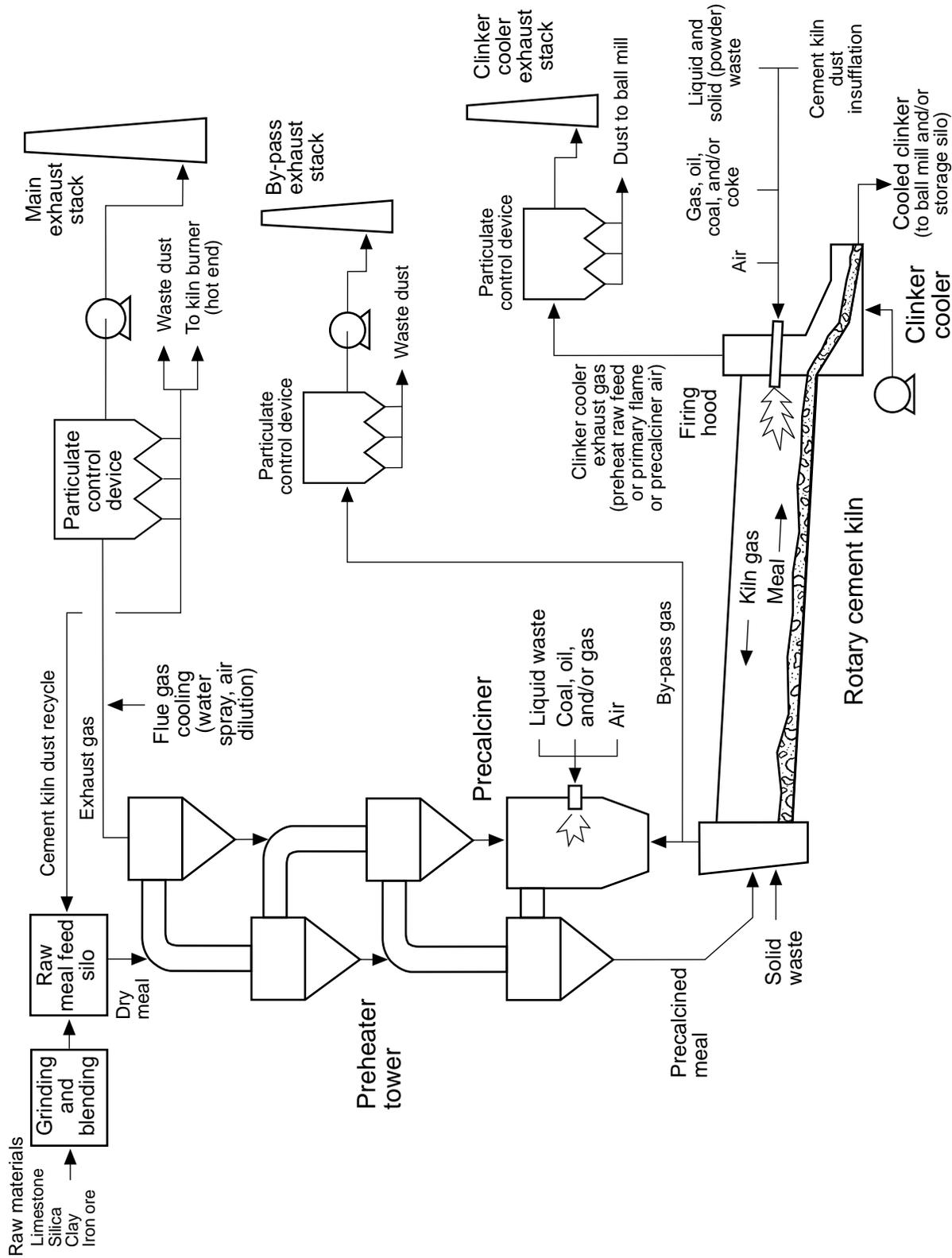


Figure 2-9. Dry preheater/precalciner cement kiln schematic.

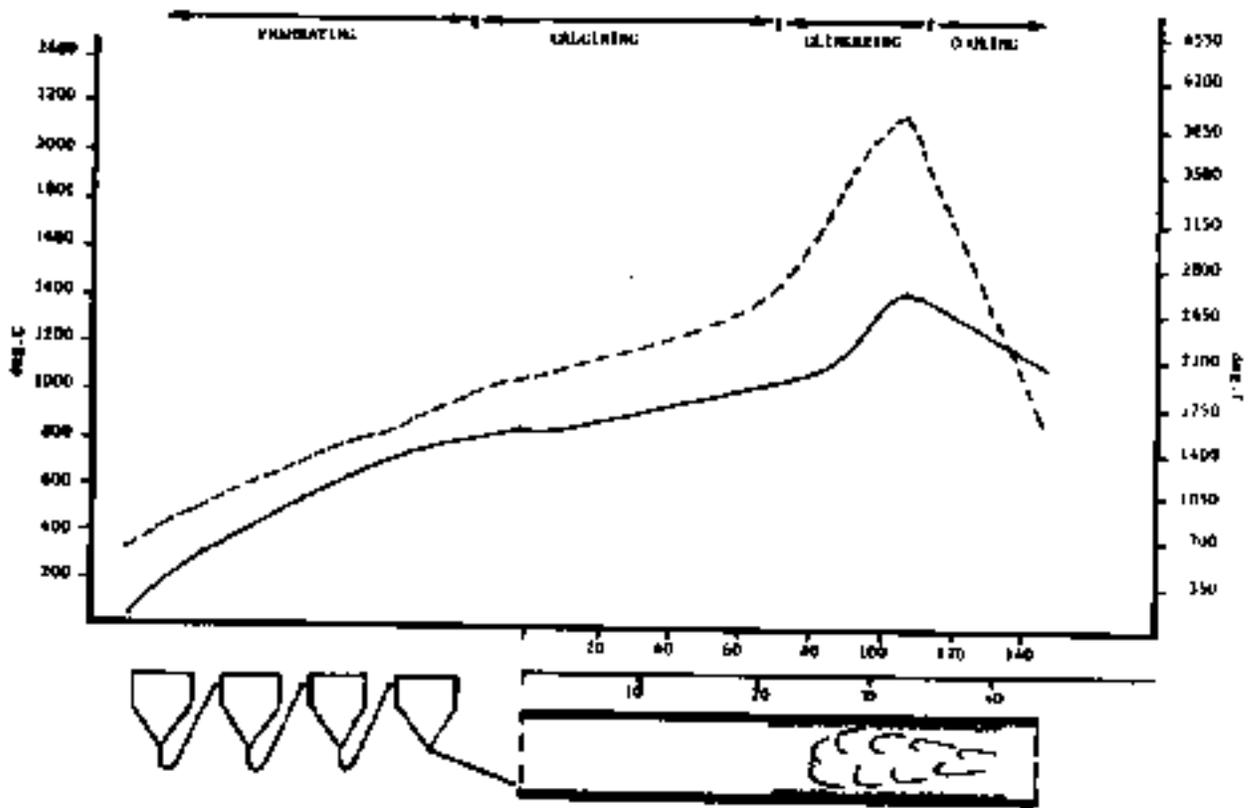


Figure 2-10. Typical gas (dashed line) and solids (solid line) temperature for a preheater cement kiln.

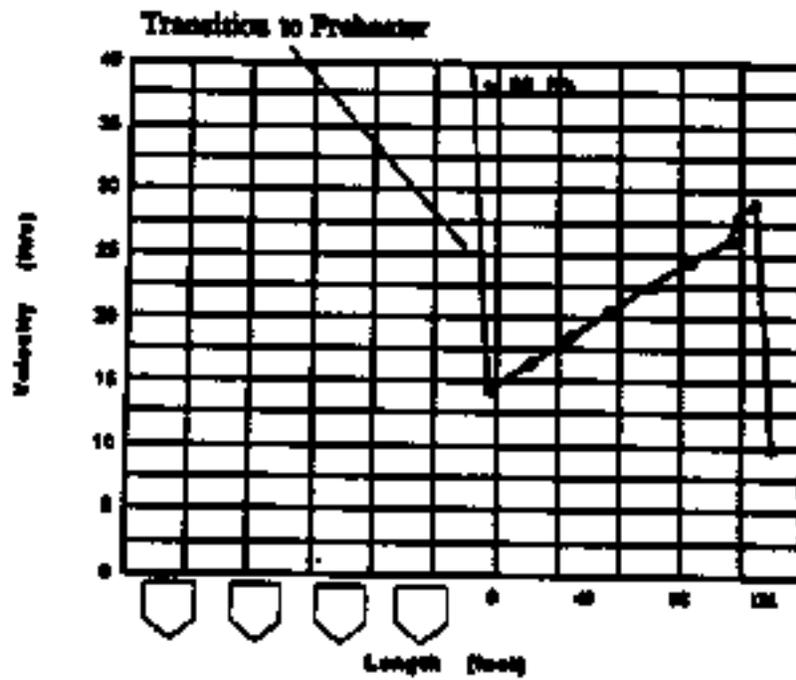


Figure 2-11. Typical gas velocities through a preheater cement kiln.

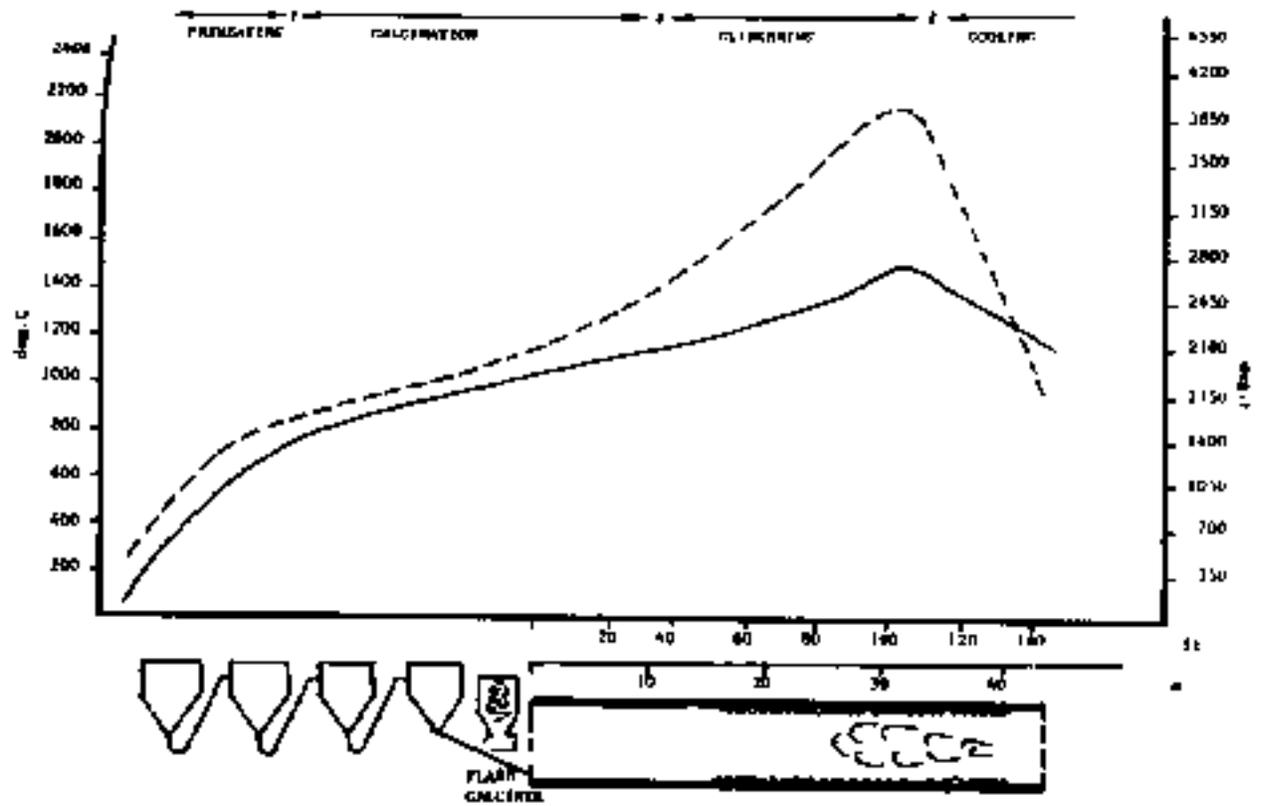


Figure 2-12. Typical gas (dashed line) and solids (solid line) temperature for a preheater/procalciner cement kiln.

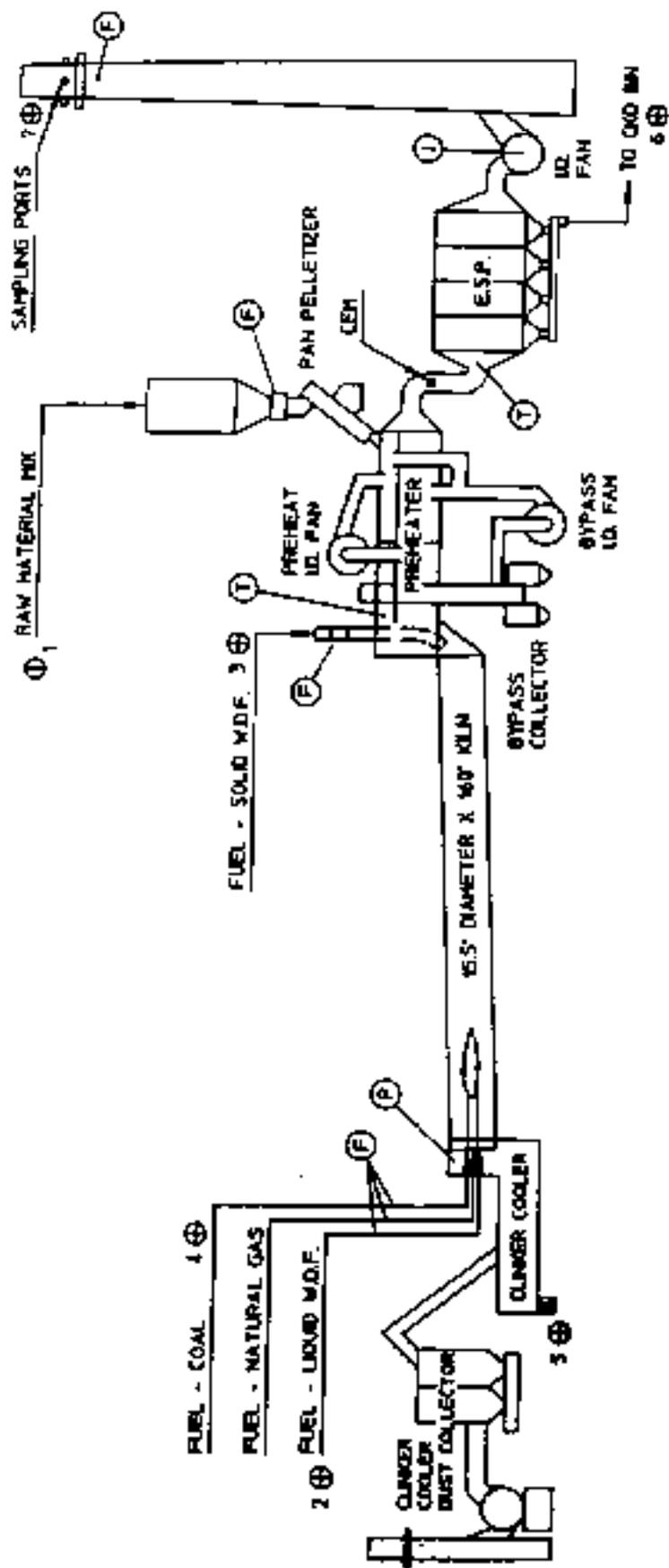


Figure 2-13. Semi-dry cement kiln schematic.

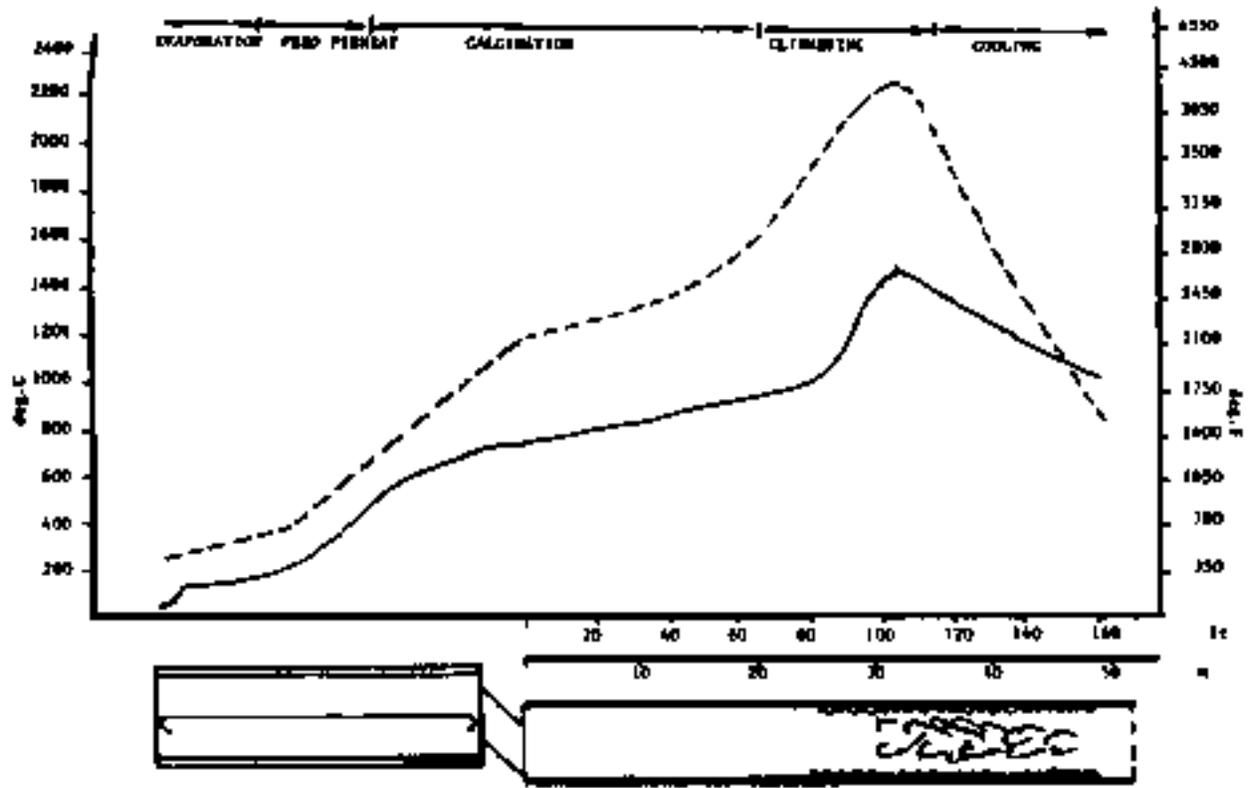


Figure 2-14. Secondary kiln material (solid line) and gas (dashed line) temperatures.

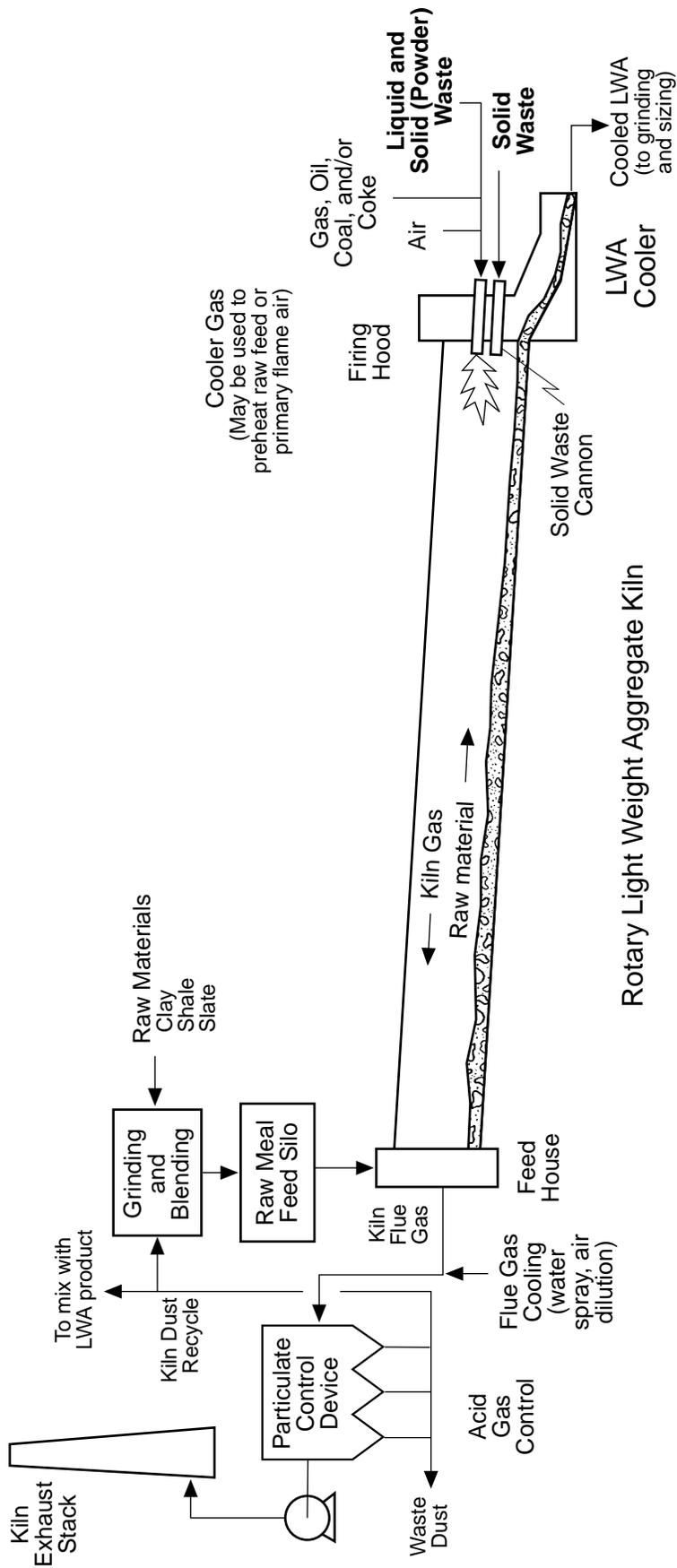


Figure 2-15. Light weight aggregate kiln.

SECTION 3

AIR POLLUTION CONTROL TECHNIQUES

The flue gas from hazardous waste burning incinerators, cement kilns, and light weight aggregate kilns can contain a variety of contaminants, including particulate matter, acid gases, metals (such as mercury, cadmium, lead, etc.), and trace organics. This section presents information on the design, performance, process monitoring requirements, and the necessary inspection and maintenance procedures for maintaining proper operation of common air pollution control devices designed for the removal of these contaminants from the flue gas.

As discussed in Section 2, cement kilns currently utilize electrostatic precipitators (ESP) and fabric filters (FF) for particulate (containing condensed metals and organics) control. Lightweight aggregate kilns utilize FFs (sometimes in combination with dry scrubbing and wet scrubbing) for acid gas and particulate control. Hazardous waste incinerators in the United States operate with a variety of different air pollution control systems, as discussed in more detail in Volume 3. These include:

- Dry scrubbing in combination with dry particulate control with FF or ESPs (“dry” air pollution control systems).
- FF or ESPs (dry PM control devices) followed by wet scrubbing (“wet/dry hybrid” air pollution control systems).
- Wet scrubbing systems for both PM and acid gas control, including various different combinations of wet scrubbers such as ionizing wet scrubbers, wet ESPs, venturi scrubbers, packed beds, and spray towers.

The following air pollution control techniques that are used on hazardous waste burning combustors are discussed:

- Cyclones — Used for coarse particulate removal.
- Fabric filters — Used for coarse and fine particulate removal.
- Electrostatic precipitators — Used for coarse and fine particulate removal.
- Venturi scrubbers — Used for both particulate and acid gas control.

- Wet scrubbers — Including ionizing wet scrubbers. Used primarily for acid gas control.
- Spray dryers and dry scrubbers — Used for acid gas control.
- Hybrid wet/dry scrubbing systems — Used for both acid gas and particulate control.
- Flue gas cooling — Includes techniques such as water quench, air dilution, or heat exchangers.
- Other metals control techniques — Including activated carbon used for metals and organics control, earth-based sorbents for semi-volatile metals control, and specific mercury control techniques including selenium coated filters, sodium sulfide injection, and mercury scrubbers.
- Catalytic oxidation — Used for organics control.
- Sulfur-based control — Used for organics control, in particular PCDD/PCDF.
- Air pollution control systems types — Discussion of typical intergrations of various individual air pollution control devices that are used, including “dry”, “wet”, and “hybrid wet/dry” scrubbing systems.

3.1 CYCLONES

Cyclones are typically incorporated as a pre-filtering process for removing large particles from the flue gas. Cyclones can operate at relatively high temperatures and function without moving parts, making operation simple. The cyclone chamber provides angular (swirling) gas flow which causes the suspended particles to accelerate toward the chamber walls. Particles, being denser than gas, separate from the gas stream and impact the cyclone chamber walls. The cyclones are erected vertically and the particles fall under gravity to the collection hopper.

3.1.1 Design Principles

The cyclone device is typically positioned immediately downstream of the primary combustion chamber. The cyclone’s service environment is dependent on its construction material. Cyclones can be constructed to withstand harsh environments such as extreme weather conditions and high temperatures since they have no moving parts.

The cyclone is typically a vertically erected conical or cylindrical shaped chamber which receives particle laden flue gas in the upper chamber region, as shown in Figure 3-1. The gas enters either tangentially or axially in a downward spiral path around the chamber walls. The spiralling motion causes the particles in the gas flow to accelerate to the chamber walls, where their momentum causes them to separate and fall out of the gas stream. The particles drop to the bottom of the cyclone by gravity and downward motion of the gas. The particles fall into the collection hoppers and are removed by an ash removal system. The cleaned gas still carries significant levels of fine particulate which remain suspended in the flow due to their airborne characteristics. The treated

gas reverses direction at the bottom of the chamber and returns up the center of the chamber and exits out the top.

3.1.2 Performance

Cyclone removal efficiency is dependent on the gas velocity, rate of change of gas direction, and the particle size distribution, density, and composition. The main limitation of the cyclone is the inability to effectively remove small particles less than 5 μm in diameter. For small particles, the inertial separating force (particle momentum) is low and the particles are more prone to remain suspended in the gas stream.

The removal efficiency of a cyclone can be improved by increasing the swirling velocity of the gas, which increases the inertial separating force or particle momentum. This is effectively accomplished by reducing the diameter of the cyclone chamber or increasing the gas flow rate. Cyclone performance is affected by gas flow rate, since this affects the swirling velocity in the cyclone. Cyclone efficiency is relatively insensitive to dust loading, and in fact, the efficiency can increase with higher loading due to particle interactions.

Cyclone efficiency is generally poor compared with the efficiency of electrostatic precipitators and fabric filters. Cyclone efficiency is less than 20% for sub-micron particulate. Efficiency varies linearly with particle size, typically ranging from 5% for 0.5 μm particles to 50% for 3 μm particles.

3.1.3 Process Monitoring

The pressure drop and inlet gas temperature are monitored to assure proper operation. The pressure drop is monitored so that any tendency of the cyclone to plug can be signaled by high pressure drop. Also, leaks and cracks in the cyclone can be detected by reduced pressure drop. Pressure drop is also a function of gas flow and may be used as an indicator of capture efficiency. Generally, efficiency increases with higher pressure (i.e., higher gas flow). Monitoring of the inlet gas temperature may be required, depending on the cyclone's application and construction material, to operate above the acid dew point and avoid corrosive conditions.

3.1.4 Inspection and Maintenance

Cyclones have minimal maintenance requirements due to the lack of moving parts. Cyclone wall corrosion, leakage, particle deposits and plugging should be regularly checked. Life expectancy of cyclones is long and is only limited by material corrosion, erosion and thermal stresses and cracking. Overall, the cyclone requires very little routine maintenance and off-line maintenance is not conducted in a hostile environment.

3.2 FABRIC FILTERS

Fabric filters (FF), also commonly known as baghouses, are used to remove gas suspended particles much like the filtration device on a common household vacuum cleaner. The fabric filter is utilized in relatively low temperature environments (around 350°F) but always above the dew point of water and common acid gases. The particle laden gas stream enters the FF chamber and

passes through vertically suspended filter bags. Particles in the flue gas are collected on the filters. Particle build-up is periodically removed from the filters by one of a variety of methods. The collected particles fall to a collection hopper situated below the filter bags. Fabric filter characteristics include:

- High capture efficiency (including fine particulate).
- Capture efficiency relatively independent of particle characteristics.
- Frequent routine maintenance is required.
- Monitoring, inspection, and maintenance is simple.

3.2.1 Design Principles

Fabric filters are used to remove suspended particles from flue gas by capturing the particles on the surface of a porous fabric. Particle laden gas enters the collection device and passes through an array of cylindrical filtering bags which retain the particles; and the clean gas exits through the outlet duct. The design of the FF system slows the gas velocity and evenly distributes the gas to all the filter bags. Particles collect on the filters and form a dust cake on the surface of the filters. As the dust layer builds, it becomes more difficult for particles to penetrate. This increases both the pressure drop across the filters and the collection of the particles. It is actually the dust cake which achieves the high efficiency collection of particulate. For this reason, unless the filters are preconditioned (i.e., an artificial filter cake is built-up) prior to operation, filter efficiency is lowest at start-up and immediately after the bags are cleaned.

Fabric filters are usually externally heated and/or insulated to ensure that the device remains above the minimum required operating temperature to prevent condensation which can plug and corrode the filter bags (typically greater than 250°F). This is especially important during start-up and shutdown operations, when temperatures are likely to drop below the gas dew point. A FF's maximum operating temperature is limited by the working temperature of the fabric. For many common filtering fabrics, the maximum operating temperature is below 500°F. Fabric filters are equipped with spark arresters upstream to prevent fugitive sparks and hot flyash from burning the filters.

Filters are most effective at collecting particles when coated with dust, however, too high a coating will create a high pressure drop across the filter. The pressure drop across the FF is an important parameter since it relates directly to energy cost for the induced draft fan. Typical differential pressures for FFs are 1 to 6" w.c.. The filters need to be cleaned periodically. When removing the dust build-up, it is important not to remove too much dust cake or else excessive dust leakage will occur while fresh cake develops. There are four principal types of cleaning systems: pulse jet, reverse gas, shaker, and sonic.

The pulse jet system utilizes high pressure air to clean the filters, as shown in Figure 3-2. The high pressure air inflates the bags, cracking the external dust cake. When the air is removed, the bags return to their original shape and the dust cakes drop into the collection hopper. Pulse jet systems can be cleaned while on-line, allowing continuous operation of the unit. Filters can be maintained from outside the collector, which allows the maintenance to be performed in a clean, safe environment. This vigorous cleaning technique tends to limit filter bag life.

In reverse air systems, the dirty gas enters the fabric filter and passes from the interior to the exterior of the bags, as shown in Figure 3-3. The FF must be divided into modules which are taken off-line during cleaning. Low pressure air is introduced from the exterior of the bags, collapsing the bags and cracking the interior dust cake which falls to the collection hopper. The cleaning is accomplished with relatively low air pressure, resulting in maximum bag life. This method is preferred for easily damaged fabrics.

Shaker systems, shown in Figure 3-4, move the tops of the bags in a circular path, causing a wave motion through the bag length. This causes the dust to crack and fall to the hopper. Bags must have high abrasion resistance for this cleaning technique. In addition, individual bags must be taken off-line for the cleaning process.

Sonic cleaning, if used, usually augments another cleaning method. Sonic energy is introduced into the filtering device. The sonic waves generate acceleration forces that tend to separate the dust from the fabric.

Fabrics used for the filter bags are usually woven with relatively large openings in excess of 50 μm in diameter. Fiber types include natural fibers such as cotton or wool (not often used), and synthetic fibers such as nylon, acrylic, Dacron, Teflon, Nomex, Polypropylene, Goretex, and fiberglass. The synthetic fibers are typically resistant to moisture and acid/alkali components in the flue gas, however they have limited operating temperatures, typically around 500°F. The fibers may be either woven or felted. Woven fibers have a definite pattern, while felted fibers are randomly compressed into a dense mat. Newly developed ceramic and metal fiber bags have improved temperature resistance (greater than 1000°F operations) and increased structural durability compared with conventional fabric media. The selection of the fiber bag material and construction is important to fabric filter performance. Deciding factors for fabric selection include:

- Temperature — Ability to withstand maximum continuous service temperature, and temperature surges. For typical fiberglass or teflon bags, the maximum rating is about 500°F. New ceramic fibers are being developed that are able to withstand a much higher temperature level.
- Corrosion resistance — Ability to resist degradation from acids, alkalis, solvents, or oxidizing agents.

- Hydrolysis — Ability to handle effects of humidity. High moisture can cause blinding of the fabric.
- Dimensional stability — Ability to tolerate shrinking and stretching fabric.
- Fabric mechanical strength — Ability to withstand the structural demands exerted on the fabric by the gas flow and cleaning system.

3.2.2 Performance

Fabric filters are very efficient at removal of particles of all sizes. Fabric filter collection is reported to be relatively independent of inlet mass loading. Three primary mechanisms are responsible for particulate capture on a relatively clean fabric: inertial impaction, direct interception, and Brownian diffusion. Both inertial impaction and direct interception are associated with relatively large particles, whereas Brownian diffusion is associated with smaller submicron particles. As discussed above, after a period of operation, a cake forms on the fabric surface, and “sieving” becomes a dominant collection mechanism. Sieving occurs when the particle is too large to pass through the surface cake which has built up on the fabric. Emissions of particulate through a fabric filter are due to particulate seepage through the dust cake and fabric, gas flow through gaps or tears in the fabric, and gas flow between gaps between the bags and the tubesheet. Due to these mechanisms, the particle size distribution of the particulate escaping the fabric filter has been shown to be similar to that in the inlet gas stream. Particle leakage through a fabric cake occurs due to the cake build up process:

- Individual particles strike edges of pores and form chains that bridge across the pores.
- As more and more pores become covered with cake, the gas velocity through the remaining pores increases significantly.
- The large gas velocity through the uncovered pores prevents the pores from being bridged.
- These uncovered pores become leakage points.

Fabric filter efficiencies typically range between 99 and 99.9% for particle sizes as low as 0.1 μm . Particle capture is relatively insensitive to particle and dust physical characteristics such as particle resistivity and dust loading. Efficiency is decreased as the air-to-cloth ratio increases as gas velocity rises. Air-to-cloth ratio is a ratio of the gas volume flow rate to the filter surface area and is a measure of the superficial gas velocity through the filter. Typical air-to-cloth ratios range from 3 to 5 acfm/ft², with lower air-to-cloth ratios of 2 acfm/ft² providing improved performance. Particle capture efficiency is also dependent on the frequency of bag cleaning, cake build-up, and fabric type and weave, as well as on the physical condition of the bags.

Factors which specifically affect the efficiency of a baghouse include:

- Holes and tears in the bag and fabric abrasion mainly due to too vigorous a cleaning cycle.

- Chemical attack of the fabric.
- Inadequate cake buildup.
- Thermal degradation of the bag fabric.
- Gas-to-cloth ratio (superficial flue gas velocity).
- Frequency of cleaning.
- Fabric specifications (i.e., fabric type and weave).

Fabric filter technology has made significant advances with the improvement in FF bag materials. As a result, FFs are quickly becoming a preferred APCD, especially since ash effluent is dry and does not require the handling and disposal processes of liquid waste. Recently developed techniques to improved fabric filter collection efficiency that have been demonstrated include:

- Use of electrostatically enhanced filters; shown to have higher collection efficiency, lower pressure drops, and lower lifetime costs compared with conventional units. This techniques is still in the design and development stage.
- Use of a fabric material made of polytetrafluoroethylene (PTFE) membrane. The PTFE has a smaller pore size compared with conventional felt fabrics, resulting in increased particulate matter collection. Levels below 0.001 gr/dscf have been demonstrated.
- Flue gas conditioning with ammonia and SO₃ has been shown to improve fabric filter collection efficiency by increasing particulate cohesivity which improves the pore bridging ability, leading to reduced direct particle penetration. It also enhances the ability of the particulate to remain in place once caught, reducing the indirect penetration losses.

3.2.3 Upgrade Options

Upgrades to improve FF performance may involve enlarging the device to achieve a higher air-to-cloth ratio and selecting improved filtering materials and pre-coating agents. Three options are available for improving the performance of fabric filters including:

- Replacing existing FF unit with larger unit to reduce air-to-cloth ratio.
- Adding to the existing FF a parallel FF and thereby reducing the air-to-cloth ratio.
- Upgrading the existing FF material to high performance filtering materials and the use of precoating agents. This option typically represents the least costly upgrade procedure.

3.2.4 Process Monitoring

Fabric filter operations are monitored by flue gas inlet temperature, gas flow rate, and pressure drop across the system. The baghouse temperature must be maintained above the acid condensation point in order to reduce corrosion and fabric wear. This is most important during system start-up and shutdown conditions. If acid deposition occurs after shutdown, the acid moisture will settle on the fabric and eventually leave behind a residue which may contribute to the brittleness of the bags and cause failure when put into operation again. An atypically high pressure drop can signify that

bags are binding or plugging, gas flow is excessive, or fabric cleaning is inadequate. Low pressure drop signifies possible filter holes and leakage, leakage between the bag and bag supports, or inadequate dust cake formation. The FF performance can be monitored with an opacity meter. Intermittent “puffing”, which is an indication of pinhole leaks in the filter bags, after cleaning, can be detected with opacity monitoring. Additionally, holes in bags can be detected using fluorescent powders. The powder is injected into the inlet of the fabric filter to inspect for leaks. Leaks are detected by inspection for the powder on the clean side of the bag using ultraviolet light.

3.2.5 Inspection and Maintenance

Fabric filters are relatively simple to operate and require minimal maintenance and repair. However, they require frequent routine inspection and maintenance. Several FF inspections and maintenance items are required on a daily and weekly basis. Filter bags require periodic inspection for correct tensioning and conditions such as tears, holes due to abrasion, and dust accumulation on the surface. The typical filter bag life is as much as 10 years using reverse air cleaning, but this can be reduced to 2 years for improperly operated systems. Filter bags are fragile and prone to hole formation if not handled carefully.

3.3 ELECTROSTATIC PRECIPITATORS

Electrostatic precipitators (ESPs) are common air pollution control devices which have been utilized for many years in both the United States and abroad. Electrostatic precipitators are generally efficient at removing fine particles from flue gas. Electrostatic precipitators are available in a variety of designs and can operate in a dry or wet mode and in hot or cold gas conditions. ESPs are known for the following characteristics:

- High capture efficiency.
- Lowest capture occurs with 0.1 to 1 μm particles.
- Extensive monitoring requirements.
- Automatic controls.
- Low routine maintenance.

ESPs have several advantages, but most significant is the high collection efficiency and low gas pressure drop.

3.3.1 Design Principles

Electrostatic precipitation is a process by which gas suspended particles are electrically charged and passed through an electric field which propels the charged particles towards collecting plates, as shown in Figure 3-5. The charged particles stick to the plates, and periodically a rapping (impact) mechanism dislodges the collected particles from the plates. The dislodged particles drop into the collection hopper for removal.

In the particle charging step, particles in the gas stream are charged by the development of a current of negative ions generated from a high-voltage corona discharge. The corona is established between an active electrode (usually a fine wire or plate of negative polarity) maintained at a high voltage, and a smooth cylindrical or plate electrode at ground potential. The corona ionizes the flue gas as it passes around the electrode, forming a large number of ions in the region near the electrode surface. Negative ions are attracted to the ground pipe or plate. Particles passing through the corona field are subjected to intense bombardment by the negative ions and become charged.

The negatively charged particles are electrically attracted to the grounded collection surface. The particle “migration velocity” toward the collection surface, which is influenced by the particle diameter, particle charge, and collecting field intensity, typically ranges from about 0.1 to 3 ft/sec.

Electrostatic precipitators can be found in both high and low temperature applications from the material temperature limits of 1300°F and down to the condensation point of flue gas constituents. Precipitators are commonly designed for either hot- or cold-side treatment. Hot-side precipitators have larger collecting plate areas and are constructed of suitable steels to handle continuous high temperature operation. The “cold-side” categorization refers to the ESPs operating at gas temperatures below 500°F.

The general configuration of an ESP is a wire (or rod) discharge electrode positioned at an equal distance between two collecting plates. The electrostatic precipitator casing houses many passages of parallel collecting plates with wires (or rods) suspended at regular intervals through the passage. The plates are further compartmentalized into fields, with each field typically energized by its own set of power supplies. A negative high-voltage direct-current power is applied to the discharge electrodes, and the collecting plates are grounded. The high-voltage direct-current power produces a corona in the wire-to-plate spacing by ionizing the gas. The corona then creates an avalanche of negative ions traveling from the negative discharge electrode to the grounded collecting plates. Suspended particles passing through the wire-to-plate spacing are bombarded by negative ions and become charged. The high voltage electricity produces an electric field between the wire and the plate which provides the electromotive force to attract the charged particles to the collecting plates.

Electrostatic precipitators can be classified into three types: tubular, wire-to-plate, and flat plate. A wire-to-plate type ESP is shown in Figure 3-6. It consists of parallel plates of sheet metal collection surfaces with wire electrodes hanging between the plates. Flat plate ESPs, as shown in Figure 3-7, differ from wire-to-plate types in that the electrodes consist of flat plates rather than wired. The plates increase the electric field used to collect the particles, and provide increased surface collection area. However, a flat plate ESP operates with little or no corona, which leads to large rapping losses, especially if the flue gas velocity is high. The tubular type, shown in Figure 3-8, consists of an array of tubes, round or multi-sided, which act as the collection surface, with a discharge electrode located in the center of each tube.

Also, there are two typical arrangements of the electrodes used in the ESP: single-stage or two-stage, as shown in Figure 3-6. In the single stage arrangement, the discharge and collecting electrodes are located in the same chamber. In the two stage arrangement, the discharge electrodes

are placed in the first chamber, where particulate charging is accomplished. Collection electrodes are placed in a second chamber located downstream of the first chamber. Particles are removed from the gas in the second chamber.

The following process characteristics dictate the specific ESP design:

- Gas volume flow rate.
- Particle loading.
- Gas temperature.
- Particle size distribution.
- Particle composition.

To accommodate these process characteristics, the following physical and electrical characteristics of an ESP may be varied:

- Number of fields.
- Number of passages per field.
- Wire-to-plate spacing.
- Collection plate surface area.
- Wire (or rod) diameter.
- Aspect ratio (length to height).
- Maximum secondary voltage.
- Maximum secondary current.
- Number of sparks per minute.

The charged particles which accumulate on the collecting surfaces must be periodically dislodged. Dislodging the collected particle layer is accomplished in several ways using either mechanical rapping devices or water for wet ESPs as discussed in a following section. Typically, dry electrostatic precipitators utilize mechanical rapping devices which strike the collecting plates and dislodge the particles. Rappers are classified into two categories:

- Impulse types which produce an impact or hammer blow. A magnetic system provides controlled blows (essentially continuous rapping) which eliminates rapping puffs characteristic of intermittent rapping systems. Impulse rappers are most useful for cleaning collecting plates.
- Vibrator types which produce a continuous vibration for some duration. These are usually operated intermittently. They are usually used for corona-electrode cleaning.

The particles fall into the collection hoppers and are removed for disposal. Cleaning of the ESP collecting plates is critical because collected particles may be lost by reentrainment into the gas stream while still inside the precipitator.

Newly designed ESPs have larger wire-to-plate spacings and use rigid rod discharge electrodes instead of wire. The newer ESPs are capable of operating at higher voltage, which increases the electric field strength and the subsequent particle capture. Many ESPs are equipped

with advanced controlled power supplies which monitor electrical condition and maximize performance while minimizing power consumption. Advanced control units provide features such as intermittent energization and spark rate control. Intermittent energization switches off power repeatably for extremely short durations and maintains ESP performance while minimizing power consumption. Spark rate is important in the electrical operation. Sparking is a phenomenon which occurs because an ionized discharge to the collecting surface resembles an electrical arc. Excessive sparking will reduce the applied voltage and waste power; insufficient sparking may indicate that the ESP is not operating near its full potential. With automatic controls, a desired spark rate can be specified and will automatically be monitored and maintained.

3.3.2 Performance

Operating efficiency of the ESP increases with increasing plate area, increasing voltage and decreasing gas flow rate. Capture efficiency is dependent on:

- Specific collection area (SCA).
- Operating voltage.
- Particle characteristics.

The precipitator's size is measured in terms of specific collection area (SCA), which is the ratio of collection surface area to gas volume flow rate. Older ESP designs have specific collection areas (SCAs) which are typically under 300 ft²/kacfm with a plate-to-plate spacing of about 9 inches. The newer designs incorporate wider plate-to-plate spacings with rigid rod discharge electrodes replacing weighted wire type electrodes. The newer ESPs have state-of-the-art microprocessor power controls, and the geometry permits higher voltage potentials. The particle collection is also subsequently improved.

Electrostatic precipitators are least efficient at capturing particles in the 0.1 to 1 μm diameter size range; however, when designed and operated properly, the ESP is still capable of excellent collection of particles in this size range. Electrostatic precipitators capture submicron particulate with approximately 90 to 95% efficiency. From the efficiency on submicron particles, the efficiency increases linearly to 99.9% for particles of 5 μm. Operation is sensitive to fluctuations in gas flows, temperature, particulate and gas composition, and particle loadings. This is because the electrostatic precipitator's effectiveness is strongly influenced by the resistivity of the particles in the gas stream.

The ESP is very efficient at capturing particles of all sizes, however, it is not efficient at capturing particles that have either high or low resistivities. Resistivity is a measure of the resistance of the particulate matter to being charged and is a function of particle composition and gas temperature. Particles with high resistivity (greater than 2x10¹¹ ohm-cm) are difficult to charge and collect. Also, once collected, they do not readily give up charge to the collector plate and tend to build up on the electrode. The ion current generated by the electrodes must pass through the particle layer before reaching the grounded plate. The current gives rise to an electric field in the layer, and when the dust layer builds, can become large enough to cause sparking, known as "back corona." When sparking occurs the electrical power input to the ESP must be reduced. The reduction limits the collection efficiency of the process. Low resistivity particles (less than 2x10⁸ ohm-cm)

can also be a problem. At this resistivity, particles are easily charged and collected, but the low resistivity will cause the collected particles to give up their charge to the collector plate and easily become re-entrained in the flue gas. Particles with resistivities between 2×10^8 and 2×10^{11} ohm-cm are most efficiently collected. Parameters which influence particle resistivity include mineral composition, density, and flue gas temperatures, moisture, and sulfur content. Resistivity increases with increasing temperature and decreasing moisture and sulfur content. Effective acid gas removal upstream of the ESP results in an increase in resistivity and a corresponding decrease in ESP efficiency. Resistivity can be reduced by adding a conditioning agent such as sulfur trioxide, ammonia, or water vapor to the flow.

Other factors which may adversely affect ESP performance include:

- Flyby of the particle due to exceptionally high operating flow rates in which the particle travels past the collection plates with enough speed so as not to be affected by the charged field.
- Misalignment of the electrodes and collectors plates.
- Dust buildup on the electrodes or collection plates.
- Erosion or corrosion of the collection plates.
- Leakage of scrubber liquid when pH is too high (wet ESPs only).
- Re-entrainment occurring from redispersion of collected particles during rapping of the electrodes, seepage of collected dust from the hoppers, and direct scouring of collecting electrode surfaces by the gas streams.
- Undersized equipment.
- Presence of “back corona”, as discussed above, which is due to particle buildup on the collection plates.

Within the last 2 to 3 years, manufacturers (for example BHA/Precipitech in Kansas, MO) have developed advanced PC-based ESP controllers which regulate ESP control to improve power delivery. The advanced controllers are limited to the same peak power, however, the controllers are capable of managing power delivery and avoiding slow power ramping, such that over time a higher average power through put is achieved. In addition, these “smart” ESP controllers can incorporate a PM setpoint and use data from an opacity type meter to provide feedback to control PM emissions directly. In addition, these controllers can be readily modem linked to allow remote ESP performance monitoring, potentially reducing maintenance costs. Purchase costs estimates for these type controllers are on the order of \$70,000.

3.3.3 Upgrade Options

ESP retrofit upgrade enhancement options include:

- Rapping — Improve rapping cycle frequency and procedures to minimize PM reentrainment during rapping.
- Electrical power control system — As discussed above, the addition of advanced controlled power system which monitors the electrical field condition can significantly improve ESP performance. Systems may include “intermittent energization”, “pulse energization”, and spark rate control systems. Intermittent energization acts to rapidly shut off and on the electric power to the ESP for short durations. This cycling limits the available time for detrimental back corona to form. Spark rate control optimizes the operating voltage to as high as possible for more efficient particle capture. Pulse energization consists of superimposing narrow high voltage pulses onto a base DC voltage as a way of overcoming high resistivity particle problems.
- Geometry — Modification of internal plate and electrode geometry to increase plate to electrode spacing, allowing for high voltage potentials and increased PM capture.
- Flue gas conditioning — Addition of water into the flue gas will act to lower the gas volume flowrate and gas temperature, reducing particle resistivity and increasing particle collection. Also, reagents such as sulfur trioxide or ammonia may be injected into the flue gas to condition particles for lower resistivity.
- Gas distribution — Improve flue gas distribution so as to provide a uniform velocity distribution to all sections of the ESP. Acts to minimize particle reentrainment and gas leakage, and reduces local occurrences of high flue gas velocities where PM capture may be low due to low particle residence time. This may be accomplished with the use of flow straighteners such as screens and turning vanes.
- Specific collection area — An increase in the size of the ESP, usually done by making the existing unit taller, acting to reduce the gas velocity, increase particle residence time, thus increasing the capture efficiency.

Note that specific retrofit procedures which are most applicable to a given facility must be chosen on a case-by-case basis, depending on the current condition of the existing facility.

3.3.4 Process Monitoring

To assure proper operation, the inlet gas temperature, flue gas flow rate and electrical conditions are monitored. On-line electrostatic precipitator performance is typically monitored with an opacity meter, however, continuous and reliable monitoring of electrostatic precipitator performance is difficult. An electrostatic precipitator’s performance is sensitive to flow rate, particle

composition and temperature, and the electrostatic precipitator's response to these parameters is relatively slow.

Temperature has a direct effect on particle resistivity, and therefore electrostatic precipitators must be operated within the designed temperature range. For cold-side ESPs, the temperature range is limited to temperatures above the condensation point and below the electrostatic precipitator's material limit usually specified by the manufacturer. For hot-side electrostatic precipitators, high temperature is preferred within the maximum operating range specified by the manufacturer. Particle resistivity peaks at around 400°F and is lowest at high and low temperature.

The electrical conditions do depend on the type of ESP. For the conventional cold-side wire-to-plate ESP, the voltage will range from 25 to 50 kV with even higher voltage for wider wireto-plate designed electrostatic precipitators. Spark rate is often optimized on site but is generally between 50 and 150 sparks per minute. The higher the secondary current the better. Secondary current may be quenched by excessive particle loading. The secondary current density, which is the secondary current divided by the collecting plate surface area, is often less than 100 nA/cm². The secondary current density can be calculated for each field by dividing the field secondary current by the plate surface area in that field. Generally, the first fields have the lowest current density because a significant percentage of the current goes into charging the particles which are captured in fields downstream.

To summarize, the following monitoring activities are required for optimum ESP operation:

- Inlet gas temperature.
- Gas flow rate.
- Electrical conditions.
- Rapper intensity.
- Hopper ash level.

3.3.5 Inspection and Maintenance

Maintenance is required for cleaning carbon deposits on plates which can cause short circuits, corrosion of plates, and erosion of electrodes. Electrostatic precipitators are fairly sophisticated devices requiring automatic controls for rectifier equipment, measurements systems for rapper intensity, hopper dust level, and metering systems of gas process variables such as gas flow and temperature. Because of this complexity, highly trained maintenance personnel are required. However, routine maintenance requirements for electrostatic precipitators are low compared with fabric filters. The frequency of inspections and maintenance are typically monthly for external systems such as power supplies, monitors, etc., and annually for internal systems such as electrode conditions, electrical connections, etc. Internal inspections and maintenance are conducted in hostile environments due to the potential mechanical and electrical energy of the electrostatic precipitator. Annual inspections of the following are necessary: electrode alignment; electrode pitting; ash build-ups; ash hardening; hopper performance; electrode insulation; and rapper operations. To summarize, the following inspection and maintenance activities are required for optimum ESP operation:

- Highly trained personnel.
- Low routine maintenance.
- Inspection of electrode misalignment, pitting, ash build-up, ash hardening, hopper blockage, electrode insulation cracks, and rapping performance.

3.3.6 Wet Electrostatic Precipitators

Wet electrostatic precipitators, shown in Figure 3-9, utilize water to rinse the collected particle layer off the collecting surface. Wet ESPs must be operated at or below the adiabatic saturation temperature of the irrigating fluid (water) so that the fluid is not evaporated. There are several types of wet ESPs, depending on the irrigation method:

- Self irrigating — Captured droplets wet the collecting surface.
- Spray irrigation — Spray nozzles continuously irrigate the collecting surface.
- Intermittently flushed irrigation — The ESP operates as a dry precipitator with periodic rinsing to replace rapping.
- Film irrigation — A continuous liquid film flushes the collecting surface.

The wet electrostatic precipitator is used effectively in the following conditions:

- After flue gas has been through a wet scrubber.
- Low gas temperature and high moisture content.
- High sub-micron particle concentration.
- Liquid particle collection.
- For handling dust wet.

3.4 VENTURI SCRUBBERS

Venturi scrubbers are a commonly used for particulate and acid gas control on hazardous waste incinerators.

3.4.1 Design Principles

The conventional venturi scrubber consists of a converging section, a throat section (either rectangular or circular), and an expansion section, as shown in Figure 3-10. An alkaline recirculating liquid is usually injected at an angle, in one or more streams, into the throat section or just upstream. The engineering principle, as shown in Figure 3-11, is to accelerate the gas to a high velocity in the throat section, causing atomization of the liquid. In some cases, however, spray nozzles are used to atomize the liquid. The solution droplets are then accelerated to their terminal velocity. These droplets provide a large surface area for collection of fine particles and are many times larger than the particles in the flue gas. The particles are captured when they collide with the slower moving droplets. As the mixture decelerates in the expanding section, further impaction occurs and causes

the droplets to agglomerate. Particle capture is primarily related to the amount of liquid atomization achieved, which is proportional to the pressure drop (gas velocity) across the device.

Once the particles have been trapped by the liquid, a separator (e.g., cyclone, demister, swirl vanes) is used to remove the liquid from the cleaned gas. Mist eliminators consist of a mesh of fine wire or wave plates. They provide a large area of collection surface area while maintaining a high void space. Their use minimizes the risk of blockage by entrained solid particles and moisture in potential downstream operations.

The most prominent feature of the venturi design is a converging throat section which causes acceleration of the flue gas flow. The scrubbing slurry is introduced at the inlet of the throat and is sheared into fine droplets by the high velocity flue gas stream. A turbulent zone downstream of the throat promotes thorough mixing of the gas and slurry droplets. As the droplets slow down through the diverging section, they collide and agglomerate and are separated from the cleaned gas stream by gravity as the gas passes on to the stack.

Venturi scrubbers use one of two approaches: wetted or non-wetted, as shown in Figures 3-10 and 3-12. When the gas entering the venturi is not at saturated conditions, the wetted approach is used. In this approach, a protective film of liquid is established on the convergent portion of the venturi. This liquid is introduced upstream of the throat and flows down the converging sides into the throat, where it is atomized. The gas is cooled by evaporation and reaches the throat at near saturation conditions. When inlet gases are hot and a significant amount of liquid needs to be evaporated, the wetted approach is preferred. The non-wetted approach is restricted to gases with subsaturation temperatures entering the throat. If the hot gases enter the throat, they will vaporize the water droplets and reduce the device's ability to capture particles.

Scrubbers work best when the flue gas entering the scrubber is fully saturated with water so that none of the injected water droplets tend to evaporate. Evaporation produces a flux of water vapor out from the surface of the target droplets that inhibits the capture of smaller flue gas particles. If the liquid is cooled to a temperature below the gas temperature, the capture of small particles will be enhanced. This occurs due to condensation of water vapor from the flue gas onto the target droplets coupled with the tendency of particles to migrate toward and collect on cool surfaces.

3.4.2 Innovative High-Energy Scrubbers

3.4.2.1 Flux force/Condensation/Collision

Flux force/condensation/collisions scrubbers are a variation on the venturi type scrubber. The Calvert Collision Scrubber (CCS), shown in Figure 3-13, is an example of this type of scrubber. Initially, the flue gas is quenched with cooled scrubber water. Gases entering the scrubber are split into two streams which are directed to separate venturi throats where scrubber liquid is injected into the gas stream. The discharged gas/liquid streams from the two venturis are directed toward each other, causing them to collide at a high relative velocity. The head-on collision of the streams causes the droplets to shear into fine droplets, thus improving the efficiency of the device. Mist eliminator is used to remove entrained droplets. Through the use of cooled scrubber liquid, a "flux force condensation" technique is utilized. Flux force condensation is based upon the principle that

when a gas stream is saturated with water and then cooled, a portion of the moisture will condense, and the fine particles in the gas stream serve as condensation nuclei. As moisture condenses on the particles, they grow in mass and are more easily collected by conventional impaction. Therefore, the condensation enhances the scrubbing system's collection of fine particles, acid gases and metals.

3.4.2.2 Free-Jet

Free jet scrubbers have the same basic configuration of venturi type scrubbers (i.e., quench, scrubber, and moisture separator). Figure 3-14 shows several types of free jet scrubbing systems. The energy for moving the gases through the system and cleaning the gases is provided by the injection of a compressible fluid (typically steam or air) from a supersonic ejector nozzle which is located inside the flue gas duct. The amount of fluid added through the ejector is proportional to the mass of gas flowing through the system. The turndown capacity of the system is high because the ejector supplies the energy required to move the gases through the system. At the exit of the ejector nozzle, water is injected into the high velocity flow. The velocity of the steam or air breaks the water into small droplets. The flue gas and ejector fluid mixture then passes through a subsonic nozzle in which additional water spray is injected. Finally, the gas passes into an expansion section where free jet mixing takes place, aiding in further particulate agglomeration and capture. The primary advantage is improved capture efficiency compared with conventional venturi scrubbers and lower total energy requirements. Disadvantages include the potential need for on-site steam supply for the ejector driven systems.

3.4.2.3 Rotary Atomizing

In rotary atomizing scrubbers, the flue gas is saturated and passed through a "curtain" of liquid droplets, generated by a rotary atomizer disk. Rotary atomizer spins at speeds above 10000 rotations per minute, creating the droplet curtain. Advantages include efficient collection of submicron particulate compared to venturi type scrubbers and independence on the flue gas flow rate. Disadvantages temperature limitations of rotary mechanical equipment and lack of operating experience.

3.4.2.4 Rotor Filter

Flue gas passes through two rotors, each made up of five counter-rotating wheels and driven by a separate electrical motor (Valenti, 1993). The wheels project V-shaped airfoil-type spokes that generate vacuum and centrifugal forces when they are in rotation. Particulates are mechanically removed from the flue gas by the centrifugal force of rotation, which will funnel them into the cape, or wall of the Rotor Filter. The leading edge of the spoke causes the particles to conglomerate into larger particles, which facilitates their removal. Additionally, it has been shown to remove gaseous pollutants such as sulfur oxides by conglomeration. Rotor filters have been shown to achieve performance levels of 0.0067 gr/dscf on a medical waste incinerator.

3.4.2.5 Electrodynamic Venturi

The Electrodynamic Venturi (EDV) concept involves a series of steps consisting of saturation, expansion, condensation, ionization, and filtration (Pilney et al., 1993; Foisy and Karell, 1993). The flue gas is saturated in a water spray tower and passed into an “Agglo-filtering Module” in which the gas is expanded; expansion of a gas saturated with water vapor produces a state of supersaturation. Particulate matter act as condensation nuclei and a film of water is formed on the surface of the particulate. The supersaturation gas then enters an “Electro-filtering Module”; a high voltage electrode is mounted on the axial centerline of the module to charge the wetted dust particles and droplets prior to filtration. In the final stage, the flue gas containing the ionized encapsulated particulate is passed through a curtain of positively charge water droplets. Particulate matter is removed by impaction with the water droplets, which is boosted by the electrostatic attraction effect. EDVs have been shown to achieve performance levels of 0.005 gr/dscf.

3.4.3 Performance

To obtain a high collection efficiency, the flue gas throat velocity must be maintained at a specified level. Approaches that can be used to adjust for varying flue gas flow conditions include:

- Variable throat geometries with adjustable throat inserts (shown in Figure 3-15).
- Adjustable butterfly valves, dampers, or baffles in the throat region (shown in Figure 3-15).
- Adjustment of the elbow area in the throat section. Most scrubbers have a “flooded elbow” which helps collect entrained droplets before exiting the venturi.

The liquid surface tension and liquid turbidity are important to capture efficiency. If the surface tension is too high, small particles will “bounce” off the water droplets. High surface tension also has an adverse effect on droplet formation. High liquid turbidity will cause erosion and abrasion of the venturi section.

High pressure differential venturi scrubbers achieve higher particle removal, however, capture of submicron particles is still relatively inefficient. High pressure differential venturi scrubbers, also known as high energy scrubbers, are often equipped with variable throats for tuning the capture performance and minimizing pressure drop. The high pressure differential is costly in terms of electrical power requirements and is impractical for larger units.

The capture efficiency of venturi-type scrubbers is affected by the following:

- Inadequate scrubber liquid feed due to erosion and corrosion of the scrubber liquid transport system.

- Erosion of the venturi wall dimensions.
- Erratic pressure drops due to changes in the gas flow rate.
- Scaling of internal parts.
- High temperatures resulting in atomized scrubber liquid droplets evaporation.

Advantages to the use of venturi scrubbers include:

- Secondary capture of acid gases.
- Performance is independent of the chemical and physical properties of the particles.
- Can handle high humidity flue gas streams.
- Operates at low temperature thus increasing the change of condensing and capturing volatile metals and organic constituents.

Disadvantages to the use of venturi scrubbers includes:

- Steam plume visibility. Flue gas heating may be required to eliminate the steam plume.
- Generation of secondary liquid waste stream. The particulate matter collected in a venturi is wet. This may be advantageous since it minimizes the potential for particulate blow-off during handling and disposal. However, it creates a secondary liquid waste stream with an increased volume compared to dry collection techniques.

3.4.4 Process Monitoring

The essential parameters which should be monitored for optimum venturi scrubber performance include:

- Scrubber blowdown frequency.
- Scrubber water suspended solids.
- Liquid pH.
- Gas inlet temperatures.
- Pressure drop across the venturi.
- Gas flow rate.
- Liquid feed rate.
- Liquid-to-gas ratio.

The scrubber operation is monitored by liquid spray rate, gas flow rate, liquid pH, scrubber blowdown rate and inlet gas temperature. The pressure drop is a good indication of system

performance (particle capture efficiency). The pressure drop is usually controlled with a variable venturi throat. A pH monitor is used to measure the scrubber liquid pH in order to control the amount of caustic material added to the scrubber sump. A low scrubber liquor pH will cause corrosion, while a high pH will cause scaling.

3.4.5 Inspection and Maintenance

Maintenance concerns include prevention of corrosion and scaling on all scrubber internal surfaces, excessive dust build-up, nozzle damage (abrasion/erosion), plugging and fluid leakage. However, because the venturi is self cleaning, it has high resistance to fouling. Visual inspection is usually required for the throat, nozzles and liquid pump. Venturi scrubbers are often applied to hazardous waste incinerator facilities since they are easily operated and integrated with acid gas control technologies. A more detailed discussion of the inspection and maintenance of all types of wet scrubbers is included in Section 3.5.4.

3.5 WET SCRUBBERS

Wet scrubbers appear in a variety of configurations with widely variable efficiencies for controlling acid gas and particulate emissions. Wet scrubbers are used for the simultaneous removal of soluble gaseous pollutants and particulates. The majority of hazardous waste incinerators use packed bed scrubbers, plate tower scrubbers, and/or venturi scrubbers for air pollution control.

In wet scrubbing, the flue gas enters the absorber where it is saturated and contacted with the sorbent solution. The sorbent reacts with the acid gases to form salts, which are generally insoluble and may be removed by clarifying, thickening, and vacuum filtering of the scrubber blowdown. Typically, wet scrubbers have a 2-stage arrangement, as shown in Figures 3-16a and 3-16b: the first stage (typically a venturi type scrubber) for HCl and HF removal and a second stage for SO₂ removal (typically a packed or spray tower type). This is done to avoid the build-up of chlorides in the scrubber liquor, which can be highly corrosive. In the first stage, water is used to quench the gas to saturation conditions and HCl and HF are captured in a venturi type set up. In the second stage, a sorbent slurry is used for SO₂ removal in a packed, tray, or spray tower.

The primary advantages of wet scrubbers are that they can typically provide higher levels of acid gas control compared with dry scrubbers and they generate low amounts of waste for treatment and disposal because acid gas absorption is more efficient when the gases are saturated (Sedman and Brna, 1987). However, wet scrubber system disadvantages include:

- Require waste water treatment facilities or drying equipment for scrubber byproducts processing prior to disposal.
- Not as efficient at particulate removal compared to dry scrubbers.
- May require stack gas reheat requirements prior to exhausting to atmosphere.

- Prone to corrosion problems and may require expensive materials of construction.
- Higher operating and maintenance requirements compared with dry scrubbers.
- Accumulate of suspended and dissolved solids in scrubber liquors. To keep from being entrained by the gas flow, liquid must be replaced and replaced with fresh liquor.

3.5.1 Design Principles

Wet scrubbers remove particles from the gas by capturing the particles in liquid droplets and separating the droplets from the gas stream. The liquid injected to capture the pollutants can be water or a solution. This solution is often referred to as scrubbing liquor or scrubbing slurry. The majority of operating scrubbers use lime or limestone as the scrubbing solution because of its wide availability and low cost. Sodium-based scrubbing solutions are also used, but to a lesser extent. This section will focus on lime slurry injection type wet scrubbers which have been proven effective in the removal of particulate, HCl, SO₂, and volatile metals.

3.5.1.1 Scrubber Designs

There are a number of scrubber designs currently used on hazardous waste incinerators. These include types such as spray tower, tray tower, packed tower, and ionizing wet scrubbers.

Spray Tower — A common wet scrubber design is the spray tower, shown schematically in Figure 3-17. Spray scrubbers consist of a vessel with a bank of liquid spray nozzles which are mounted across the vessel cross section. Atomized scrubbing liquid (usually water or a dilute solution of an alkaline agent in water) produced by the nozzles fall through the gas stream, which travels up through the vessel. The scrubbing slurry absorbs flue gas acid gases, forming a disposable sludge. The cleaned gas passes through the mist eliminators to removed entrained liquid and particulate. The liquid droplets must be large enough so that their terminal velocity is larger than the gas velocity, otherwise the droplets will be carried out of the vessel.

Tray Tower — Another scrubber design is the tray tower (also known as an “impingementtype”) scrubber, shown in Figure 3-18. The flue gas enters at the base and passes upward through holes in one or more perforated plates mounted horizontally across the scrubber. Scrubbing slurry is sprayed onto the top tray from above, and then overflows down onto the subsequent bottom trays. Each of the trays has many small openings; the flue gas is forced up through the openings, forming small jets. The slurry on the tray becomes a “froth” due to the gas passing through it, providing very good contact of the flue gas with the slurry. The jets prevent the passage of the liquid layer through the tray openings. The main disadvantage of tray tower scrubbers is that they cannot handle load variations (flue gas flow variations). At low flue gas flow rates, the slurry will drop through the sieve (weeping), while at too high of a flow rate, the slurry mixture is blown out of the scrubber. Additionally, the tray holes are prone to plugging, and the scrubber must be shut down and cleaned periodically.

Packed Tower — Packed tower scrubbers, shown in Figure 3-19, incorporate a bed of packing material mounted across the scrubber vessel. A liquid is injected down through the packing material, which is usually a random mixture of individual pieces such as balls, saddles, rings, or shaped solids. The flue gas enters at the base of the tower and flows up through the packing against the slurry flow which is introduced at the top of the scrubber. The packing slows the flue gas down, distributes the gas and liquid slurry flows, and provides increased surface area for the gas to contact the slurry, resulting in high removal efficiencies. Operational problems of packed beds include changes in gas velocity hinders liquid movement through the packed bed, and plugging of packed bed with solid deposits.

Ionizing Wet Scrubbers — Ionizing wet scrubbers (IWS) combine the principles of electrostatic particle charging, inertial impaction, and gas absorption to simultaneously collect submicron particles, liquid droplets, and acid gases. As shown in Figure 3-20, the IWS consists of two sections: a high voltage ionization section and a packed scrubber section. The gas stream passes through the ionization section where the particles are electrostatically charged. The charged particles then enter the packed bed section where particles are removed by attraction to neutral surfaces (collection plates) and impaction on the packed bed materials. A water or caustic recirculating stream continuously washes the packed bed to remove collected particles and acid gases. Because the IWS is a fractional removal device, particle removal efficiency can be increased by employing multiple units in series. IWS advantages include increased particulate matter as well as acid gas collection efficiency compared to typical venturi type and other wet scrubbers, and low pressure drops.

3.5.1.2 Reagent Preparation and Injection Equipment

The scrubber slurry side of the process starts with the fresh scrubber slurry being pumped into the scrubber. The portion of the scrubber that contains the slurry solution is often referred to as the reaction tank. Next, the scrubbing slurry is pumped from the bottom of the tank to the slurry nozzles located approximately two-thirds of the way up the tower. The nozzles spray down against the flue gas flow. The scrubbing solution reacts with the flue gas and most of the particles fall back into the reaction tank, but some of the slurry (the smaller particles) can become entrained in the flue gas flow and travel up toward the mist eliminators. The mist eliminators serve to trap most of the particles entrained in the flue gas, and they are then washed down to the reaction tank by wash water spray.

Not all of the slurry pumped from the bottom of the reaction tank is sent to the slurry nozzles. A small percent is removed as waste and is made up for by the fresh slurry feed. The spent slurry is diverted to a thickener or hydroclone which removes moisture. The dewatered slurry is disposed of, and the excess moisture is recycled back into the reaction tank and is also used as mist eliminator wash water.

Limestone and lime-based scrubbing slurries are by far the most commonly used scrubbing reagents. The main advantages of using lime or limestone include:

- The process is simple and has few process steps.
- Capital and operating costs are low and limestone is abundant.
- SO₂ removal efficiency can be as high as 95%; HCl and HF removal efficiency can exceed 99%.

The main disadvantages of lime and limestone based scrubbing systems include:

- Large quantities of waste must be disposed of in an acceptable manner.
- Limestone systems have a tendency for scaling, plugging, and erosion.
- Large slurry flows are needed, resulting in large pumps with high electrical consumption.

In addition to lime and limestone scrubbing slurries, dual alkali systems are also in use which utilize a mix of sodium carbonate (NaCO₃) and lime or limestone. The main advantage of the dual alkali process is that scaling (deposits of calcium solids on the scrubber surfaces) is minimized. The main disadvantage is that sodium may leak out of the system with the waste and potentially contaminate ground water.

Typically, wet limestone and lime scrubbers employ on-site wet grinding (slaking for lime) for slurry preparation. Figure 3-21 shows a typical limestone reagent preparation system. The raw limestone with a diameter of approximately 1 inch is fed through a weigh belt feeder to a ball mill.

Water is added at the feed chute of the mill. From the mill, the limestone is sent to a classifier which separates the coarse limestone from the fine limestone. The classifier sends the fine limestone to the limestone feed tank to be made into scrubber slurry. The coarse limestone is sent back to the mill for more grinding. Grinds ranging from coarse (70% of the limestone passing through a 200 mesh sieve) to fine (95% passes through a 325 mesh sieve). The finer the grind, the better the reduction will be, but the energy consumption for fine grinding is high.

The spray nozzles used to control the slurry mixing with the flue gas typically operate between 5 and 20 psi and have corkscrew tips. The nozzles produce many droplets of approximately 2500 to 4000 μm in diameter. The SO₂ reduction chemistry occurs on the droplet surfaces, so the smaller the droplets, the greater the amount of surface area that is available for reaction, improving SO₂ removal efficiency. However, to decrease the droplet size, nozzles with smaller openings are required. The pressure required to push the slurry through smaller nozzles is high, and smaller nozzles tend to plug.

3.5.1.3 Mist Eliminators

Mist eliminators are used on wet scrubbers to collect slurry droplets entrained in the scrubbed flue gas stream and return them to the scrubbing liquor at the bottom of the scrubber. Mist eliminators are located at the exit to the scrubber. Most of the droplets leave the flue gas flow due to gravity, but the small droplets can be carried out with the gas. If these droplets are not removed from the gas before it exits the scrubber, it can deposit on the ductwork, the induced draft fan, and the walls of the stack. This may lead to pluggage and corrosion.

Most mist eliminators are of the impingement type: the small liquid droplets impact a collection plate, coalesce, and fall by gravity back into the scrubbing liquor. The mist eliminators are sprayed with wash water to remove accumulated solids. The wash water is generally a mixture of fresh water and clear water from the slurry dewatering system.

3.5.1.4 Waste Treatment and Disposal

There are several types of waste treatment and disposal methods currently in use. The earliest method of waste disposal was simply to discharge the spent wet slurry to a settling pond. However, site availability and pond management costs have limited ponding in recent years. The most popular disposal approach in practice today is to perform two separate stages of dewatering and then sending the filter cake to a landfill.

The first stage of dewatering (primary dewatering) can use thickeners or hydroclones. After the primary dewatering, the sludge is between 20% and 30% solids. Secondary dewatering is accomplished with vacuum filters, or centrifuges. Vacuum drum filters make up 80% of the secondary dewatering equipment population. Normally, before the dried sludge goes to a landfill, the sulfites must be mixed with flyash and lime. Since gypsum needs no further treatment before it can be landfilled or sold to wallboard manufacturers, some scrubbers employ forced oxidation equipment in the reaction tank to convert the calcium sulfite semihydrate to gypsum.

3.5.2 Performance

To achieve optimum performance, several design and operating parameters must be considered including:

- Concentration and pH of caustic (such as limestone or sodium) in scrubbing slurry.
- Scrubbing slurry flow rate compared to gas flow rate.
- Uniform distribution of the scrubbing slurry.
- Uniform distribution of the flue gas.

The amount of limestone in the slurry controls the amount of calcium ion available to react with the bisulfite ion. The chemical equations show that, theoretically, one molecule of limestone is required to remove one SO₂ molecule. However, due to real world limitations on how well the limestone and flue gas can mix, up to 1.2 molecules of limestone are typically used for every molecule of SO₂.

To achieve very good contacting of limestone to acid gases, one should simply increase the concentration of limestone in the scrubber solution. However, if too much limestone is added, the pH of the solution will rise (the solution will become less acidic). The acid gas removal reactions work most efficiently at pH levels below approximately 6.3. Therefore, the amount of limestone added must be high enough to allow contacting with the acid gases, but not so high as to raise the pH above 6.3. Figure 3-22 shows the effect of scrubber solution pH on SO₂ removal.

In addition to limestone concentration in the scrubbing solution and scrubbing solution pH, the slurry solution flow rate also determines what level of acid gas reduction can be achieved. The slurry flow rate is related to the flue gas flow rate and is referred to as the liquid to gas ratio (l/g). In general, the higher the liquid to gas ratio, the better the acid gas removal efficiency will be. Typical limestone scrubbers operate at liquid to gas ratios of approximately 30 gallons of slurry for every 1000 cubic feet of flue gas. Since the flue gas flow rate varies with load, so must the slurry flow rate if the design liquid to gas ratio is maintained. Figure 3-23 demonstrates how the liquid to gas ratio (at a constant pH) impacts the SO₂ removal efficiency. As may be seen, liquid to gas ratios above 30 gallons per 1000 cubic feet of flue gas do not significantly impact SO₂ reduction efficiency.

Even if the concentration of limestone, the pH, and the liquid-to-gas ratio are optimum, good acid gas removal efficiencies will not be achieved unless the scrubbing slurry is sprayed evenly into the flue gas. To mix the slurry with the flue gas as rapidly and evenly as possible, it is best to have many small nozzles distributed across the scrubber cross section. If only one or two nozzles are used, pockets of flue gas can escape the scrubber without being treated. Unfortunately, small nozzles have a tendency to plug, so the final design must be a compromise between many small nozzles that evenly distribute the scrubbing slurry but have a tendency to plug and a few large nozzles that do not evenly distribute the slurry but will not plug.

Finally, care must be taken to ensure that the flue gas flow is evenly distributed across the scrubber. For example, if most of the flue gas goes up the right side of the scrubber and the scrubbing solution is evenly sprayed across the scrubber, there will not be enough scrubbing solution to react with all the acid gas on the right side, causing poor acid gas reduction. The flue gas inlet duct at the bottom of the scrubber is designed to promote even distribution of the flue gas across the scrubber cross section. In some cases, perforated plates are used to help distribute the flow, but these cause the pressure drop across the scrubber to increase and results in a higher electricity consumption by the fan.

3.5.3 Process Monitoring

For the reasons previously stated, wet scrubber operation is monitored by the following key parameters:

- Pressure drop across the scrubber.
- Concentration and pH of scrubbing slurry.
- Liquid-to-gas ratio via gas flow rate and slurry flow rate.
- Accumulation of solids within the scrubber.
- Induced draft fan power consumption.
- Reagent preparation system operation.
- Inlet and outlet gas temperatures.
- Dewatering process.

3.5.4 Inspection and Maintenance

Scrubber operators must constantly monitor and control the system to ensure proper performance. For example, when load changes occur, the scrubber operator needs to reset the limestone feed rate and use the pH monitor as a backup. In addition to good operation and communication, a preventive maintenance program specified by the manufacturer should be implemented; this should include inspection of scrubber module, mist eliminators, dampers, ducts, fans, slurry equipment, valves, and instrumentation for corrosion, erosion, scale deposits, leaks, and plugging. Visual inspection can allow identification of small problems before damage becomes so extensive that major repair is required.

Mist eliminators tend to be subject to buildup of slurry solids and chemical scale, causing the passages to restrict the flow of the flue gas. The first sign of scale buildup is typically noticed by an increase in pressure drop across the scrubber. Water washing is typically sufficient to prevent serious buildup problems.

Because the scrubber control system is based on flue gas and scrubber flow rates, the operating staff should routinely monitor and record readings from all instruments used to measure these flows. If any of the readings appear abnormal, they should be investigated. To verify liquid flow rates or evaluate pump/nozzle erosion, the operator should monitor pressure in the slurry header and the recirculation pump discharge. An increase in the pressure usually indicates plugging of nozzles. A decrease can indicate wear of the nozzles or pump impellers. Slurry flow in pipes can be checked by touching the pipe. If it is cold at the normal operating temperature, then the line is plugged.

The slurry feed requirement is usually controlled by the pH indicator. The sensor lines where pH measurement elements are used should be frequently backflushed and calibrated with buffer solutions to ensure reliable operation.

3.6 DRY SCRUBBING

In some respects, dry scrubbing systems represent a less complicated and cleaner control system than wet scrubbers. This is because no mist eliminator is required, the number of pumps and amount of piping are greatly reduced, and the waste material is in the form of dry particulates, which eliminates the need to treat liquid scrubber wastes and significantly reduces the waste volume.

Dry sorbent injection, shown schematically in Figure 3-24, involves the injection of a dry sorbent fine powder into the flue gas. Acid gas removal occurs as the sorbent reacts with the acids in the flue gas to form solid salts. The solids salts are collected in a downstream particulate collector. The particulate collector can be either an ESP or a fabric filter, however, a fabric filter is typically preferred due to increased capture efficiency and sorbent utilization. This is because the removal process continues in the fabric filter; captured sorbent, fly ash, and condensed volatile matter is

held on the fabric and remains exposed to the flue gas, thus allowing for further reaction of unused sorbent with the flue gas in the particulate collector. Dry sorbent injection is usually performed after the flue gas has been cooled, typically with a water quench.

Typically, hydrated lime or sodium carbonate (nacholite or trona ores) sorbents are used. The choice of sorbent depends on the preferred operating temperature. Lime is effective at high temperature whereas sodium must be used at lower temperatures. For lime, SO_x removal is optimized at 1750°F while HCl and HF is best at 800°F. In cases where efficient capture is required, this may require the use of multiple injection locations. Typically, large quantities (50 to 300% excess) of sorbent are required for efficient control in dry systems. Increased control efficiency and decreased consumption of sorbent can be achieved by increasing flue gas humidity and recycling the reaction products captured in the particulate control device back into the flue gas stream.

In some cases, the sorbent may be injected directly into the furnace section of the combustor, known as “furnace sorbent injection” (FSI). Typically, FSI provides extended sorbent/flue gas contact times compared with injection just upstream of the particulate collector. Due to the high temperatures, limestone is exclusively used; the limestone calcinates to produce lime which then reacts with the acids. The primary disadvantage of FSI is that poor sorbent utilization is achieved due to the hindrance of the lime-acid (in particular chlorine) reaction at high temperature. In some innovative arrangements, FSI is used in combination with injection upstream of the particulate collector to provide optimum acid gas removal.

The primary advantage is the production of a dry secondary waste. Additionally, it has been shown that mercury may be removed from the flue gas when calcium hydroxide is present. Disadvantages include low utilization of sorbent, high particulate loadings, and the encouragement of fouling and erosion of the heat transfer surfaces for FSI.

3.7 SEMI-DRY SCRUBBING

3.7.1 Design Principles

The “spray dryer absorption” (SDA) process, shown in Figure 3-25, is considered a “semi-dry” process since a wet sorbent material is used, but the residue produced is dry. In the SDA process, sorbent is mixed with water to form a slurry solution. The flue gas is dispersed, usually by vanes, through a reactor vessel. There are many reactor designs; cocurrent or countercurrent; up- or down-flow; single or multiple gas entrances. The slurry is injected into the reactor as a finely atomized spray. Acid gases present in the flue gas are absorbed into the small liquid droplets and reacted with the sorbent to form a salt. As the droplets pass through the reactor, heat from the flue

gas evaporates the water, cooling the flue gas and forming solid particles of salt. Similar to the dry process, dry solids, including salt, unreacted sorbent, and fly ash, are collected downstream of the reactor in a particulate removal device, which is typically a fabric filter, although ESPs can also be used. In some systems, a portion of the dried product is removed from the bottom of the spray dryer, while in others, it is carried over to and collected in the downstream particulate removal device. As in the dry process, the feed is sometimes recycled to decrease reagent consumption.

The SDA process is capable of higher acid removal efficiencies (typically greater than 90% for HCl and 80% for SO₂) compared with the dry process (Sedman and Brna, 1987). However, the following operations are critical to its success:

- The reactor temperature must be maintained high enough to ensure complete sorbent-slurry evaporation and to ensure the production of a free flowing product.
- Lower flue gas temperature favors efficient acid capture, however, the flue gas outlet gas temperature must be maintained well above the saturation level, otherwise corrosion problems will occur.
- Fine atomization of slurry spray and good flue gas/slurry droplet mixing is required. Additionally, if droplets are too small, a very fine particulate is produced, making particulate removal difficult.
- The flue gas must be well dispersed throughout the reactor vessel.
- Usage of large amounts of sorbent; typically, 50 to 100% excess of the sorbent is required. As with dry sorbent injection, to improve sorbent usage, the collected solids may be either recycled as a dry powder or dissolved and injected through the atomizing nozzle.
- Also, to avoid corrosion or product stickiness, the particulate collector and collection hopper must be either well insulated or heated, and air leakage must be controlled to minimize cold spots.

For spray dryers, also known as wet/dry scrubbers, hot flue gas enters the top of the dryer (scrubber) vessel where it is intimately mixed and cooled with a finely atomized lime slurry spray. Figure 3-26 illustrates several spray dryer arrangements. The moisture is completely evaporated, leaving the solids as suspended particulates. Mixing occurs in a turbulent flow field. The quenched and chemically conditioned flue gas then flows to a fabric filter and/or an electrostatic precipitator. The major equipment found in a typical spray dryer scrubbing system includes the spray dryer absorber, the particulate-collection system, reagent and slurry preparation and handling equipment, solids transfer, and process control and instrumentation. In spray dryer systems, the particulate collector is downstream and is considered an integral part of the system.

The spray dryer absorber provides the initial contact between the atomized reactive alkali and the acid-gas contaminants. There are two types of atomizers illustrated in Figure 3-26: rotary disks (or wheels) and dual-fluid pneumatic nozzles. In each case, the slurry is atomized as droplets into the dryer, reacts with the acid gases, and dries to a fine powder which is then carried over into the ESP or fabric filter and removed. The particulate collector also serves as an additional contact point between the dried reactants and acid gases, providing additional removal. Some spray dryer systems operate with partial recycling of the particulates by mixing the captured particulates with the fresh lime in either slurry or dry form before being reinjected into the associated scrubber.

The chosen atomization method affects the design of the spray dryer absorber vessel, including the physical dimensions. For a rotary-atomizer type of spray dryer, which projects the droplets radially outward and perpendicular to the gas flow, the length-to-diameter ratio of the dryer (L/D) is typically 0.8 to 1. The droplets decelerate rapidly owing to the drag forces of the downward-moving flue gas and eventually attain the speed and direction of the flue gas. To avoid wall deposition, the designed radial distance between the atomizer and the dryer wall must be sufficient to allow for adequate drying of the largest droplets. In a dual-fluid pneumatic nozzle type of spray dryer, which atomizes the droplets in the direction of the gas flow (downward), the L/D is typically 2:1. In this design, the sidewall deposition is a minor problem. For either design, optimum spray dryer performance is achieved through proper choice of the L/D, droplet size, and residence time. The designed residence time for most spray dryers is 10 to 12 seconds, however few systems operate at 100% of the design flow rate. Thus, actual residence time for most systems is 12 to 15 seconds. Spray dryers range from 25 to 50 feet in diameter.

3.7.2 Performance

The application of a spray dryer results in: a flue-gas temperature of 200 to 300°F; approximately 20% less gas flow through the particulate-matter collector due to lower gas temperatures; a particle size distribution with a mean diameter of 20 to 30 μm ; and a significantly increased dust loading. The increased particle size distribution and decreased flow rate are beneficial, but the decreased temperature and increased dust loading tend to increase pressure drops across fabric filters and to decrease efficiency across ESPs. The increased dust loading caused by the reacted products ranges from as little as 1.5 gr/acf at 500 ppm of SO_2 to as high as 14 gr/acf at 3000 ppm of reacted products. Therefore, increased dust loading must be taken into account in the design of the particulate-matter collector and the associated dust-handling support system.

3.7.3 Process Monitoring

The following process monitoring parameters are the same as those for wet scrubber applications, with the exception of waste treatment system.

- Pressure drop across the scrubber.
- Concentration and pH of scrubbing slurry.
- Liquid-to-gas ratio via gas flow rate and slurry flow rate.
- Accumulation of solids within the scrubber.
- Induced draft fan power consumption.
- Reagent preparation system operation.
- Inlet and outlet gas temperatures.

Most operational problems associated with spray dryers are due to low temperatures at the exit of the dryer. When the gas approaches the water dew point, acid condensation may result in the downstream equipment. Therefore, the flue gas exit temperature is a critical process monitoring parameter.

3.7.4 Inspection and Maintenance

Spray dryer inspection and maintenance is very similar to that required by wet scrubbers. Operators must constantly monitor and control the system to ensure proper performance. For example, when load changes occur, the scrubber operator needs to reset the limestone feed rate and use the pH monitor as a backup. In addition to good operation and communication, a preventive maintenance program specified by the manufacturer should be implemented which is similar to the wet scrubber activities.

Visual inspection of the scrubber section and tanks should be performed on a regular basis to identify leaks, scaling, corrosion and erosion problems. Visual inspection can allow identification of small problems before damage becomes so extensive that major repair is required.

Because the scrubber control system is based on flue gas and scrubber flow rates, the operating staff should routinely monitor and record readings from all instruments used to measure these flows. If any of the readings appear abnormal, they should be investigated. To verify liquid flow rates or evaluate pump/nozzle erosion, the operator should monitor pressure in the slurry header and the recirculation pump discharge. An increase in the pressure usually indicates plugging of nozzles. A decrease can indicate wear of the nozzles or pump impellers. Slurry flow in pipes can be checked by touching the pipe. If it is cold at the normal operating temperature, then the line is plugged.

The slurry feed requirement is usually controlled by the pH indicator. The sensor lines where pH measurement elements are used should be frequently backflushed and calibrated with buffer solutions to ensure reliable operation.

3.8 FLUE GAS COOLING

The objectives of flue gas cooling are to:

- Protect low-temperature air pollution control equipment such as fabric filters and cod-side ESPs.
- Saturate the flue gas prior to wet scrubbing.
- Condense vaporized pollutants such as volatile toxic metals.
- Prevent the formation of certain classes of organics due to fly ash catalyzed reactions. For example, by cooling the flue gas rapidly, the formation of PCDD/PCDFs can be reduced.
- Recover waste heat.

Flue gas cooling is required prior to particle and acid gas removal in low temperature devices such as baghouses, cold ESPs, and wet scrubbers. There are four methods for cooling the flue gas leaving the incinerator:

- Air dilution.
- Heat exchanger.
- Water quench.
- Radiation and convection duct cooling.

Radiation and convection cooling utilizes heat transfer from the flue gas flow in a long uninsulated duct. This is the simplest method in principle. However, this method is not considered for further review due to large space requirements, particle sedimentation in the duct, and the lack of the ability for precise temperature control during flue gas temperature and flow fluctuations. The three other methods are discussed below.

3.8.1 Air Dilution

3.8.1.1 Design Principles

For air dilution cooling, shown in Figure 3-27, cool air is injected directly into the hot flue gas stream. The amount of dilution air required is dependent on the initial temperature of the flue gas and the amount of temperature reduction desired, as shown in Figure 3-28. The resulting mix of the two gas streams produces a stream at an intermediate temperature. Air is usually injected tangentially into the axially flowing flue gas stream. Special air mixing jets may be used so that thorough mixing of the two streams is obtained within a relatively short distance.

3.8.1.2 Performance

The use of air dilution as a cooling method has certain disadvantages, including:

- Air dilution creates a substantial increase in the total flue gas volume flow rate. This additional flow requires downstream pollution control equipment to be considerably larger.
- The control of both flue gas temperature and velocity is not possible. Downstream devices which are affected by velocity (e.g., pressure drop and efficiency for filters and venturi scrubbers) may be adversely affected by changes in quench air requirements to maintain a target flue gas temperature.
- There is potential for the intake of ambient moisture and dust if the dilution air is not preconditioned. This may cause problems in the downstream equipment and may introduce additional pollutants into the flue gas.

- Potential for either exceeding the capacity of the blower, causing the exiting flue gas stream to be too hot, or the blower flow rate cannot be turned down sufficiently to provide minimum air flow, causing the flue gas stream to be too cold.

Because of these limitations, air dilution cooling is not generally used as the only means of gas cooling; however, it is often used to make small changes in flue gas temperature, such as precooling of the flue gas upstream of a heat exchanger to protect the heat exchanger tubes from high temperature degradation. Advantages of air dilution cooling include ease of use and implementation and low maintenance requirements.

3.8.1.3 Process Monitoring

The outlet gas temperature and blower flow rate are easily monitored by thermocouple and flowmeter, respectively, to assure proper operation.

3.8.2 Heat Exchanger

Heat exchangers can also be used for cooling of the hot flue gas stream. In a heat exchanger, heat is transferred from the flue gas through a common wall to a cooling fluid. Note that boilers are a type of heat exchanger.

3.8.2.1 Design Principles

Heat exchangers transfer heat through a combination of convective and conductive processes. A wide variety of heat exchangers are commercially available, including gas-to-gas and gas-to-liquid types, as shown schematically in Figure 3-29. In a gas-to-gas heat exchanger, the cooling fluid is typically air (e.g., a recuperator used to preheat combustion air). In a gas-to-liquid heat exchanger, the cooling fluid is a liquid, typically water. The liquid is usually contained in a closed circuit, and liquid cooling is often provided by ambient air blowing.

3.8.2.2 Performance

Liquid heat exchangers are more efficient than gas-to-gas heat exchangers due to their increased capacity to remove heat. However, as mentioned earlier, they have increased in complexity since they typically utilize a closed loop cooling fluid. Liquid heat exchangers also have an increased tendency to promote the condensation of acid gases and subsequent corrosion of common walls.

Advantages to the use of heat exchangers for flue gas cooling include:

- No increase in flue gas volume. Unlike air dilution, and due to the cooling fluid and hot flue gas streams being separated, the volume of the flue gas remains the same. Therefore, it is not necessary to increase the size of flue gas cleaning equipment.

- Recovery (and potential use) of waste heat.

Disadvantages to the use of heat exchangers include:

- The heat exchanger cooling capacity is limited by the heat transfer rate, which is determined by the cooling fluid flow rate, the inlet temperature, and the thickness of particulate matter deposits on the cooling surface. Note that if the flue gas contains significant amounts of particles, particle buildup on the tubes act as an insulator and impair the heat transfer efficiency, known as tube “fouling”. This can be mitigated by the use of high temperature particle removal devices upstream of the heat exchanger or by the use of soot blowers to keep the tubes clean.
- Tube corrosion from condensation of flue gas components (chlorine, sulfur, metals).
- Mechanical failure due to thermal expansion of different exchanger parts at different rates.
- Hot-side tube blockage from soot and flyash deposits.
- Tube erosion in heavily dust laden gas streams.
- Loss of coolant from fire, explosion, power outage, system leak, or mechanical failure of the pump, resulting in a system failure. For heat exchangers using liquid cooling, however, loss of coolant will not cause an immediate rise in temperature due to the remaining thermal inertia of liquid coolant. Additionally, liquid heat exchangers can avoid the immediate effects of a power or pump failure by the use of an elevated supply tank to provide the head necessary to push the fluid through the system.
- Increased flue gas flow rate and temperature, resulting in an inability to provide sufficient cooling liquid, causing a possible system failure due to the flue gas temperature levels.

3.8.2.3 Process Monitoring

The outlet gas temperature and coolant flow rate are easily monitored by thermocouple and flowmeter, respectively. The temperature of the cooling fluid is also monitored to assure proper operation, especially if the system has one pass.

3.8.2.4 Maintenance

If the hot flue gas contains significant amounts of particles, the heat exchanger tubes will require frequent cleaning. As mentioned above, this problem can be mitigated by the use of a high temperature particle removal device upstream of the heat exchanger or by the use of soot blowers to keep the tubes clean. Other maintenance procedures include service of the pumps and blowers.

3.8.3 Quench

In a water-quench cooler, as shown in Figure 3-30, the hot flue gas is cooled by injection of water into the gas stream. The gas temperature is reduced as the water spray evaporates.

3.8.3.1 Design Principles

The quench is typically performed in a dedicated cooling vessel. Hot gases enter the vessel and are decelerated so that water droplet evaporation occurs completely within the vessel. To ensure evaporation, the water spray must be atomized into small droplets in sufficient quantities to maintain a constant outlet gas temperature. The amount of injected water must be controlled in response to fluctuations in the flue gas temperature. Because it is difficult for the water nozzles to maintain a small droplet size over a wide range of flow rates, nozzles that are used have either variable flow areas or utilize two-phase flow (high pressure air or steam can atomize water over a wide range of flow rates). Rotary nozzles can also be used to maintain a uniform distribution of water droplets over a wide range of flows.

A water quench is almost always used upstream of a gas scrubber when the inlet flue gas temperature is above the saturation point. In this situation, to ensure that the temperature is lowered to its saturation temperature (which is required by the scrubber for effective scrubbing efficiency), a surplus of water is introduced. Because droplets and particles will tend to migrate to the cooler wall, an inside film of water is often used to wash collected particles from the walls. This water is drained from bottom of the cooling vessel and discarded or recycled. The amount of water typically required to cool the flue gas is shown in Figure 3-31.

When a water quench is used prior to a fabric filter or dry ESP, it is critical that the gas temperature remain above the saturation level and that all the water droplets completely evaporate. Otherwise, corrosion and plugging problems may occur in these devices from condensed moisture and other gases. Complete evaporation is assured by fine atomization and large gas residence times in the cooler vessel.

3.8.3.2 Performance

When excess moisture in the flue gas is undesirable, the most important consideration is that the injected droplets have a uniformly small size range. Large unevaporated droplets may exit the cooling vessel before they have time to completely evaporate. These droplets may cause problems with downstream equipment and may create a non-uniform temperature distribution in the flue gas. Also, droplets may migrate to the vessel wall, reducing the cooling potential of the device.

Water quench cooling has the following advantages:

- Provides the finest and quickest temperature control of the three cooling methods.

- Potential for capturing acid gases and particles if reagents are injected with the water.
- Low maintenance requirements.

Disadvantages to using water quench cooling include:

- It has the potential to produce a secondary liquid waste stream when the liquid spray is not fully evaporated.
- It has an increased chance of a visible steam plume.
- It has difficulty in accommodating low flow rates and variations in moisture feed.
- Failure modes such as:

liquor is

mechanical

- Plugged spray nozzles, especially if a dry reagent is used for acid gas control.
- Corrosion of spray nozzles. This becomes more of a problem if the spray collected and recycled and/or if acid gases are present in the flue gas.
- Loss of quench water from fire, explosion, power outage, system leak, or failure of the pump, resulting in system failure.
- Increased flue gas flow rate and temperature result in an inability to provide sufficient quench liquid, causing a possible system failure due to flue gas temperature levels.

3.8.3.3 Process Monitoring

Quench operation is indicated by monitoring the outlet gas temperature, water flow rate, and nozzle pressure. The outlet gas temperature is monitored with thermocouples. Water flow and nozzle pressure are monitored with pressure and flowrate gauges.

3.8.3.4 Maintenance

Maintenance requirements include checking (and occasionally replacing) spray nozzles for corrosion and pluggage, and inspecting the water pump system.

3.9 OTHER METALS CONTROL TECHNIQUES

New techniques are being developed specifically for the control and capture of individual metals species from combustion sources. Mercury, in particular, due to its toxicity and volatility (making it difficult to capture in conventional air pollution control devices), has received special

attention. Techniques for its control include the use of activated carbon, selenium filters, special scrubbers, and sodium sulfide. Additionally, special sorbents have been found effective at controlling metals such as cadmium and lead.

3.9.1 Sorbents

A variety of sorbents have and are being developed that have shown the ability to independently remove trace metals from combustion source flue gases. Sorbents having demonstrated metal capturing potential are shown in Table 3-1, and include zeolites, activated carbon, calcium-based, alumina-based, and silicates. Solid sorbents capture and immobilize the metal by a combination of adsorption and chemical reaction; the metal is reacted and/or absorbed on the surface of the sorbent, which is then more easily removed from the flue gas. The actual mechanism depends on the particular metal and sorbent. Some metals react with the sorbent to form a stable compound; other presumably inert materials, such as silica sand, appear to pick up metals by some type of adsorption mechanism. Note that the adsorption procedure is important since it determines the potential leachability of metal from the captured product. The non-leachable water insoluble fraction is surmised to be that which is chemisorbed or reactively adsorbed, while the leachable water soluble fraction is that which is merely physisorbed.

3.9.1.1 Activated Carbon Adsorption

Activated carbon has been used for the “add-on” control of organics, in particular PCDD/PCDF, and mercury from combustion source flue gases, including municipal waste, medical waste, and hazardous waste incinerators. Various mechanisms have been suggested for the capture on activated carbon; these include physical adsorption in the pores of the carbon, catalytic oxidation to mercury oxides, and/or chemically mediated adsorption based on the presence of oxygen and/or chlorine (Krivanek, 1993). The presence of chlorine has been demonstrated to augment mercury capture efficiency (Felsvang, 1993).

Design Principles — Activated carbon has a very large inner pore surface (large surface to volume ratio), which can adsorptively bond a very broad range of substances. Typical activated carbon has a surface area of from 300 to 800 m²/g; high grade carbon can have surface area of 1500 m²/g. Additionally, it posses catalytic properties that can be used for simultaneous NO_x control if required. Two types of activated carbon are commonly used: formation coke (based on coal) and lignite coke. Lignite coke is more commonly used due to its low cost. In some attempts, impregnation agents have been added to the activated carbon to enhance its control efficiency.

Activated carbon can be used in a couple of different arrangements for the control of mercury and organics in combustion system flue gases. These include:

- Fixed bed process — In the fixed bed process, flue gas flows through one or more beds of activated carbon arranged in a series; spent activated carbon is withdrawn from the bottom of each bed segment. Carbon monoxide levels are continuously monitored across bed to minimize risk of fire. To prevent plugging and contamination, the bed is usually placed after a flue gas particulate control device. Although capture performance tends to increase at lower temperatures, the gas should not be below saturation temperature to avoid

condensation of moisture in the bed. Activated carbon tends to lose its adsorption capacity when it gets contaminated with moisture (Frillici, 1993). Typical bed operating temperatures range between 250 to 300°F.

- Fluidized bed process — In the fluidized bed process, flue gas fluidizes a bed containing activated carbon. The fluidized bed arrangement consumes less coke compared to the fixed bed, however, has a higher pressure drop. Circulating beds have also been used, and have demonstrated very high mercury and dioxin removal. Typical bed operating temperature is similar to fixed bed arrangements, ranging between 250 to 300°F.
- Duct injection — In the duct injection process, activated carbon is injected into the flue gas upstream of a particulate control device, typically a fabric filter or ESP. Because of the corona discharge phenomena of an ESP and combustible nature of activated carbon, an ESP is not considered the best choice for activated carbon collection from carbon injection systems. Additionally, a fabric filter provides for extended hold-up of the injected activated carbon in the flue gas, allowing for additional mercury removal compared to an ESP; for the same level of control, a higher activated carbon feed rate may be required for ESPs compared to fabric filters. However, relatively no difference between capture using ESP and fabric filter has been demonstrated (Felsvang, 1992). In some versions, a cyclone reactor is used to improve the mixing of the flue gas and the activated carbon before it passes to the particulate control device. Activated carbon may also be injected upstream of a rotary atomizer, similar in design to conventional spray drying units. The activated carbon may be injected either by itself as a powder or in a dry or wet solution in combination with an acid gas removing sorbent such as lime, calcium hydroxide, or sodium sulfide. The duct injection process consumes the least activated carbon of the three methods, typically from 50 to 400 mg/m³ of flue gas for municipal waste combustors.

Note that duct carbon injection is not recommended for facilities with “wet” pollution control systems (e.g., a type of wet scrubber) since at this time, the two have not been successfully integrated.

Performance — Literature reviews and discussions with technology vendors have indicated that the use of activated carbon with either direct duct injection or in bed arrangements can control PCDD/PCDF flue gas emissions levels from hazardous waste burning facilities to below 5 ng/dscm of total PCDD/PCDF, and TEQ levels to below 0.1 ng/dscm. Additionally, levels consistently below 0.05 TEQ ng/dscm have been achieved, and as low as 0.005 TEQ ng/dscm in select cases; although, surveyed vendor performance guarantees have been limited to 0.05 ng/dscm @ 11% O₂. Even higher control levels may be possible by optimizing critical operating parameters.

As mentioned, in addition to toxic organics control, activated carbon can also effectively control mercury. Fixed bed, fluidized bed, and duct injection arrangements have all been demonstrated to perform at 90+% mercury removal, with some as high as 99% or greater. These systems without carbon injection have poor mercury capture efficiency ranging from 0 to 40%. Again, highest control levels are achieved by optimizing critical operating parameters.

Operating parameters that effect activated carbon performance include the following:

- Activated carbon type and specifications — Carbon type may be defined by general chemical and physical properties. Carbon specifications such as chemical properties (e.g., composition, use of additives or enhancers such as iodine or sulfur impregnation) and physical properties (e.g., particle size, specific surface area, pore size) can significantly affect performance. However, experiments have shown that activated carbon type has little effect on mercury capture; coal-based, lignite-based, and wood-based activated carbon all performed at similar levels (White, 1992).
- Activated carbon feedrate — Removal rate increases with increasing activated carbon feedrate.
- Injection location for duct injection process — No noticeable difference in performance when activated carbon was injected either downstream of the municipal waste combustor economizer, at spray dryer outlet, or along with lime used for the spray dryer (White, 1992).
- Temperature — PCDD/PCDF capture efficiency tends to increase with decreasing flue gas temperature, especially at temperatures below 425°F (Christiansen, 1992). Mercury capture efficiency has also been shown to improve at lower temperatures (Christiansen, 1992), however, there may be a tradeoff; other research has shown that at higher temperatures, the bond between the mercury and the activated carbon is stronger compared to the bonding occurring at lower temperature (Gullett, 1993).

Flue gas temperature is especially important in carbon bed applications since a temperature spike in the bed may cause adsorbed PCDD/PCDF, mercury, and other heavy metals and organics to desorb and reenter the stack gas emissions stream. However, since most facilities utilize some type of PM control device upstream of the carbon bed, and the inlet temperature to the PM control device must be maintained at a certain level to avoid PCDD/PCDF formation, temperature spikes in the carbon bed should not occur.

Retrofit applicability to existing sources of cement kilns, light weight aggregate kilns and hazardous waste incinerators is discussed in Section 5 of *Technical Support Document for HWC MACT Standards Volume III: Selection of MACT Standards and Technologies*. Also discussed is detailed activated carbon performance data for medical waste incinerators, municipal waste combustors, and hazardous waste incinerators. Note that to date, activated carbon systems have not been applied to cement or light weight aggregate kilns.

Process Monitoring — Activated carbon processes are often used in conjunction with other air pollution control technologies. Monitoring for these other technologies should be reviewed in the previous sections. The following describes process monitoring to be performed for each of the carbon adsorption applications:

- Fixed bed process — Fixed bed operations are monitored by flue gas inlet temperature, gas flow rate, carbon monoxide levels, upstream and downstream pollutant concentrations, and pressure drop across the system. It is recommended that flue gas temperatures remain at least 100°F above dew point temperature, and at least 40°F above acid gas dewpoint (Steag, 1994). The bed temperature typically ranges between 250 and 300°F. Carbon monoxide levels are monitored to minimize the risk of fire in the bed.
- Fluidized bed process — Fluidized bed operations are monitored by bed temperature, bed pressure drop, and flue gas flow rate.
- Duct injection — Duct injection operations are monitored by flue gas temperature, flue gas flow rate, upstream and downstream pollutant concentrations, and activated carbon injection rate.

Inspection and Maintenance — One maintenance requirement of activated carbon systems is the treatment or disposal of the used carbon. Current treatment ideas include a wash process to remove metals, followed by destruction in the primary combustion source, or vitrifying the activated carbon and fly ash into a glass substance. Destruction in the primary combustion source may be a problem since the carbon may contain elevated levels of mercury and other volatile heavy metals which will be re-released when the carbon is burned. Alternatively, the used carbon may be directly landfilled, or landfilled after stabilization by techniques such as cementation or polymerization.

Recent studies have shown that post-treatment may not be necessary for captured ash and carbon contaminated with mercury (Felsvang, 1993). Captured activated carbon and fly ash were stored for 3 years in different arrangements: open container, plastic bag, solidified by water addition, and stored in open container at elevated temperature (50°C). No significant revolatilization of mercury was seen in any of the situations during the three year period. Additionally, leaching studies performed on by-product ash gave results that were typically below EPA levels. However, the oxygen deficient methane rich environment of a landfill may enhance the desorption of previously captured mercury.

To date, no work has been performed to determine the leachability of PCDD/PCDF adsorbed on the carbon. Thus potentially, the carbon injection technique may only serve to transfer the PCDD/PCDF from the flue gas to a landfill leachate if disposed of directly.

Inspection requirements include close monitoring of carbon monoxide levels, and ash and carbon build-up to prevent fire hazards. Use of combustible substances like activated carbon requires consideration due to risk of fire and explosion. When present with oxygen, activated carbon may self-ignite at temperatures as low as 200°C.

3.9.1.2 High Temperature Earth Based Sorbents

The use of sorbents such as sand, limestone, alumina, silica, bauxite, and dolomite at temperatures in the range of 500 to 900°C have been demonstrated to capture metals such as lead and cadmium. Some of these efforts include:

- Gao and Silcox (1993) studied the capture of lead and cadmium by use of a diatomaceous earth sorbent (composed of silica, alumina, and iron oxide) in lab scale fixed and fluidized beds, and a pilot scale rotary kiln. Sorbent capture took place in a temperature range of 600 to 870°C. Lead was retained at 100% efficiency. Cadmium was not efficiently captured. Leachability of the capture metal decreased with increasing operating temperature.
- Ho et al. (1992) studied the capture of lead in a lab scale fluidized bed combustor with the use of sorbent bed materials including sand, limestone, and aluminum oxide. A wide range of lead control was achieved, from 4 to 90%, depending primarily on sorbent material and bed temperature. Limestone demonstrated the best capture ability. A bed temperature of 700°C was shown to provide best capture; capture fell off as temperature increased due to sorbent agglomeration and vaporization of metals; at lower temperature, due to incomplete combustion, metals were not released and were carried away with unburned soot particles. Also, a smaller sorbent size was shown to have higher capture efficiency; however, smaller sorbent was most difficult to keep in bed.
- Scotto et al. (1992) investigated the capture of lead by injection of kaolinite into the post flame region in a bench scale combustor burning lead containing wastes. Kaolinite was shown to capture lead by 99%. Additionally, the sorbent reduced the submicron particulate distribution and lead formerly found in the submicron size range was now associated with larger kaolinite particles. At high chlorine levels, the addition of sorbent was not effective at scavenging the lead vapor.
- Eddings and Lighty (1992) demonstrated that both metallic lead and lead oxide failed to vaporize when heated on a grid in the presence of a clay material.
- Hassel et al. (1990) conducted work in a pilot scale fluidized bed to evaluate use of sorbent bed materials such as silica sand, bauxite, dolomite, and aluminosilicate for the capture of copper, zinc, and bismuth. Capture efficiencies of from 60 to 90% were demonstrated for a bed operating temperature of 1600°F. Silica sand and dolomite performed the best. In case of copper, a significant portion of the captured material was present as chlorine salt, which is readily leachable. Leachability of metals from bed materials were below regulatory limits.

- Uberoi and Shadman (1991) studied the high temperature (800°C) removal of cadmium from simulated flue gases using silica, alumina, kaolinite, emathlite, and lime. Bauxite and alumina are best performers, however, bauxite products were leachable. The overall sorption process was determined to be a complex combination of adsorption, condensation, diffusion, and chemical reactions. Others were not effective at cadmium capture.
- Uberoi and Shadman (1990) studied high temperature (700°C) removal of lead from simulated flue gases using silica, alumina, kaolinite, bauxite and emathlite. All except limestone were effective for lead removal; kaolinite and bauxite were the most effective.
- Srinivasachar et al. (1992) performed a laboratory scale study of fixed bed of proprietary sorbent for the capture of Pb, Cd, As, and Zn. Capture efficiencies of from 65-100% were demonstrated with a bed temperature of from 700 to 900°C. The sorbent/metal product was shown to be non-leachable. X-ray fluorescence analysis indicated that the metal reacted chemically with the sorbent rather than being just physically adsorbed by heterogeneous condensation.
- Crosley and Kedl (1992) studied the adsorption of cesium with the use of silica at temperatures of 1000 to 1300°F. Cesium was efficiently adsorbed; most of the adsorbed cesium was non-leachable. Developed of method for selecting the appropriate sorbent based on the existence of a stable phase of metal oxide/sorbent oxide combination.

3.9.2 Mercury Specific Controls

3.9.2.1 Selenium Coated Filter

Mercury capture with selenium coated filters was originally developed for metallurgical smelting operations in Europe (Lindquist, 1991). They consist of a cylindrical shell containing porous material impregnated with selenium. Selenium has a strong affinity for mercury; it combines to form mercury selenide (HgSe), a highly stable compound. The filters are position downstream of a primary particulate control device to avoid plugging. Problems with the use of selenium filters include that the gas temperature must be 140°F or less and the gas must be clean of particulate, while keeping the gases from becoming saturated, the use of selenium produces a double threat in terms of disposal of the spent material, and filter blinding and poisoning are potential problems. Spent filters are returned to the manufacturer for recharging, although they have lives of several decades.

3.9.2.2 Sodium Sulfide Injection

Sodium sulfide injection has been successfully used for mercury control from municipal waste combustors in Europe and Canada and has been tested on one unit in the United States (White and Nebel, 1991). Sodium sulfide is a crystalline solid that is dissolved into a water solution, and is sprayed into the flue gas upstream of a particulate control device. The solution reacts with mercury to form HgS, a high stable solid reaction product. Injection is typically performed at a flue gas temperature of 260 to 300°F. It has been shown to have a capture efficiency of from 50 to 90%.

Problems with its use include the potential release of hydrogen sulfide fumes from bags of sodium sulfide as they are opened, deposits on nozzles and duct work, proper disposal of resultant secondary waste, proper solution atomization, HgS generated as a fine particulate that is difficult to capture in a particulate control device, and the fact that it can not be used with a spray drying sorbent feed because of potential CaS scaling of the sorbent feed line (Andersson and Weimer, 1991).

3.9.2.3 Mercury Scrubbers

Mercury scrubbers have been proposed that rely on the reaction of mercury with chemicals such as sodium hypochlorite or with a chelating agent and cupric chloride, to form water-soluble species of mercury which can then be removed in conventional wet scrubbers (Dalton et al., 1992). 90-95% mercury removal has been demonstrated. The primary problem is treatment of the contaminated scrubber liquors. Additional research is needed to determine optimum operating conditions and effective chemical additives.

3.10 CATALYTIC OXIDATION

Recent work by Japanese and European researchers has shown that PCDD/PCDF may be controlled by catalytic oxidation using metal (such as vanadium and tungsten oxides on a platinum oxide based substrate) catalysts that are presently commonly used for reducing NO_x emissions through the Selective Catalytic Reduction technique (SCR) (Fouhy, 1992; Hagenmaier, 1992; Ok, 1993; Hiraoka, 1990). The catalytic oxidation of PCDD/PCDF has been shown to occur in a temperature range of about 480 to 660°F. PCDD/PCDF destruction efficiencies of 95 to 98% have been demonstrated, with controlled levels below 0.1 ng/dscm TEQ. For example, operation on a full scale MWC controlled levels of PCDD/PCDF to below 0.1 ng/dscm TEQ, with most levels at or below 0.05 (Boos, 1993). See Section 5 of *Technical Support Document for HWC MACT Standards Volume III: Selection of MACT Standards and Technologies* for further discussion on MWC data. Catalysts are currently available from many vendors including Lentjes, Deutsche Babcock, Siemens, BASF, Huls, Degussa, and SGP-VA. Problems with this method include catalyst fouling and contamination from metals, sulfur, or chlorine compounds, leading to deactivation.

3.11 SULFUR-BASED CONTROL

Source testing has shown that PCDD/PCDF are either not detected or present at very low levels in coal fired boiler flue gas emissions (Junk and Richard, 1981). This has been surmised to be due to the presence of relatively higher levels of sulfur which may act to suppress PCDD/PCDF formation. This is supported by additional work on the co-firing of coal with municipal solid waste. Full scale testing on a MWC has shown that the addition of coal (containing 19 weight percent sulfur) to the municipal solid waste stream acted to reduce PCDD/PCDF levels from 10 to less than 1 TEQ ng/dscm (Lindbauer, 1992). Other studies on the co-combustion of coal with plastics and bark have shown very low PCDD/PCDF levels below 0.1 TEQ ng/dscm (Mattila, 1992; Frankenhaeuser, 1993). Interestingly, with the addition of limestone to the combustion region, as expected sulfur flue gas emissions decreased, but PCDD/PCDF emissions increased substantially, further lending evidence to the fact that the presence of sulfur suppresses PCDD/PCDF formation (Frankenhaeuser, 1992). Additional data substantiating sulfur-based control is discussed in Section

It has been postulated that the presence of sulfur as SO₂ suppresses Cl₂ formation, thus reducing PCDD/PCDF formation. However, controlled laboratory scale studies determined that gas phase SO₂ has little apparent effect on PCDD/PCDF formation, and that the presence of sulfur as an upstream reaction product acting to alter the form of the metal catalyst required for low temperature (300 to 400°C) catalytic formation (e.g., CuSO₄ instead of CuO) may be attributable to low PCDD/PCDF levels in systems with sulfur (Gullet, 1992).

3.12 AIR POLLUTION CONTROL SYSTEM TYPES

As discussed above, the choice of flue gas cleaning components and arrangement depends on characteristics of the flue gas such as:

- Particle size distribution and loading.
- Acid gas content (nitrogen, sulfur, and chlorine).
- Organics content.
- Metals content.
- Radioactivity type and level (transuranic, alpha, beta or gamma contaminated, low level, etc.).

Note that these parameters are influenced by both the incinerator type and waste composition and type. Generally, all air pollution control system can be classified as either dry, wet, or hybrid dry/wet.

3.12.1 Wet

Wet system are typically selected when the flue gas has significant levels of moisture, “sticky” compounds, and/or when acid gas control is required. In the wet system, a quench cooler is used to saturate the flue gas stream. Venturi and other novel scrubbers may be used for particulate control; additional packed bed, spray or tray type scrubber may be used for additional acid gas and volatilized component capture. The flue gas stream must then be conditioned (heated or dried) if final polishing (e.g., with HEPA filtration) to avoid moisture condensation in the filters. Advantages of wet systems include rapid and predictable gas cooling, low temperature operation aiding in capture of volatilized metals and acid gases, and ease of byproducts handled in wet form. However, disadvantages include:

- Generation of contaminated secondary liquid stream.
- Rapid degradation of dry filters located downstream of wet scrubbing form moisture carry over from cooling and scrubbing steps.

- Inefficient fine particle collection compared with dry filter systems.
- Increased corrosion potential.

3.12.2 Dry

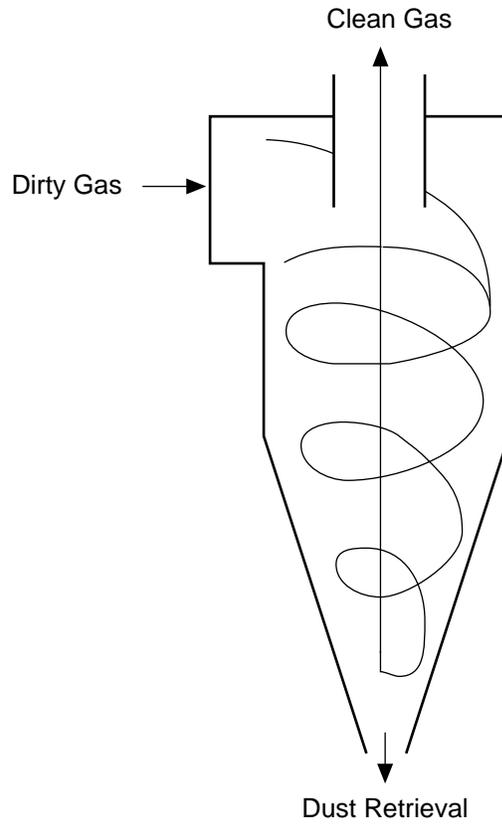
Dry systems are preferred when the flue gas leaving the incinerator does not contain acid gases. Dry systems do not saturate the flue gas to prevent condensation in the downstream devices, although water injection may be used for cooling. Dry systems utilize either high temperature coarse particle removal devices such as cyclones and ceramic or sintered metal filters, or lower temperature devices such as baghouses and ESPs. Dry systems can use spray driers to control acid gases, although large amounts of secondary wastes (captured dry solids) are generated due to their relative inefficiency.

Advantages of using dry systems include efficient capture of fine particles and avoidance of contaminated liquid waste generation, efficient control of fine particulate, and minimization of corrosion potential. Disadvantages include inefficient or nonexistent capture of acid gases and generation of large amounts of dry scrubbing product.

3.12.3 Hybrid Wet/Dry

The third type of system, a “hybrid dry/wet” combination, uses a combination of both dry and wet components, as shown in Figure 3-32. Dry/wet systems perform dry initial and fine particle removal in a manner similar to that of dry systems; however, the flue gas is passed through a wet scrubber/absorber, which is used to remove acid gases and other volatilized components. Typically, a SDA/FF and wet scrubber are used in series. The SDA is located upstream of the wet scrubber, and is utilized to dispose of the liquid effluent produced from the downstream two-stage wet scrubber. Hybrid systems may be designed to include the advantages of both wet and dry system including generation of dry secondary waste, efficient capture of fine particulate, as well as low temperature capture and control of acid gases and volatile metals. The primary disadvantage is increased capital cost and system complexity. Other potential disadvantages include the re-release of contaminants caught in the wet scrubber liquid when reinjected back into the flue gas stream to cool the flue gas, and the potential for recycling and buildup of trace constituents due to this recycling of scrubber liquor blowdown.

(a) Particle collection procedure



(b) Flue gas inlet options

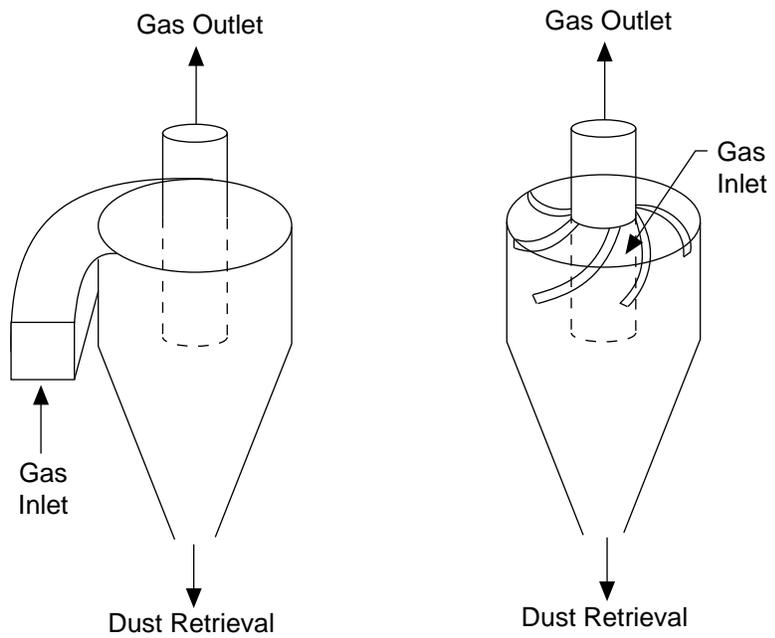


Figure 3-1. Cyclone operations.

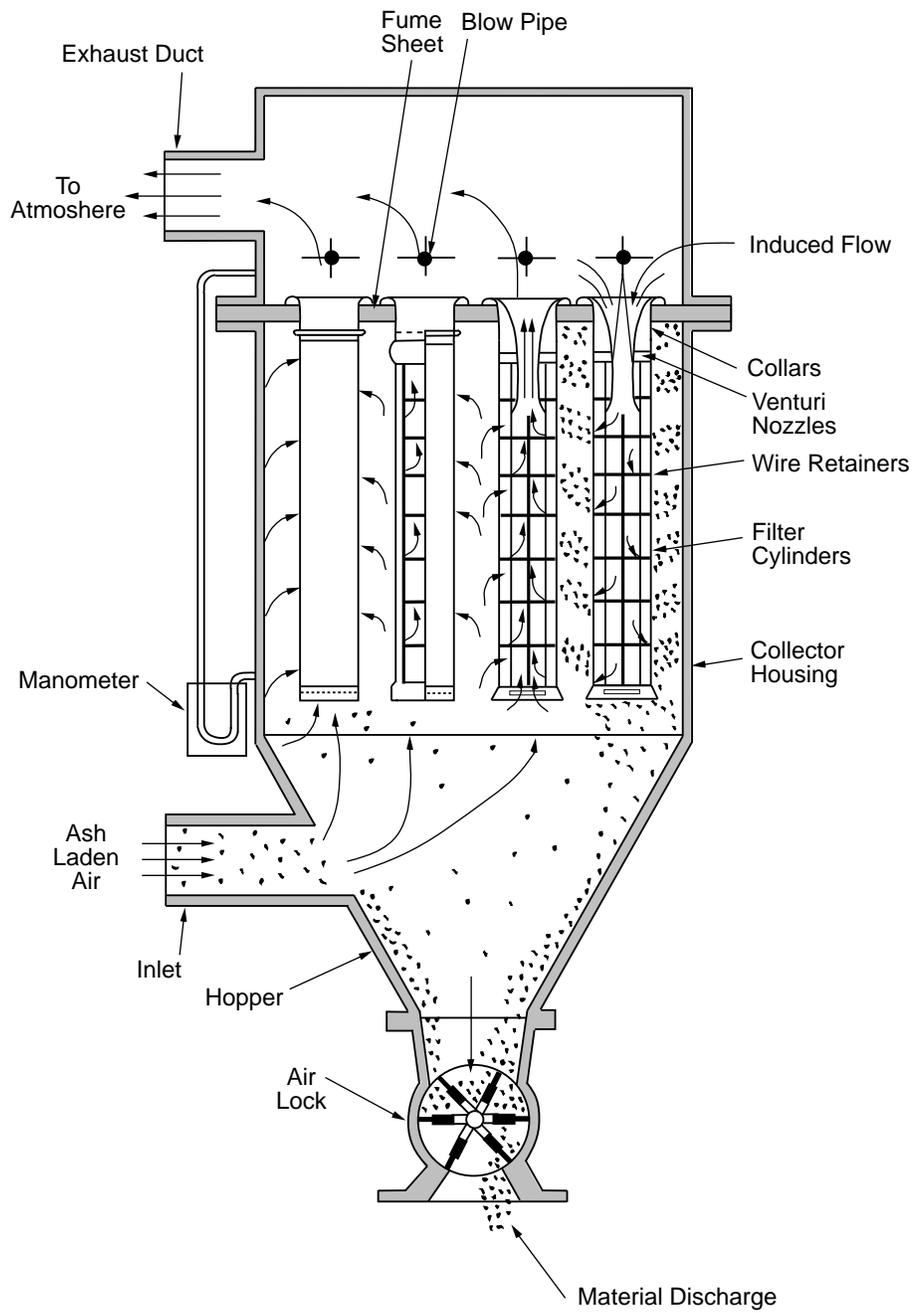


Figure 3-2. Pulse-air-jet type bag filter.

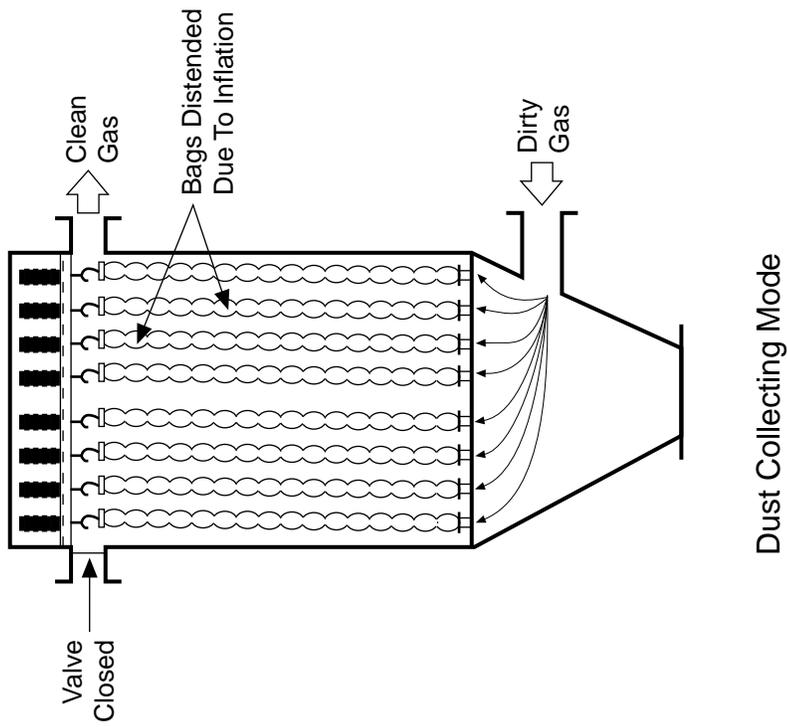
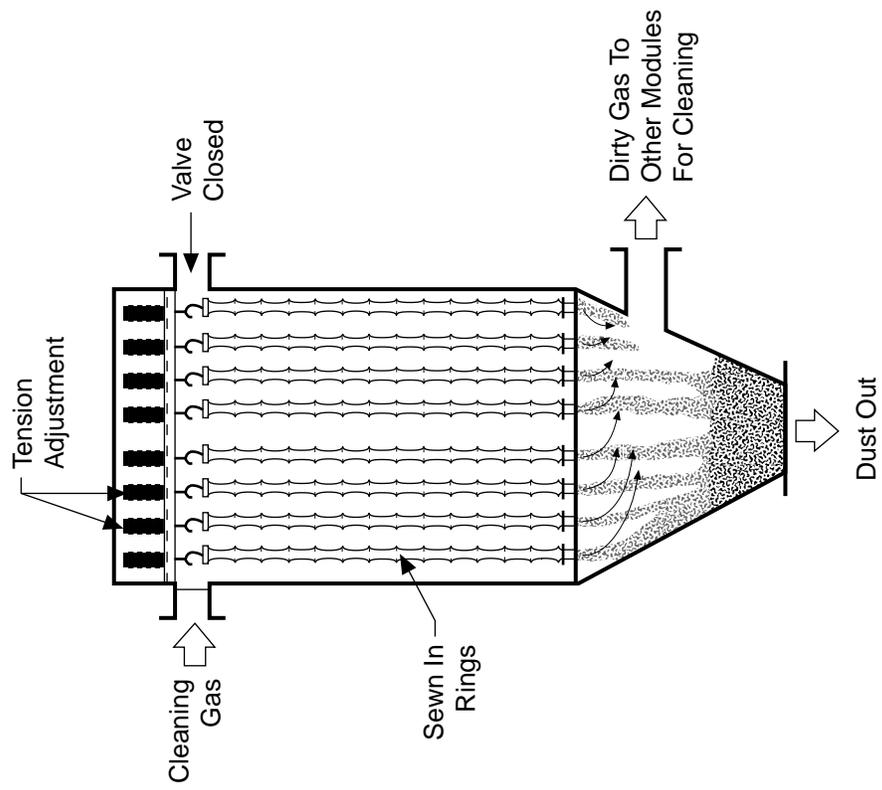


Figure 3-3. Reverse air cleaning baghouse.

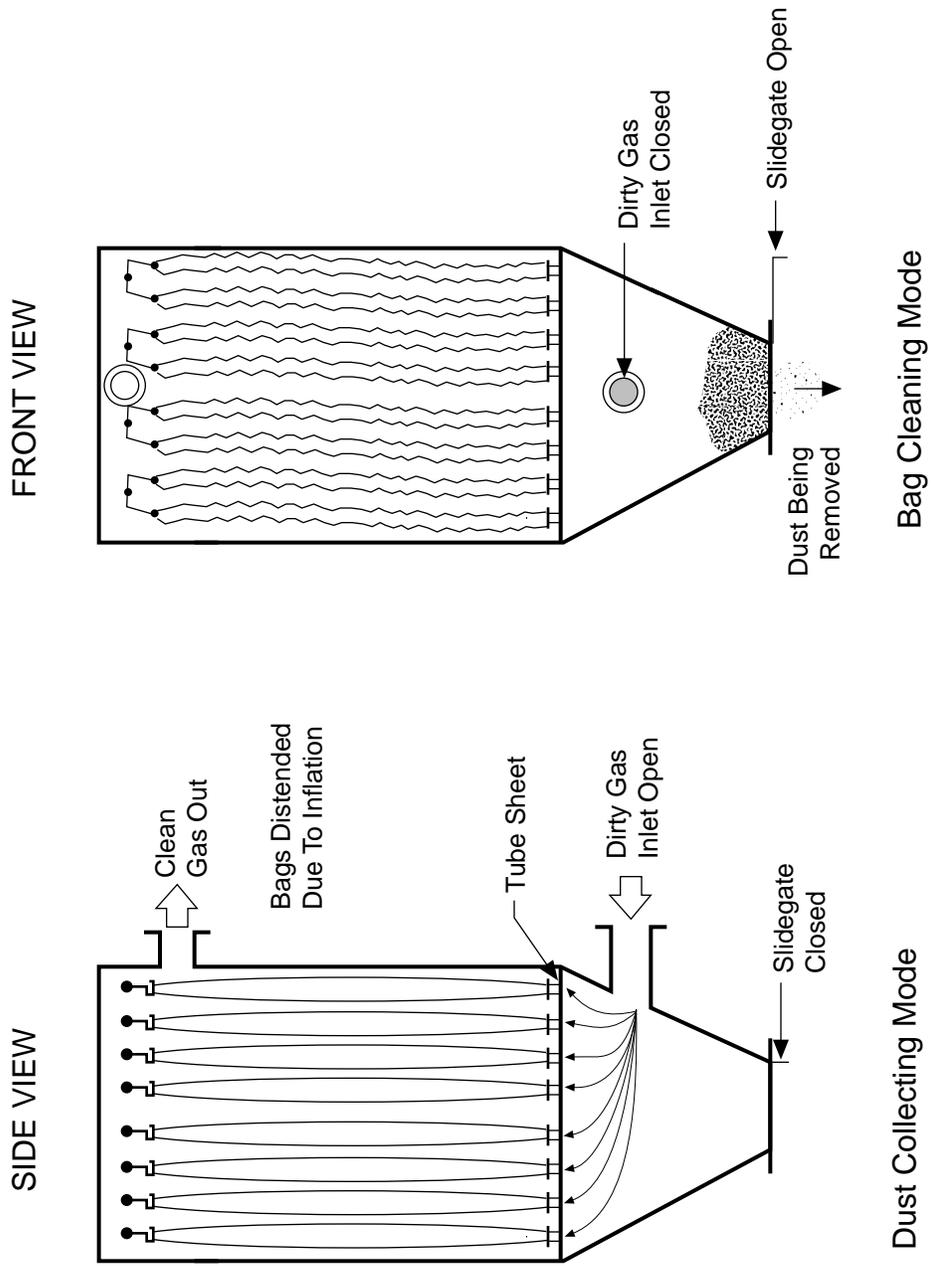


Figure 3-4. Shaker cleaning baghouse.

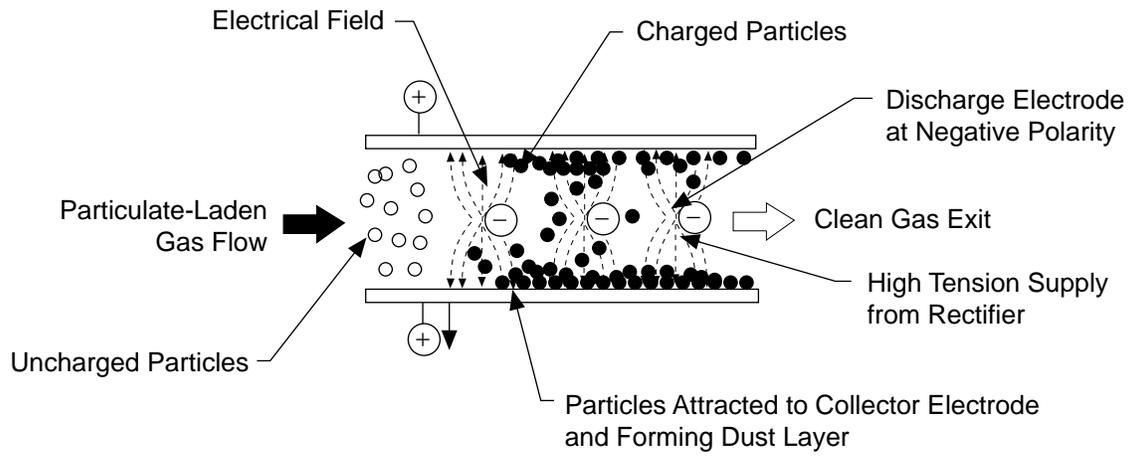
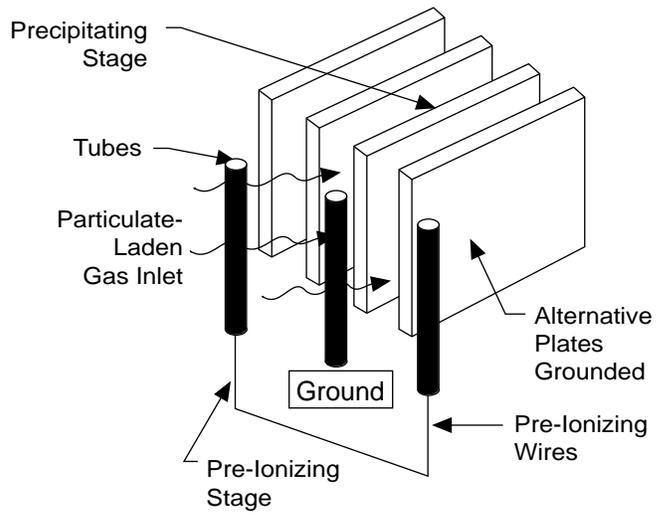
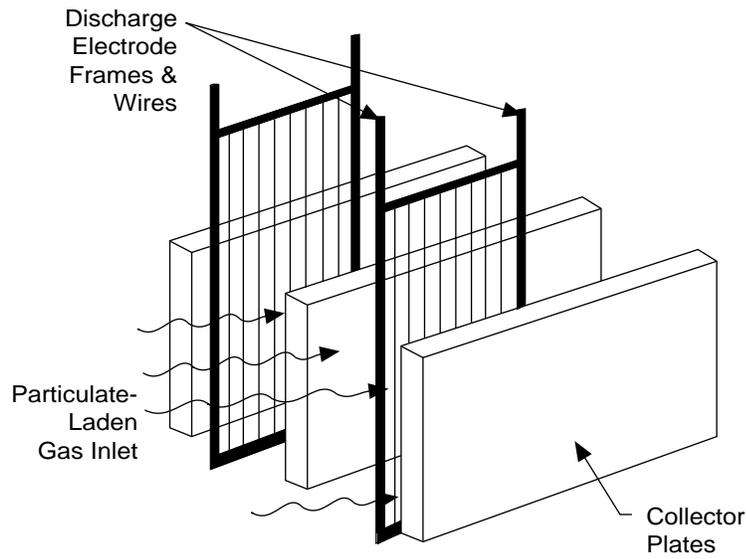


Figure 3-5. Electrostatic precipitator particle collection procedure.



(B) Two Stage Precipitator



(A) Single Stage Precipitator

Figure 3-6. One and two-stage wire-to-plate ESP operation.

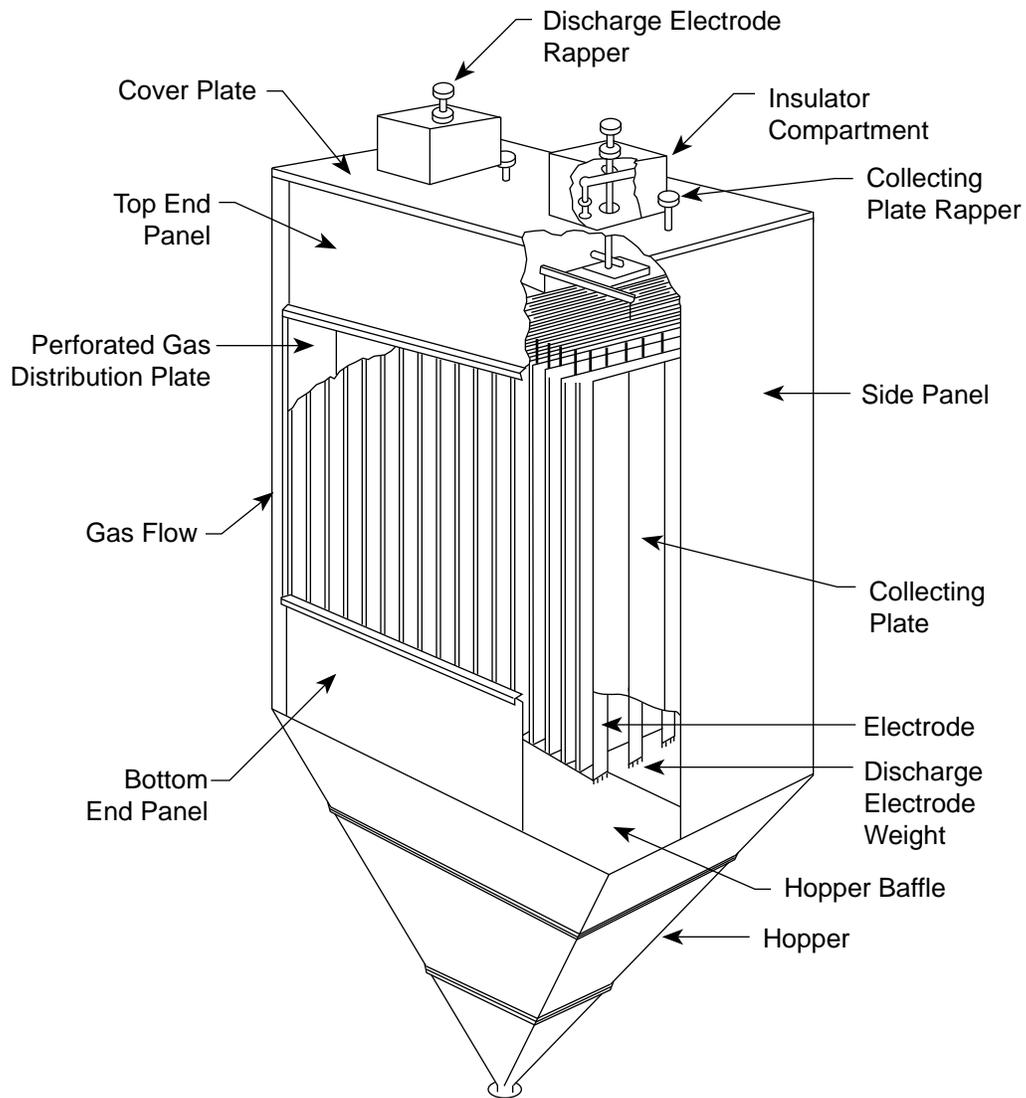


Figure 3-7. Plate type electrostatic precipitator.

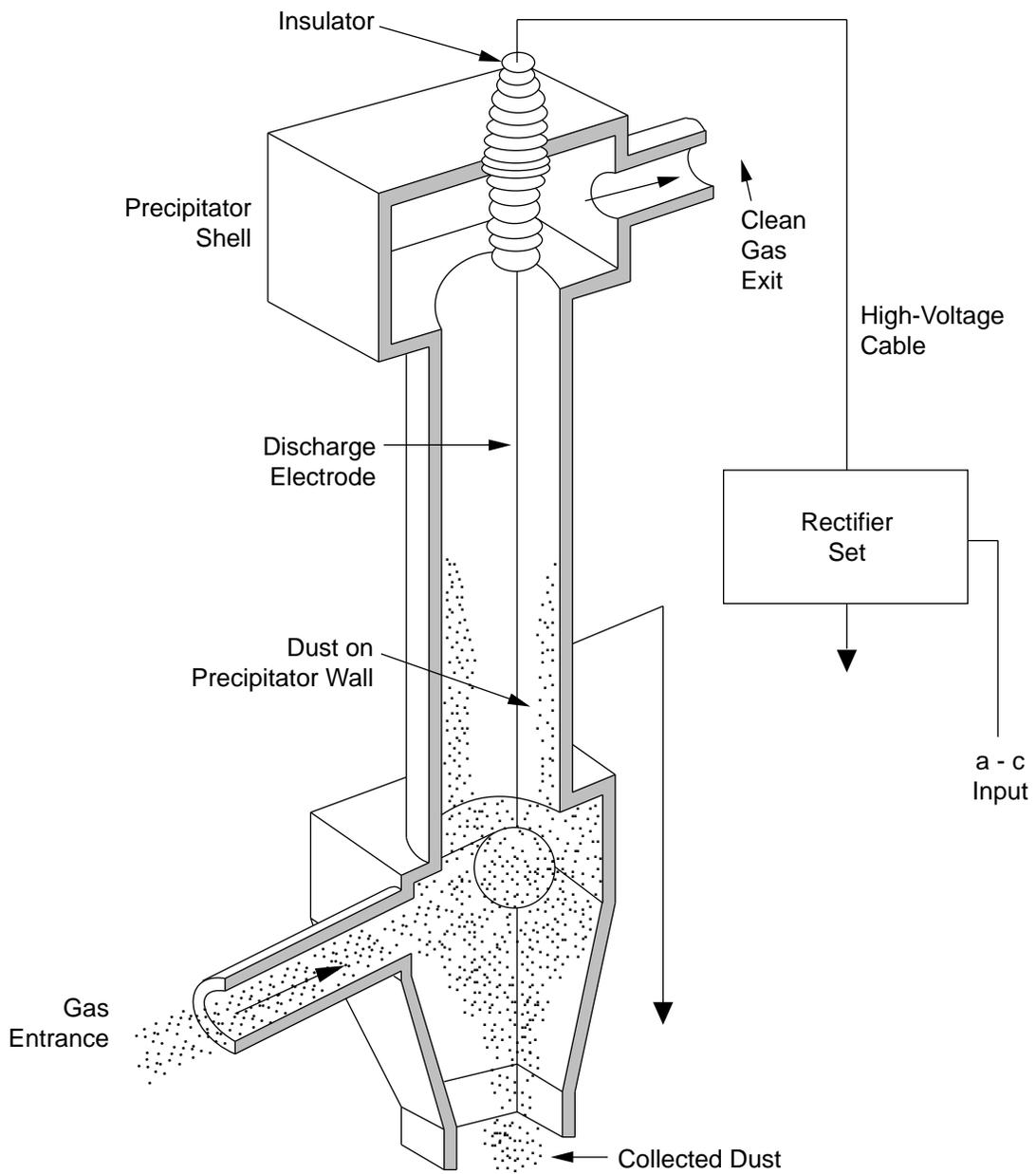


Figure 3-8. Tubular type ESP.

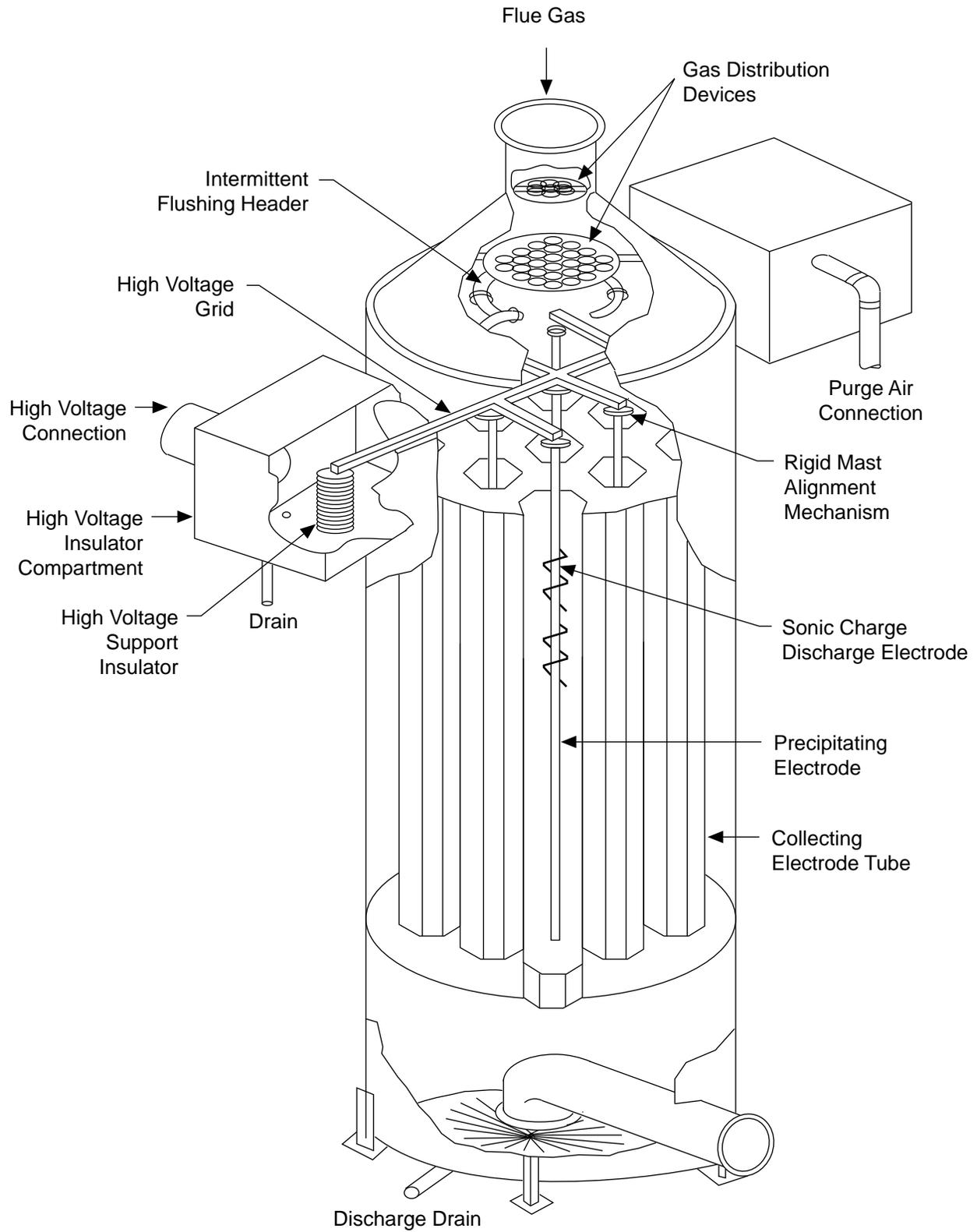


Figure 3-9. Wet ESP.

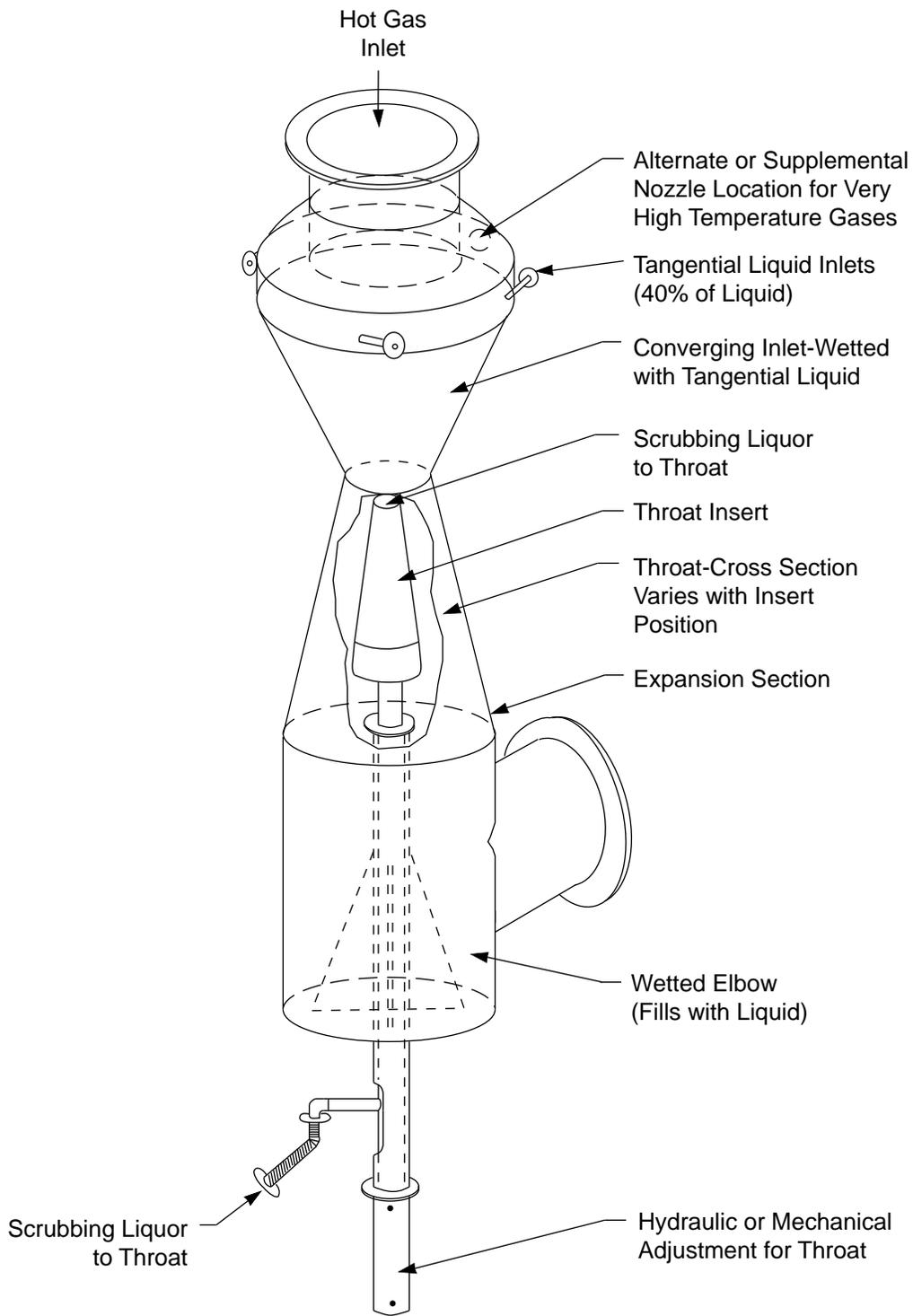


Figure 3-10. Variable throat venturi scrubber with wetted elbow.

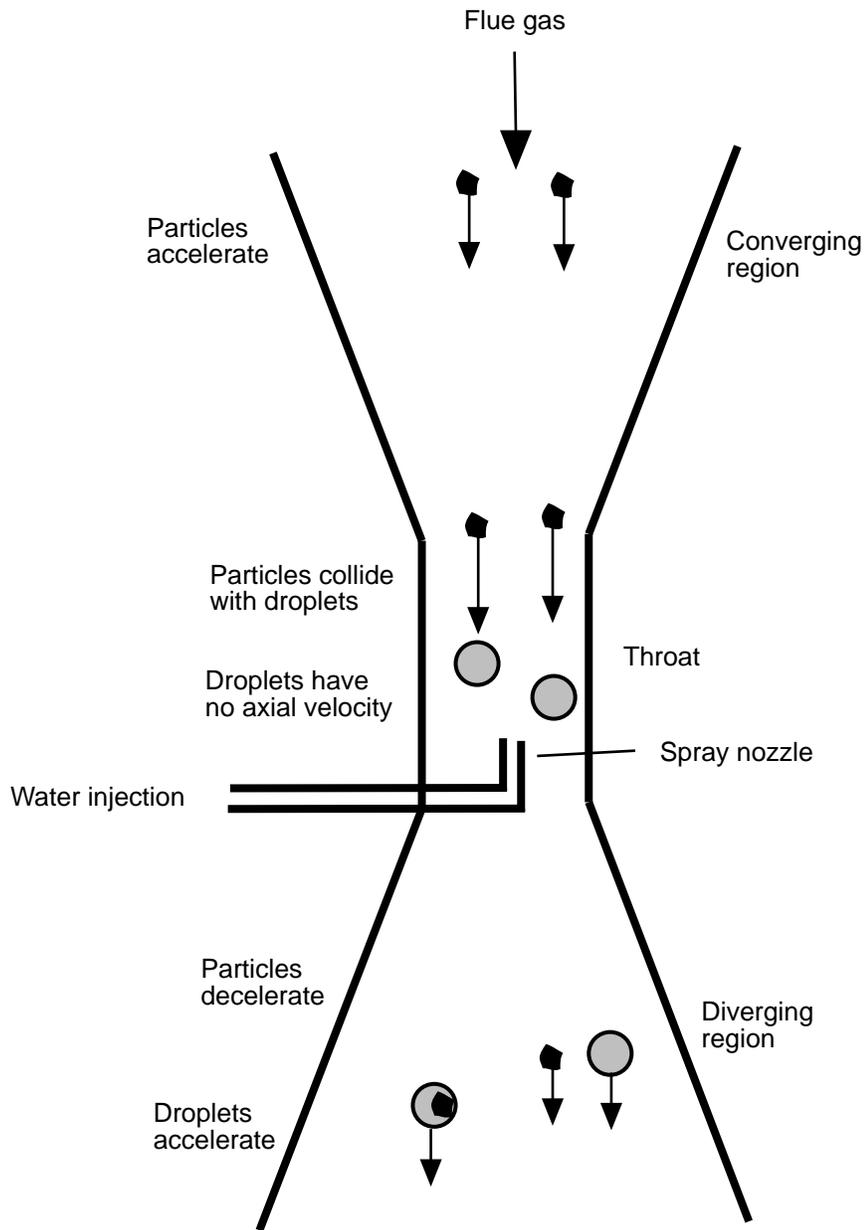


Figure 3-11. Performance principles of a venturi scrubber.

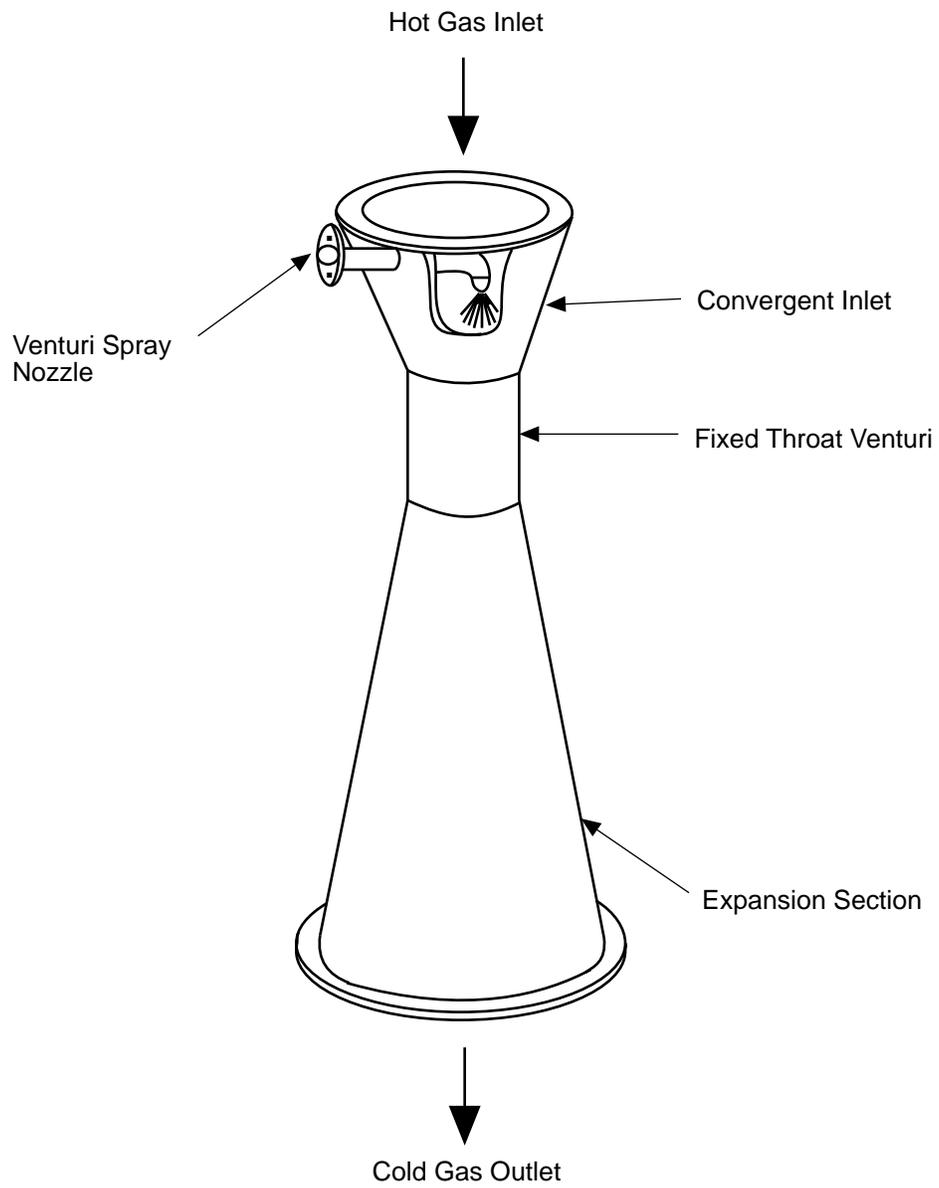
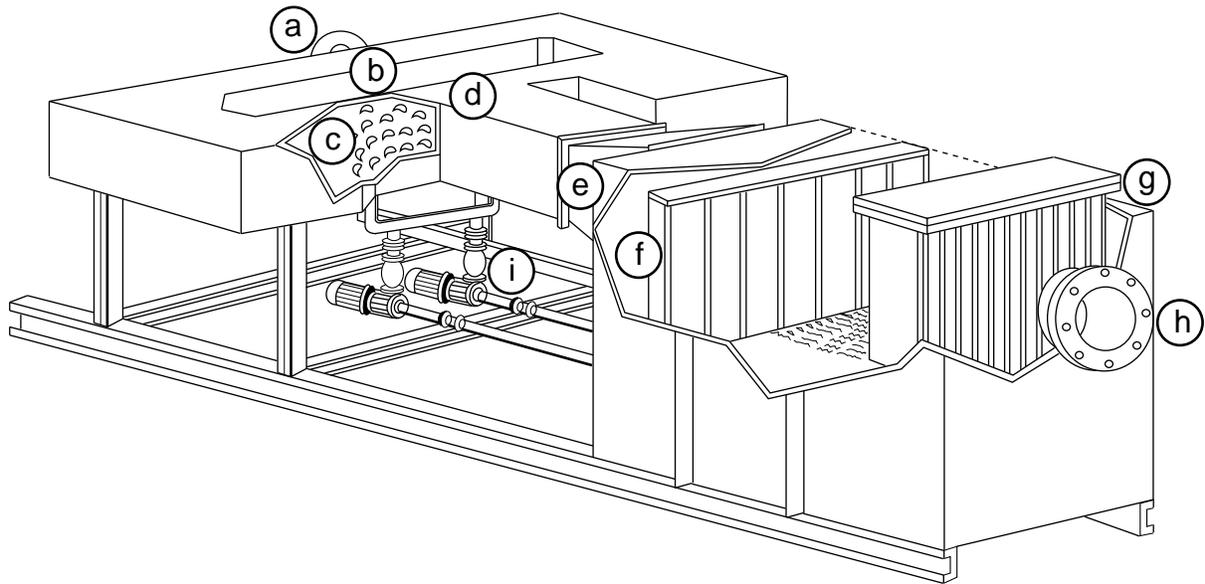


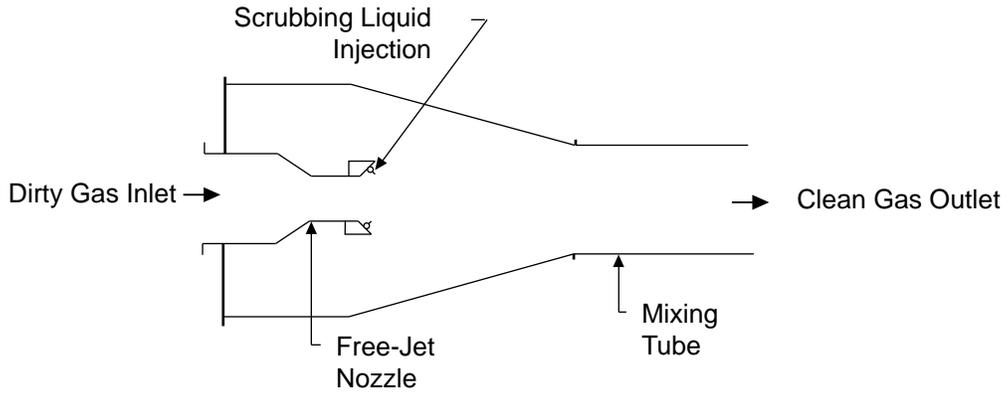
Figure 3-12. Non-wetted, fixed throat venturi scrubber.



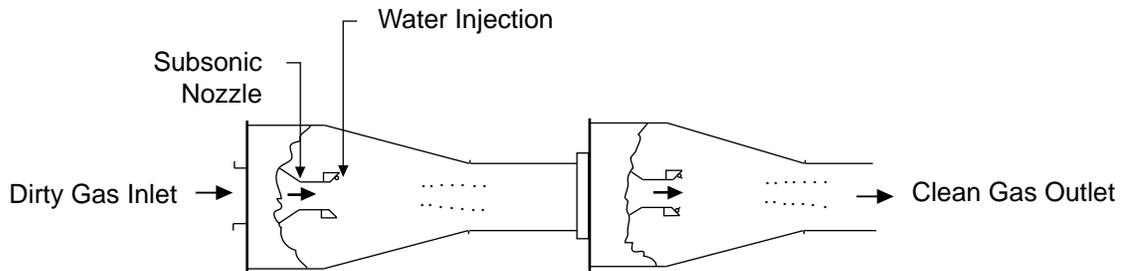
- | | |
|--|---|
| <p>(a) Gas Inlet
Flanged inlet for dust, fume and acid gas flow.</p> <p>(b) Throat Inlet
The gas is split into two equal flows.</p> <p>(c) Throats
Point of liquid injection (adjustable throats available).</p> <p>(d) Collision Zone
Submicron particulate and acid gases removed from the gas stream.</p> | <p>(e) Energy Recovery Diffuser
Gas and liquid stream expanded.</p> <p>(f) Primary Droplet Eliminator
Most of the water removed.</p> <p>(g) High Efficiency Waveforms
Fine droplet eliminators polish the gas.</p> <p>(h) Gas Outlet
Flanged connection for clean gas flow exit.</p> <p>(i) Pump
Returns water to the throat via distribution headers.</p> |
|--|---|

Figure 3-13. Force flux/condensation/collision scrubber.

Fan-Driven Free-Jet Scrubber



Tandem Nozzle Fan-Driven Free-Jet Scrubber



Ejector Driven Free-Jet Scrubber

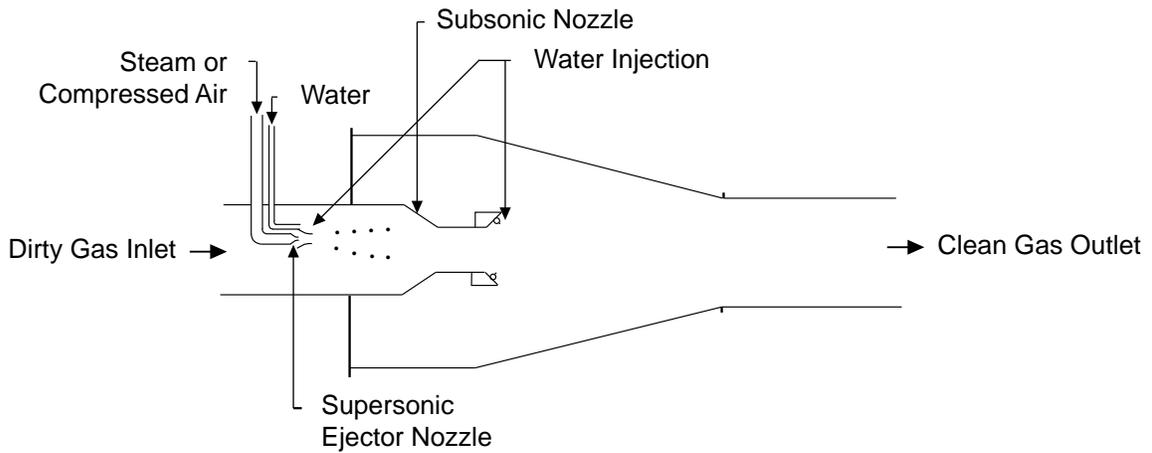


Figure 3-14. Free-jet scrubbers.

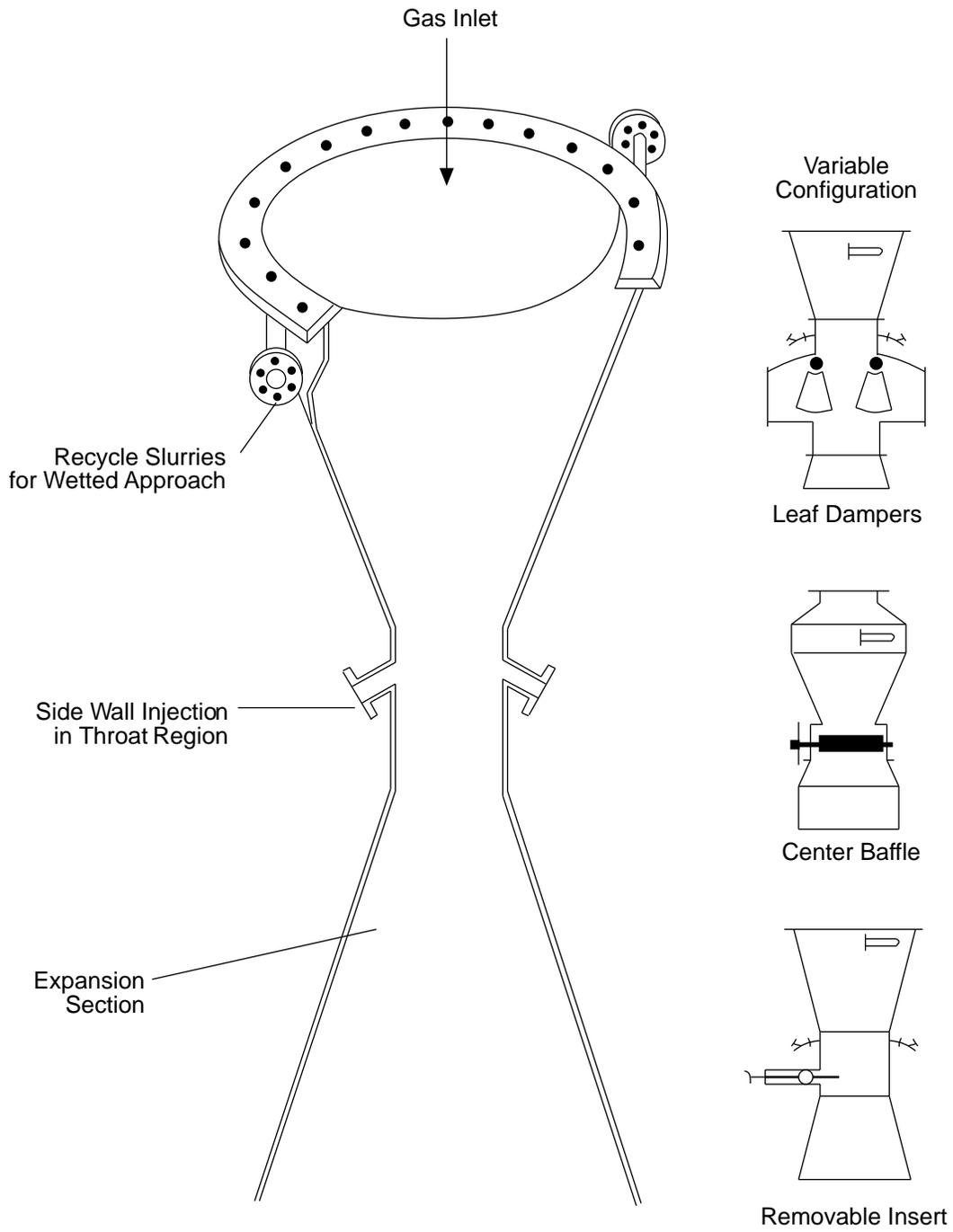


Figure 3-15. Venturi scrubber with different flow control throat mechanisms.

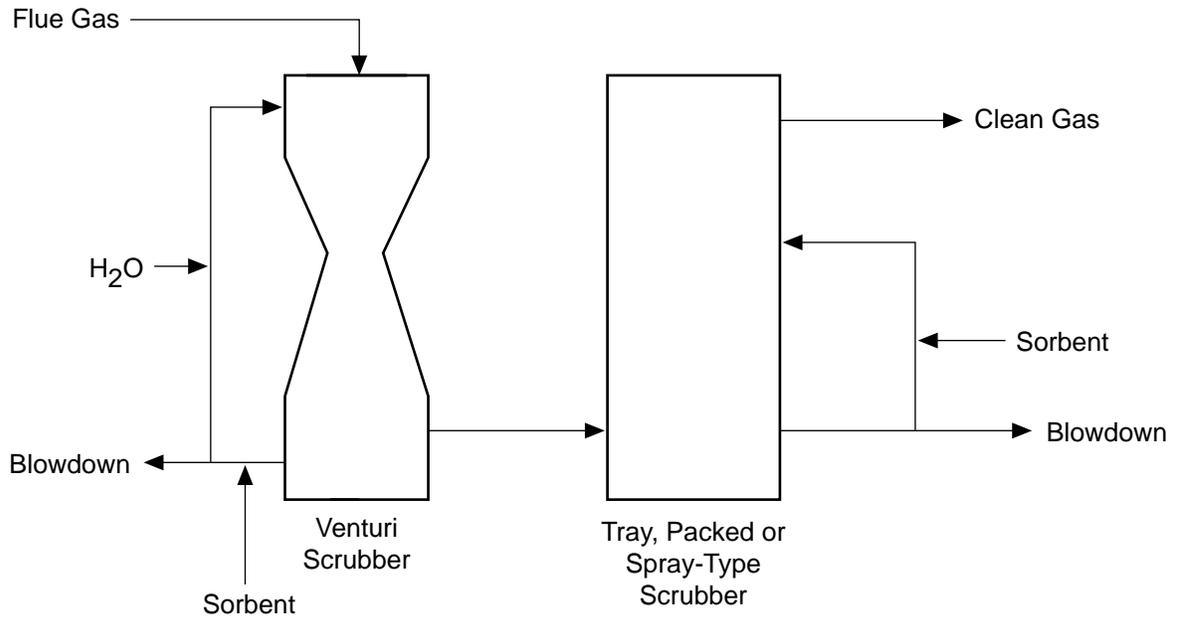


Figure 3-16a. Two-stage wet scrubbing process schematic.

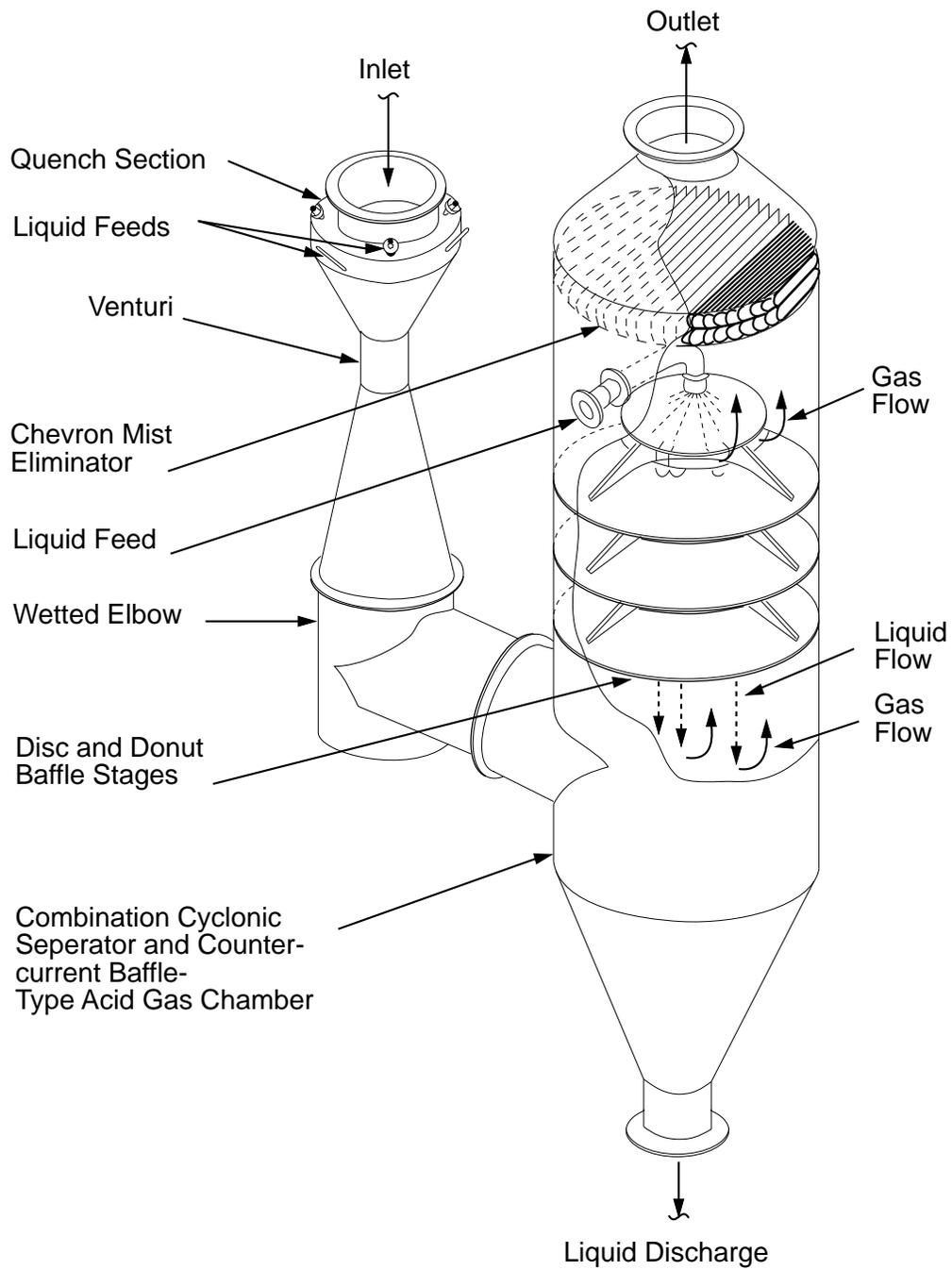


Figure 3-16b. Venturi and tray tower wet scrubbing system arrangement.

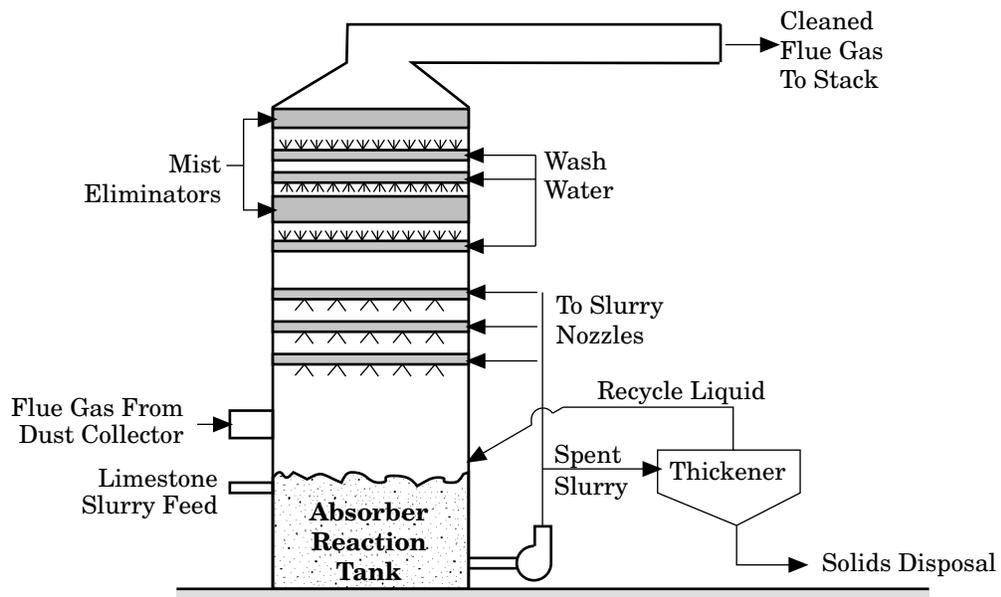


Figure 3-17. Schematic of wet scrubbing spray tower system.

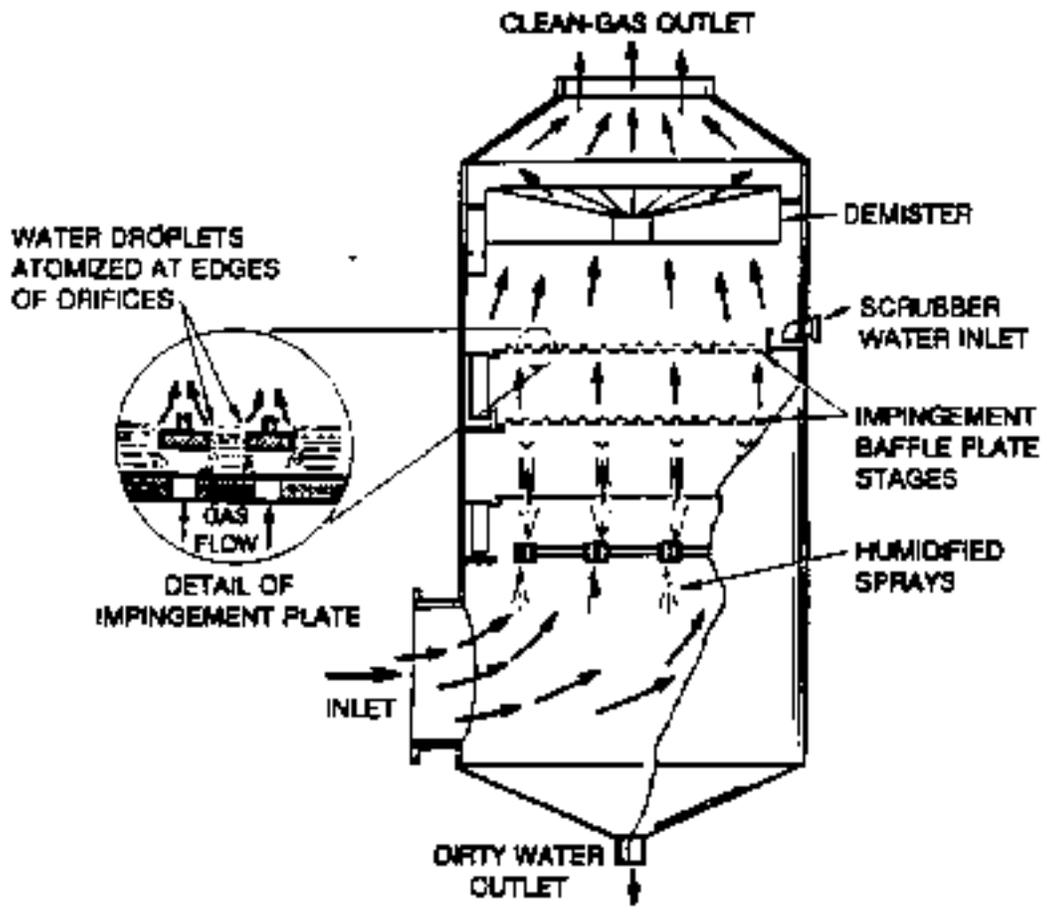


Figure 3-18. Tray tower wet scrubber.

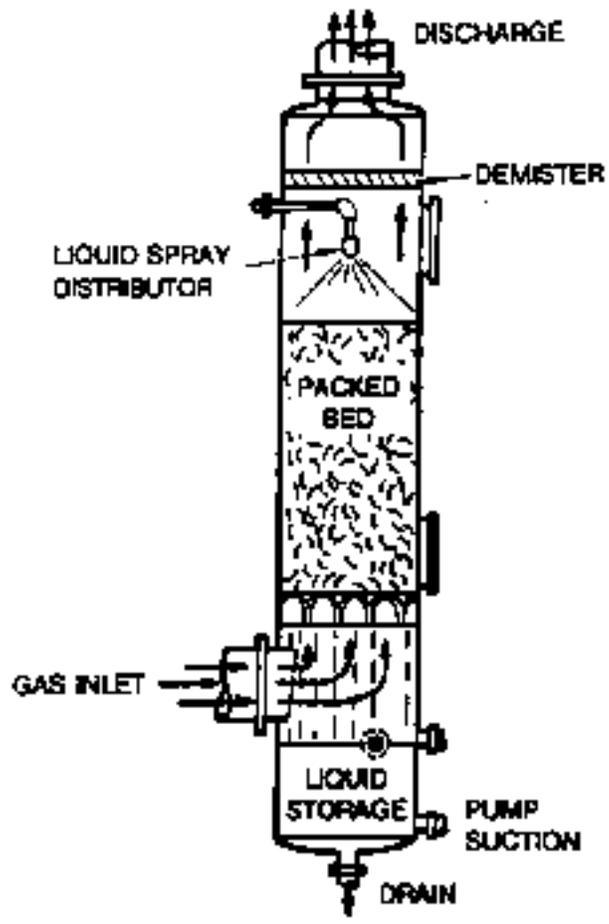


Figure 3-19. Packed bed wet scrubber.

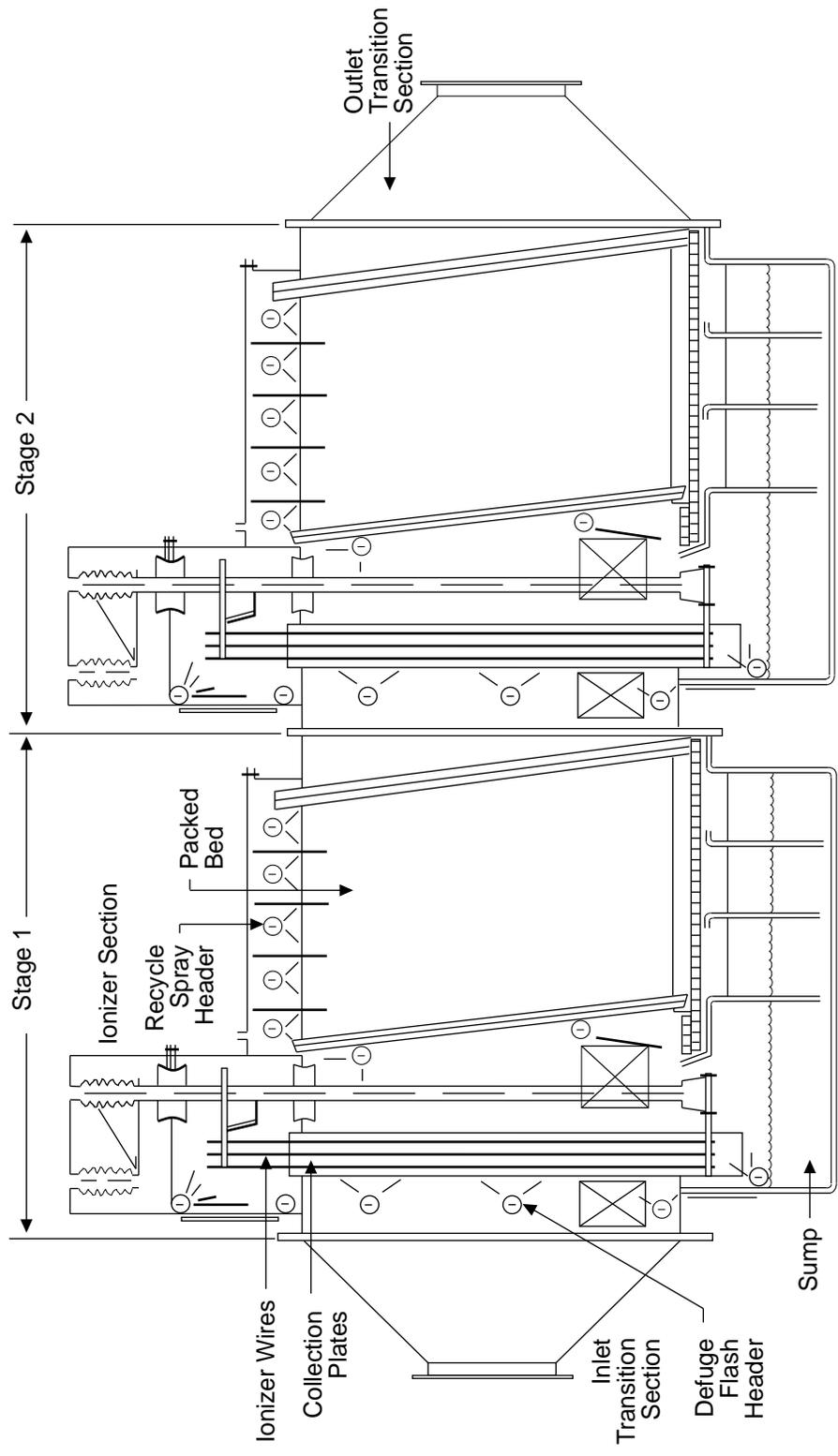


Figure 3-20. Ionizing wet scrubber schematic.

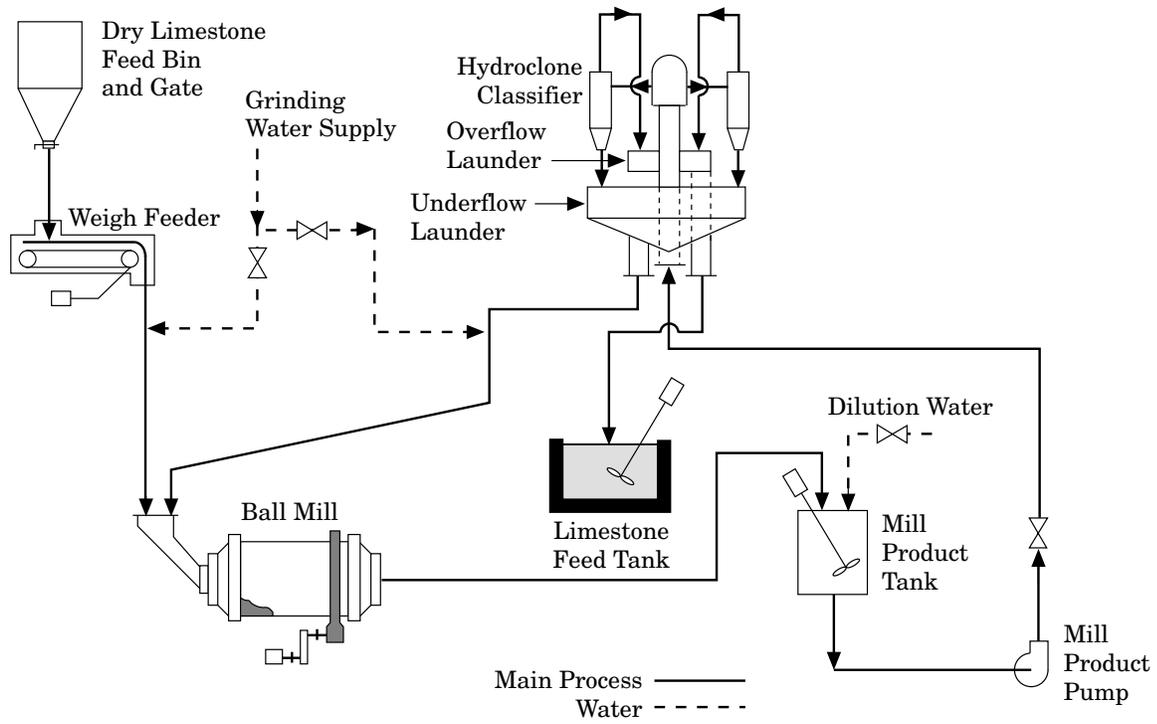


Figure 3-21. Limestone reagent preparation system.

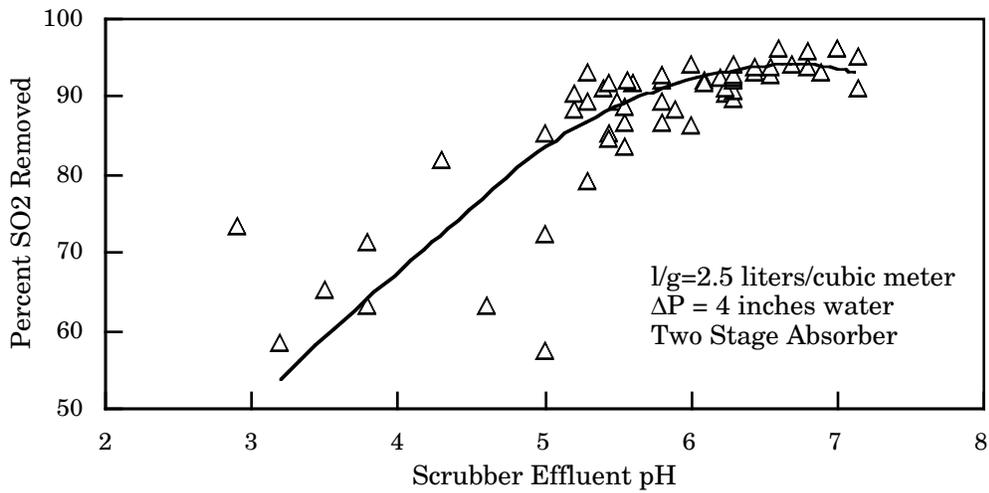


Figure 3-22. Impact of slurry pH (acidity) on SO₂ removal efficiency.

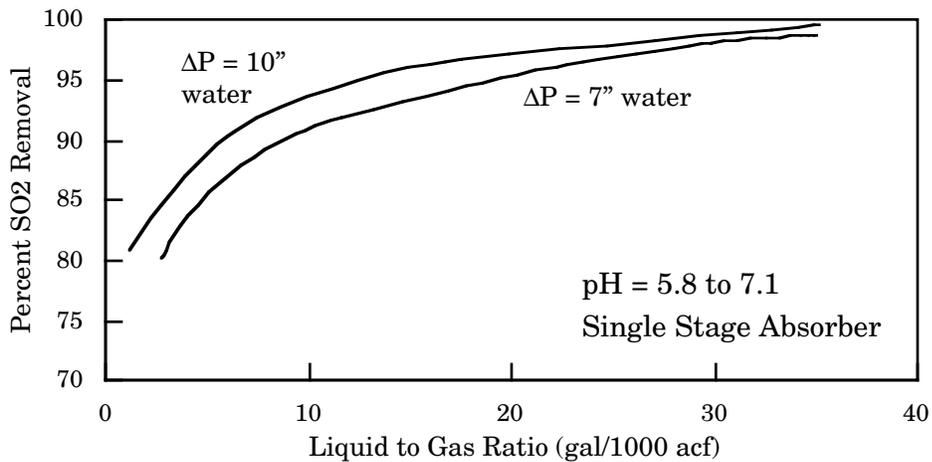


Figure 3-23. Impact of liquid to gas ratio on SO₂ removal efficiency (Elliott, 1989).

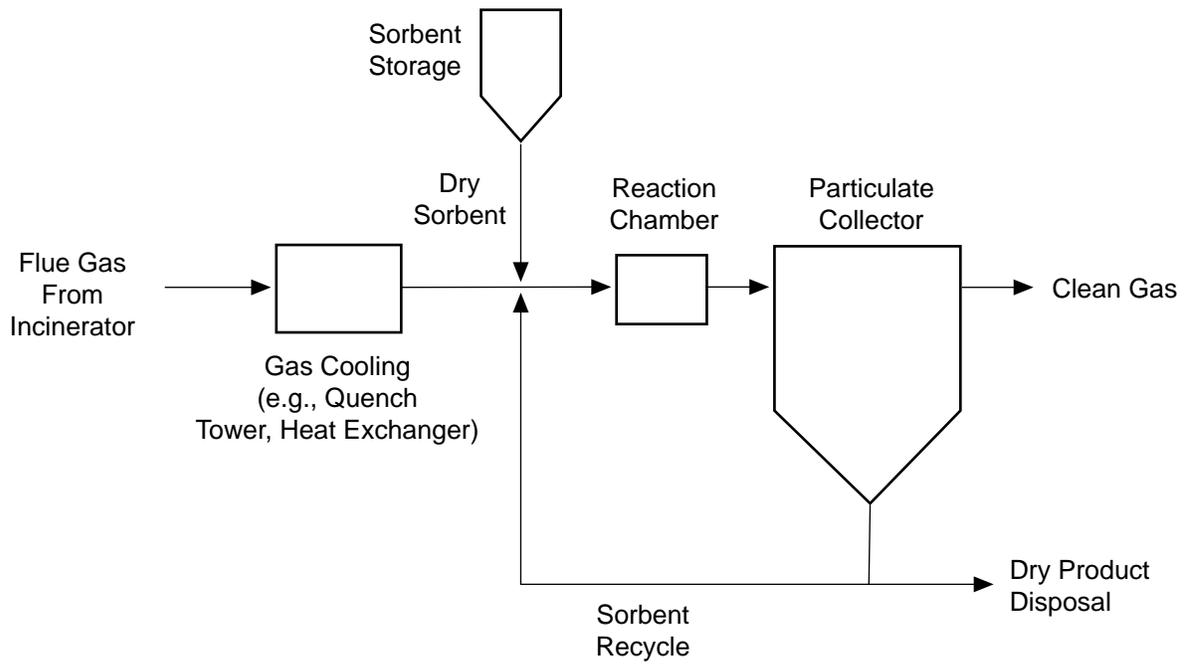


Figure 3-24. Dry scrubbing sorbent injection process schematic.

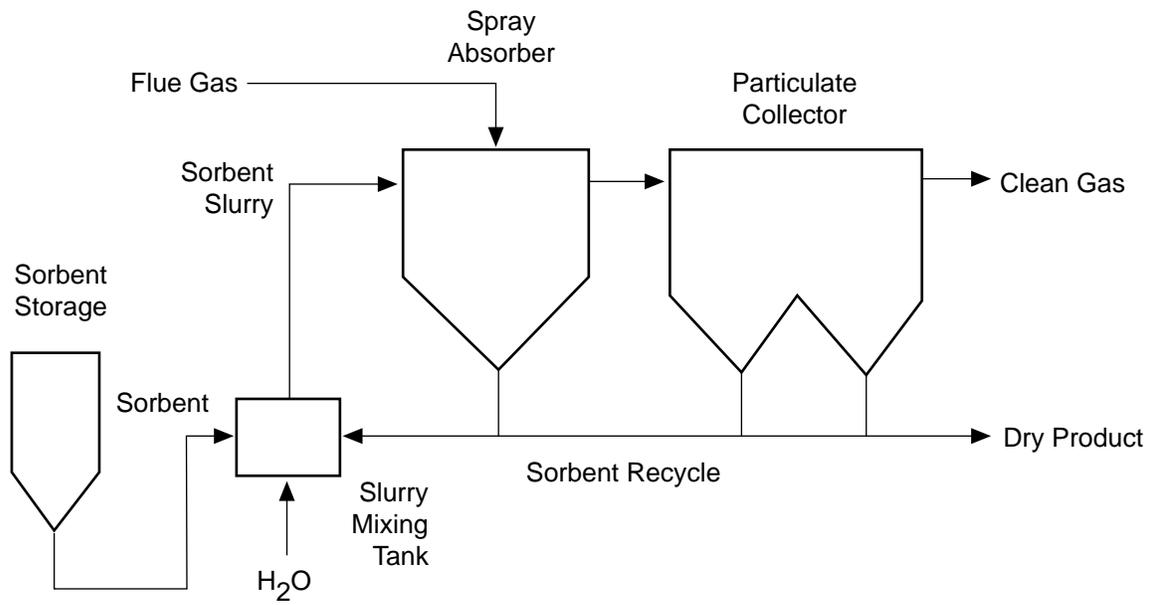
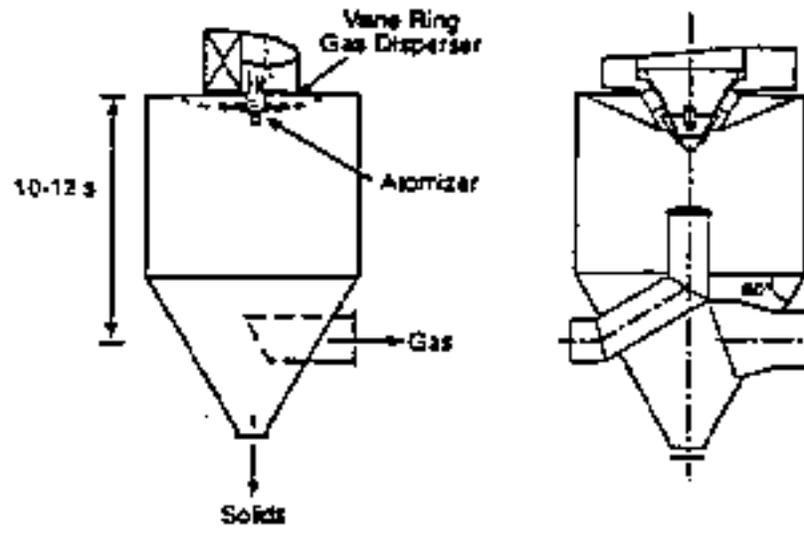
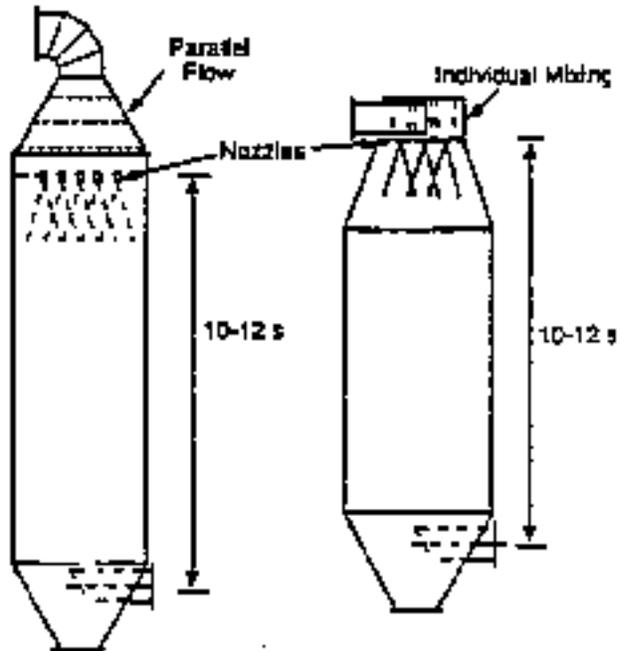


Figure 3-25. Semi-dry spray drier absorption process schematic.



A. Rotary-Atomizer Dryers



B. Two-Fluid Pneumatic Nozzle Dryers

Figure 3-26. Spray dryer designs.

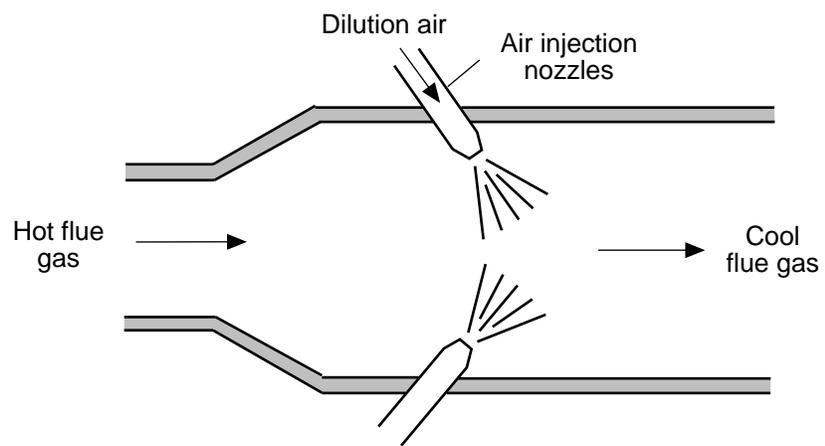
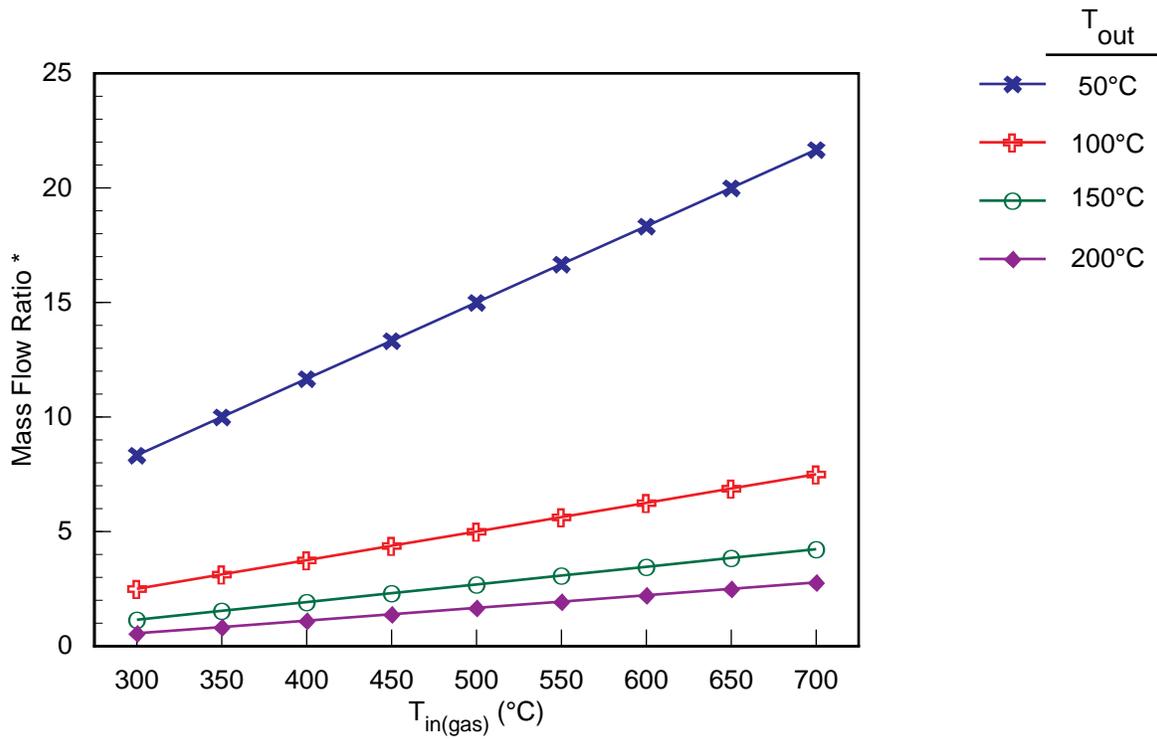


Figure 3-27. Air dilution cooling procedure.



Note: * Mass Flow Ratio = $\frac{\text{mass flow of dilution air}}{\text{mass flow of hot flue gas}}$

Figure 3-28. Example of the increase in flue gas flow rate using air dilution cooling.

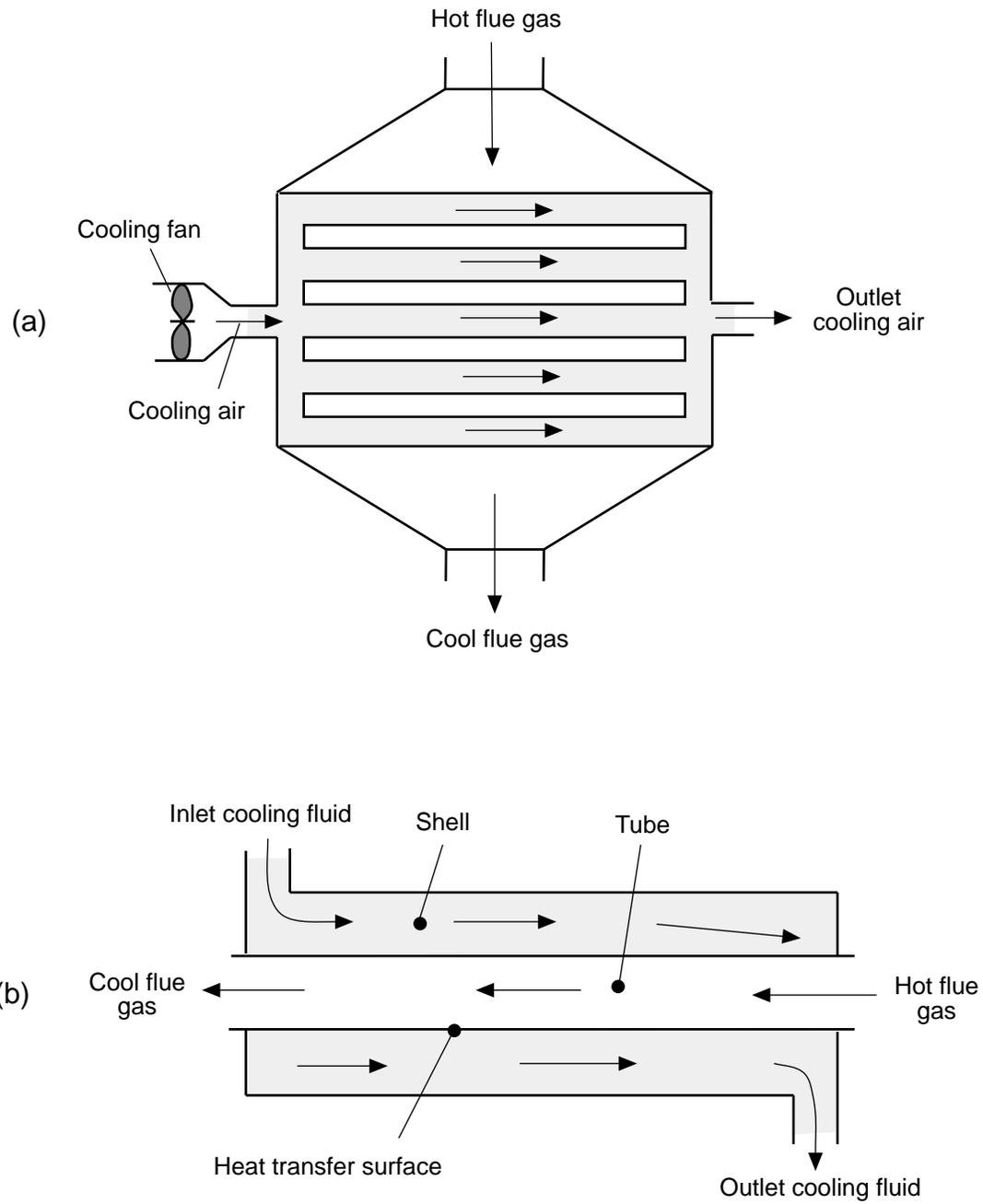


Figure 3-29. Heat exchanger schematics: (a) Gas-gas recuperator; (b) Shell and tube type.

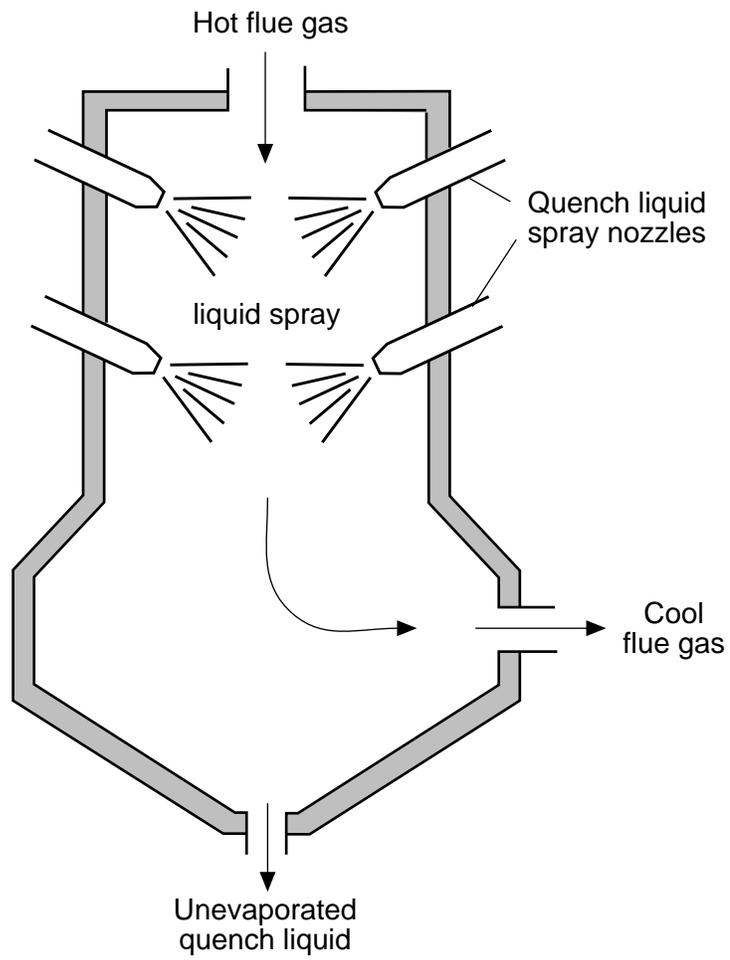
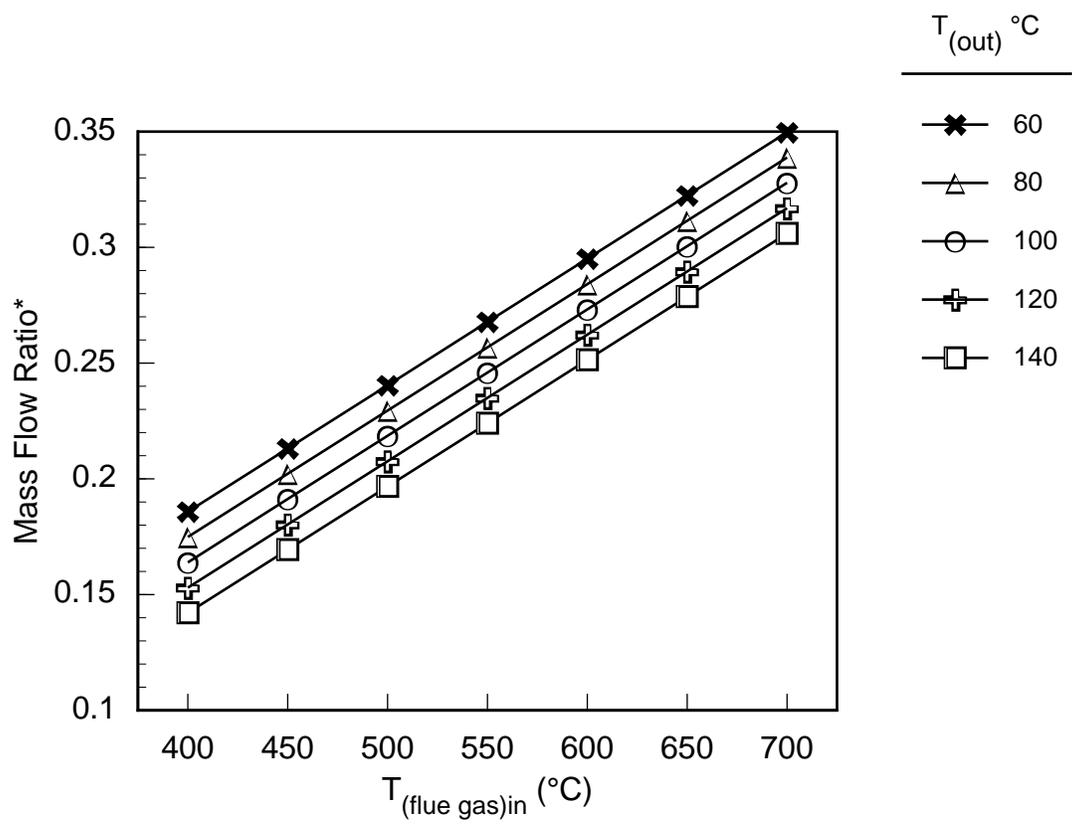


Figure 3-30. Water quench cooling procedure.



Note: * Mass Flow Ratio = $\frac{\text{mass flow of quench water}}{\text{mass flow of hot flue gas}}$

Figure 3-31. Example of increase in flue gas flow rate using water quench cooling.

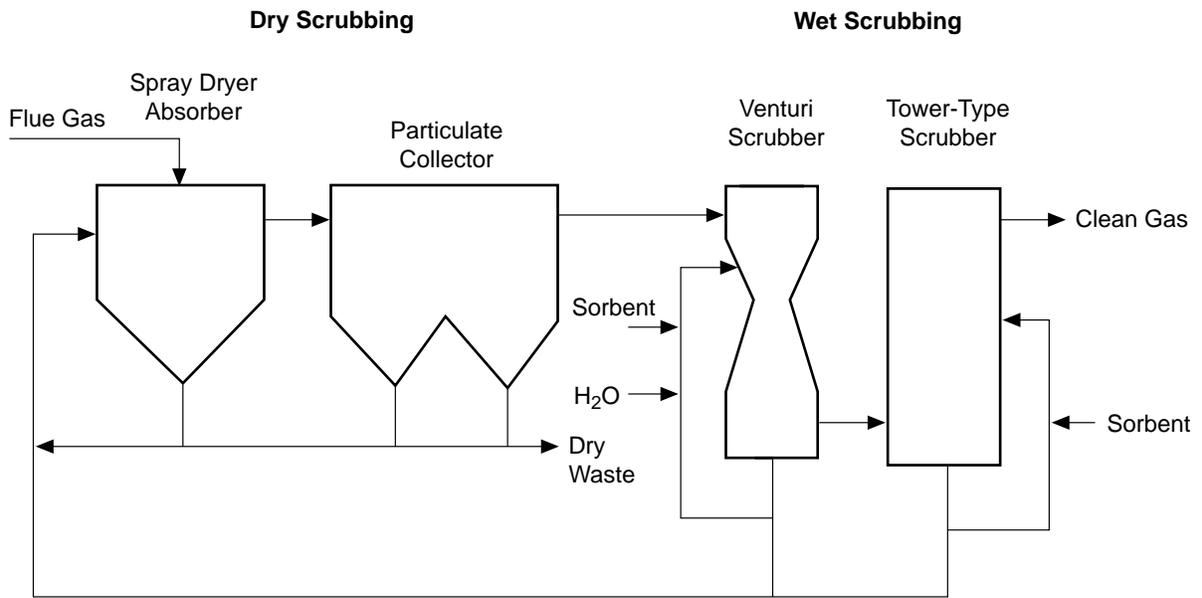


Figure 3-32. Hybrid wet/dry system schematic.

TABLE 3-1. SORBENTS USED FOR REMOVAL OF METALS FROM COMBUSTION SOURCE FLUE GASES

Sorbent	Primary Removal	Temperature Range (°C)	Removal Efficiency (%)
Zeolites Sulfur impregnated	Hg	< 100	90+
Activated carbon	Hg	< 200	
Calcium-based Calcium hydroxide/fly ash Limestone/fly ash	Hg As, Cd, Pb	< 300 600-900	
Alumina-based Bauxite	Cd, Pb	500-700	
Silicates Silica sand Kaolinite Emathlite Aluminum silicates	Pb, Cd, As	600-900	

Based from that of Clarke and Sloss (1992).

SECTION 4

MAJOR SOURCE DETERMINATION

Title 3 of the 1990 Clean Air Act Amendments requires that “major sources” of hazardous air pollutants meet emission standards based on the reduction capability of the maximum achievable control technology (MACT). The amendments define major sources as follows:

“Any stationary source or group of stationary sources located within a contiguous area and under common control that emits or has the potential to emit considering controls, in the aggregate, 10 tons per year or more of any hazardous air pollutant or 25 tons per year or more of any combination of hazardous air pollutants.”

The objective of this task was to identify the incinerator and industrial kiln (cement and light weight aggregate) facilities that meet the major source criteria. This section describes the methodology used to evaluate the facilities and the number of facilities in each source category that meet the major source definition.

4.1 METHODOLOGY

To determine which facilities are major sources, the following procedure was followed:

1. Emission rates for individual incinerators/kilns.

Emission rates for individual incinerators and kilns were obtained from trial burns conducted to determine compliance with the Resource Recovery and Conservation Act (RCRA). These tests were performed while burning hazardous waste at worst case operating conditions. The tests were designed to represent the maximum emissions conditions expected to be achieved by the given facility. These maximum conditions are suitable for the major source determination since the CAAA reads that a major source has the “potential” to emit the quantitative amounts stated above.

For compounds measured below the laboratory detection limit (i.e., non-detect values), the emission rate is unknown. Assumptions were made to estimate the emission rate for these compounds. For this study, three different cases were evaluated:

- i. Full-detection: emitted value is assumed to be the laboratory detection limit value,
- ii. Half-detection: emitted value is assumed to be half the laboratory detection limit value,
- iii. Zero-detection: emitted value is assumed to be zero.

It should be noted that trial burns are conducted at either worst case metal emission conditions or organic emission conditions. In actual operation, however, a given incinerator or kiln does not always operate under worst case conditions. Therefore, using trial burn test data to estimate emissions will provide worst case determinations of major sources. For this study, two emission rate values were used for each CAAA substance including:

- iv. maximum emission rate measured during the compliance test; and
- v. average emission rate measured during the compliance test.

Using the procedures described above provides six sets of emissions profiles for each incinerator and kiln tested. The worst case set being a combination of using full detection limits for nondetected data (i) and maximum emission rates for detected data (iv).

2. *Annual emissions for individual incinerators and kilns*

Determination of the annual emission rates (tons/year) for CAAA substances required several assumptions about the annual operating schedules, since most test reports did not supply this information. Two scenarios were considered. A worst case scenario, which addressed the phrase “potential to emit” in the amendment, assumes the units operate at 365 days/year. EPA information, however, indicates that facilities rarely operate at this capacity. Limited information from various facilities indicate that an average operating schedule is approximately 315 days/year per unit. This scenario was also addressed to represent a more realistic situation.

3. *Annual emissions for incinerators on a “Contiguous Area” under common ownership*

Since trial burns conducted to determine compliance with RCRA provide data for individual units (incinerators or kilns) only, total emissions for all units at a facility (units located on a “contiguous area” under common ownership) had to be determined, as required by the major source definition. The number of hazardous waste burning units at a given facility was obtained from the trial burn reports and EPA supplied information. At some facilities, emissions data were available for all units. However, a couple of the facilities only tested selected units whose emissions were representative of all the units on site. In these cases, the emission rates from the tested units were applied to the units that were not tested. In some cases, emissions from only one unit of many on a given site were evaluated.

4.2 INCINERATOR EVALUATION

18 commercial incinerators and 28 on-site incinerators were evaluated. Since in some cases there were more than one incinerator per facility, this amounted to 16 commercial incinerator facilities and 23 on-site incinerator facilities.

Table 4-1 summarizes the results of the study, assuming an operating schedule of 315 days/year. Columns 3 through 6 demonstrate whether the facility is a major source under the specific conditions (“Y” indicates that a facility is a major source under the given conditions, “N” indicates that it is not). The first of these columns show which facilities meet the major source criteria while considering HCl and chlorine emissions. This category is broken down to indicate which facilities

are major sources when considering the maximum and average emission measured during the trial burn. Columns 5 and 6 show the same information when excluding HCl and chlorine from the data list. Table 4-1 applies to all three detection limit assumptions (i, ii, iii).

Also shown in Table 4-1 are the number of organic, metal, and chlorine compounds considered in the study. Lack of measurements may be a reason some facilities did not meet the major source criteria. The next column of the table lists the facility's air pollution control devices (APCD). APCD acronyms are described in the glossary at the beginning of this report. The last two columns indicate the number of incinerators within the facility, and comment on how the facility's total emissions were calculated using the available information.

11 of the 39 evaluated facilities meet the major source criteria when including HCl and chlorine in the emissions summation using maximum emissions. As might be expected, a greater fraction of the commercial incinerators meet the major source criteria than of the on-site incinerators. The number of "major source" facilities drops to 5 when using the average emission of each compound measured. When excluding HCl and chlorine from the emissions list, only 1 site remains a major source (Atochem, Carrollton, KY). This facility meets the criteria because antimony emissions exceeded 10 tons/yr during the high metals feed testing.

Dropping the operating schedule from 365 days/year to 315 days/year affected the classification of only one facility. Rollins Environmental in Deer Park, Texas, dropped below the major source criteria when evaluating the average emissions and including HCl and chlorine.

Figures 4-1 and 4-2 show total hazardous air pollutant (HAP) emissions per year from each facility with and without HCl/Cl₂. The type of incinerator, commercial (COMM), or on-site (OS), and the type of control equipment (see list of acronyms for descriptions) are provided in the figures. It should be noted that Figures 4-1 and 4-2 can only be used to determine if a facility can be classified under the 25 tons/yr or greater major source category. Reference to the original report needs to be made to view data representing the 10 tons/yr criteria. In summary, only Allied Chemical (Birmingham, AL), Atochem (Carrollton, NY), Trade Waste Incineration (Sauget), and 3M (Cottage Grove, MN) were classified as major sources based on 10 tons/yr or greater emissions of a single substance. For each of these facilities HCl emissions exceeded 10 tons/yr, except Atochem where antimony was in excess of the 10 tons/year criteria. The figures clearly show that using maximum emissions instead of average emissions can have a significant impact on total facility emissions.

4.3 CEMENT AND LIGHTWEIGHT AGGREGATE KILN EVALUATION

53 cement kilns and 13 light weight aggregate kilns (LWAK) were evaluated (U.S. EPA, 1994). Since in many cases there are more than one kiln per facility, this amounts to 26 cement kiln facilities and 6 LWAK facilities.

Table 4-2 summarizes the results of the study, assuming an operating schedule of 315 days/year. Columns 3 through 6 demonstrate whether the facility is a major source under the specific conditions ("Y" indicates that a facility is a major source under the given conditions, "N" indicates that it is not). The first of these columns show which facilities meet the major source criteria while considering HCl and chlorine emissions. This category is broken down to indicate which facilities

are major sources when considering the maximum and average emission measured during the trial burn. Columns 5 and 6 show the same information when excluding HCl and chlorine from the data list. Table 4-2 applies to all three detection limit assumptions (i, ii, iii).

Also shown in Table 4-2 are the number of organic, metal, and chlorine compounds considered in the study. Lack of measurements may be a reason some facilities did not meet the major source criteria. The next column of the table lists the facility's air pollution control devices (APCD). The last two columns indicate the number of kilns within the facility, and comment on how the facility's total emissions were calculated using the available information.

All but 4 facilities meet the major source criteria when including HCl and chlorine in the emissions summation using maximum emissions. The 4 that do not meet the criteria, Essroc Corporation (Dorado, PR), Lone Star (Greencastle, IN), National Cement Company (Lebec, CA), and Southdown (Fairborn, OH) all have extremely low HCl and chlorine emissions, and (except for Lone Star) have relatively few organic measurements. When excluding HCl and chlorine from the emissions list, only 2 facilities meet the major source criteria: Ash Grove (Foreman, AR) and Holnam Inc. (Clarksville, MO). There is reason to believe that the Ash Grove data may include a toluene outlier for a single point. For this reason, calculations were performed for this site with and without the suspected outlier. Table 4-2 shows that when the outlier is excluded, and when HCl and chlorine emissions are also excluded, Ash Grove at Foreman is no longer a major source. The Holnam facility meets the major source criteria even when excluding HCl and chlorine because of its consistently high organics emissions.

Dropping the operating schedule from 365 days/year to 315 days/year affected the classification of only one facility. Lafarge Corporation in Paulding, Ohio, dropped below the major source criteria when evaluating the average emissions and including HCl and chlorine.

Figures 4-3 and 4-4 show total hazard air pollutant (HAP) emissions per year from each facility with and without HCl/Cl₂, respectively. The type of kiln, dry cement kiln (DCK), wet cement kiln (WCK) or lightweight aggregate kiln (LWAK), and the type of control equipment, fabric filter (FF) or electrostatic precipitator (ESP), also are provided in the figures. Again, note that Figures 4-3 and 4-4 can only be used to determine if a facility can be classified under the 25 tons/yr or greater major source category. Reference to the original report must be made to see data that classifies a facility under the 10 tons/yr or greater major source category. In summary, the following facilities were classified as major sources based on 10 tons/yr or greater maximum emissions of a single substance: Lafarge Corp. (Demopolis, AL), Southdown (Kosmosdale, KY), North Texas (Midlothian, TX), Keystone Cement (Bath, PA). For each of these facilities, HCl or chlorine emissions exceeded 10 tons/yr. The figures clearly show that using maximum emissions instead of average emissions can have a significant impact on total facility emissions.

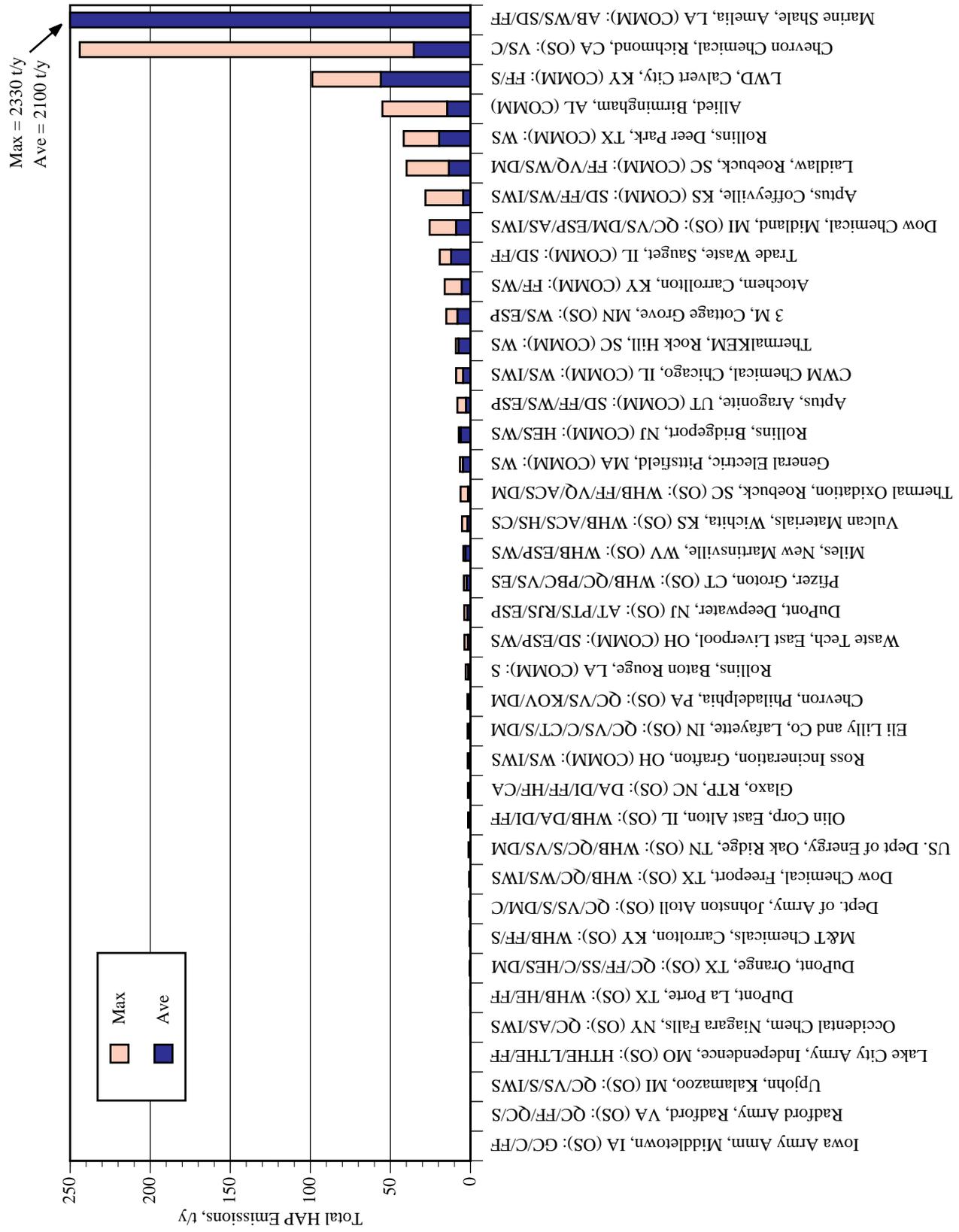


Figure 4-1. Estimated annual HAP emissions for incinerators including HCl and Cl₂.

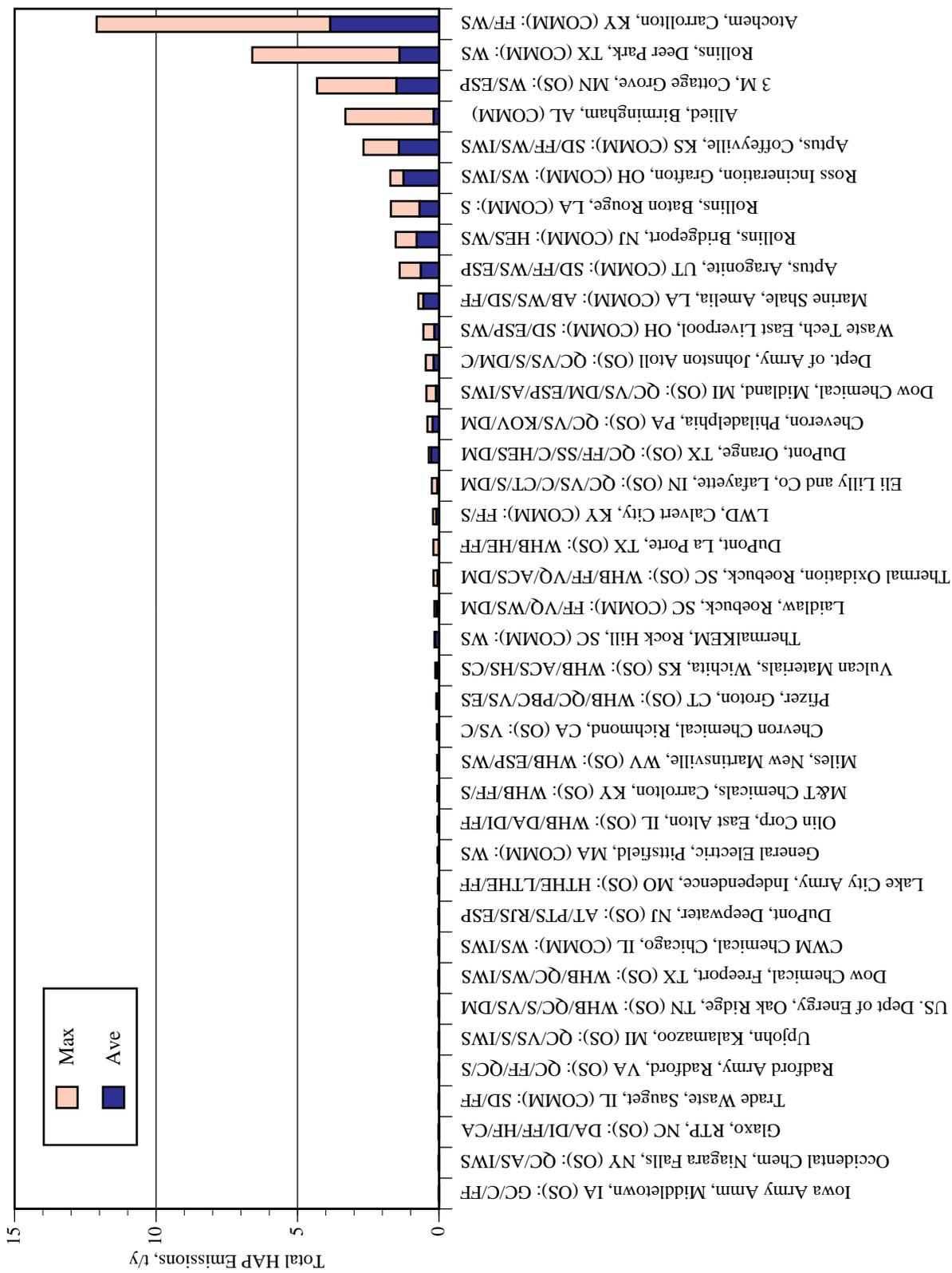


Figure 4-2. Estimated annual HAP emissions for incinerators excluding HCl and Cl₂.

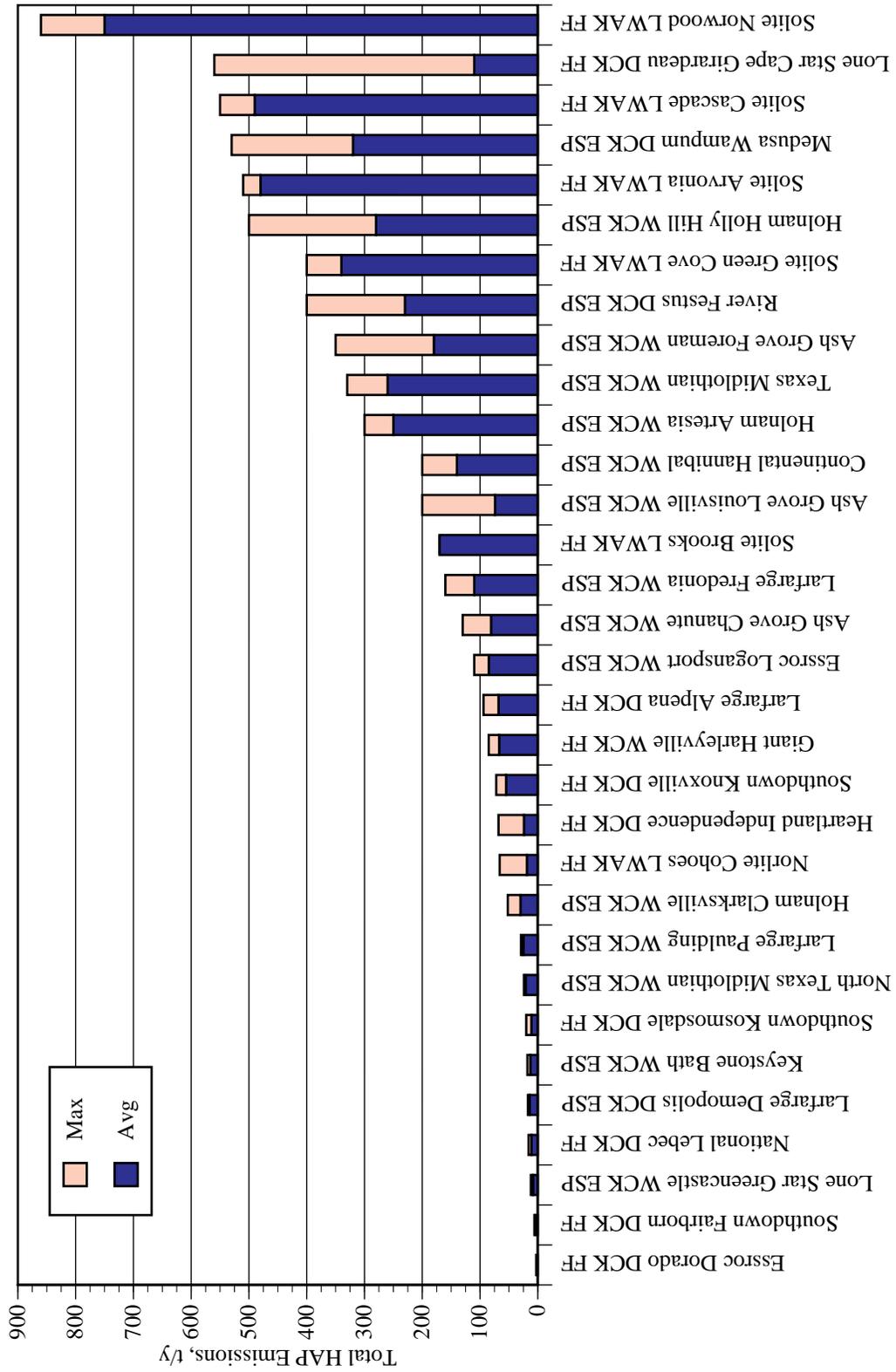


Figure 4-3. Estimated annual HAP emissions for kilns including HCl and Cl₂.

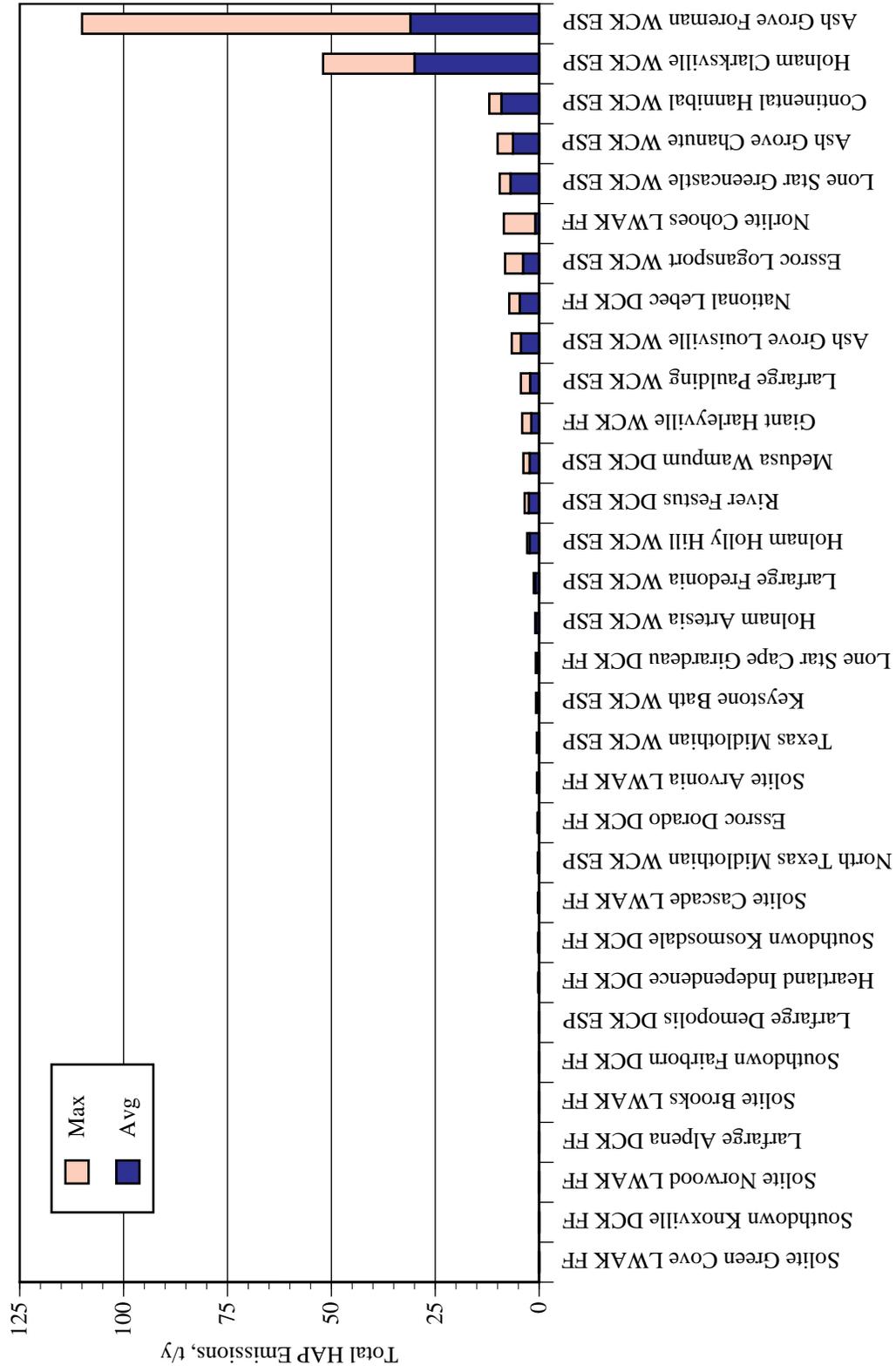


Figure 4-4. Estimated annual HAP emissions for kilns excluding HCl and Cl₂.

TABLE 4-1. MAJOR SOURCE DETERMINATION SUMMARY FOR COMMERCIAL AND ON-SITE INCINERATORS
(315 operating days/year assumption)

Facility	Type	Major Source (incl. HCl/C1)		Major Source (No HCl/C1)		No. of Organic Compounds Considered	No. of Metals Compounds Considered	HCl/C1 Consideration	APCD	# of Units On Site	Comment
		Max.	Ave.	Max.	Ave.						
Allied Chemical: Birmingham, AL	Commercial	Y	Y*	N	N	2	5	HCl	?	1	
Aptus, Inc.: Aragonite, UT	Commercial	N	N	N	N	30	8	HCl/C12	SD/FF/WS/ESP	1	
Aptus, Inc.: Coffeyville, KS	Commercial	Y	N	N	N	30	9	HCl	SD/FF/WS/IWS	1	
Atotech: Carrollton, KY	Commercial	Y*	N	Y*	N	0	6	HCl	FF/WS	1	
CWM Chemical Services: Chicago, IL	Commercial	N	N	N	N	2	0	HCl/C12	WS/IWS	1	
General Electric: Pittsfield, MA	Commercial	N	N	N	N	3	9	HCl	WS	1	
Laidlaw Environmental: Roebuck, SC	Commercial	Y	Y	N	N	2	7	HCl/C12	FF/Q/WS/DM	1	
LWD Inc.: Calvert City, KY	Commercial	Y	Y	N	N	3	0	HCl/C12	FF/S	3	Data entered for 3 indiv. units
Marine Shale Proc.: Amelia, LA	Commercial	Y	Y	N	N	0	7	HCl/C12	AB/WS/SD/FF	2	Data for unit #1. Unit #2 not operating.
Rollins Environmental: Baton Rouge, LA	Commercial	N	N	N	N	52	9	HCl	S	1	
Rollins Environmental: Bridgeport, NJ	Commercial	N	N	N	N	11	9	HCl	HES/WS	1	
Rollins Environmental: Deer Park, TX	Commercial	Y	N**	N	N	14	7	HCl/C12	WS	3	Data and info. available for 1 unit only
Ross Incineration: Grafton, OH	Commercial	N	N	N	N	1	7	—	WS/IWS	1	
ThermalKEM: Rock Hill, SC	Commercial	N	N	N	N	3	0	HCl/C12	WS	1	
Trade Waste Incineration: Saugat, IL	Commercial	Y*	Y*	N	N	3	0	HCl/C12	SD/FF	4	Data and info. available for 1 unit only
Waste Tech. Ind.: East Liverpool, OH	Commercial	N	N	N	N	7	0	HCl/C12	SD/ESP/WS	1	
3 M: Coitage Grove, MN	On-Site	Y*	N	N	N	4	7	HCl	WS/ESP	1	
Chevron: Philadelphia, PA	On-Site	N	N	N	N	0	7	HCl	VS/C	1	
Chevron Chemical Co.: Richmond, CA	On-Site	Y	Y	N	N	22	8	HCl/C12	QC/VS/KOV/DM	1	
Dept. of Army: Johnston Atoll	On-Site	N	N	N	N	26	7	HCl	QC/VS/S/DM/C	4	Data and info. available for 2 units only
Dow Chemical Co.: Freeport, TX	On-Site	N	N	N	N	2	0	HCl	WHB/QC/WS/IWS	1	
Dow Chemical Co.: Midland, MI	On-Site	Y	N	N	N	3	7	HCl/C12	QC/VS/DM/ESP/AS/IWS	2	Data entered for 2 indiv. units
DuPont: Deepwater, NJ	On-Site	N	N	N	N	2	0	HCl/C12	AT/PTS/RJS/ESP	1	Data entered for 1 indiv. unit
DuPont: La Porte, TX	On-Site	N	N	N	N	1	0	—	WHB/HE/FF	?	
DuPont: Orange, TX	On-Site	N	N	N	N	3	7	HCl/C12	QC/FF/SS/C/HES/DM	1	
Eli Lilly and Co.: Lafayette, IN	On-Site	N	N	N	N	3	0	HCl	QC/VS/C/CT/S/DM	?	Data entered for 1 unit
Glaxo, Inc.: RTP, NC	On-Site	N	N	N	N	2	7	HCl	DA/D/FF/H/CA	1	
Iowa Army Amm. Plant: Middletown, IA	On-Site	N	N	N	N	0	1	—	GC/C/FF	1	
Lake City Army Amm. Plant: Independence, MO	On-Site	N	N	N	N	0	7	—	HTHE/LTHE/FF	1	
M&T Chemicals Inc.: Carrollton, KY	On-Site	N	N	N	N	2	0	HCl	WHB/FF/S	1	
Miles, Inc.: New Martinsville, WV	On-Site	N	N	N	N	2	7	HCl	WHB/ESP/WS	1	
Occidental Chem. Corp: Niagara Falls, NY	On-Site	N	N	N	N	0	4	HCl/C12	QC/AS/IWS	1	
Olin Corp: East Alton, IL	On-Site	N	N	N	N	1	7	HCl/C12	WHB/DA/DI/FF	2	Data for 1 unit applied to 2nd identical unit
Pfizer, Inc.: Groton, CT	On-Site	N	N	N	N	14	3	HCl	WHB/QC/PBC/VS/ES	2	Data and info. available for 1 unit only
Radford Army Amm. Plant: Radford, VA	On-Site	N	N	N	N	0	1	—	QC/FF/QC/S	2	Data for 1 unit applied to 2nd identical unit
Thermal Oxidation Corp: Roebuck, SC	On-Site	N	N	N	N	3	0	HCl	WHB/FF/VQ/ACS/DM	1	
US. Dept of Energy: Oak Ridge, TN	On-Site	N	N	N	N	1	0	HCl	QC/VS/S/IWS	1	
Upjohn Co: Kalamazoo, MI	On-Site	N	N	N	N	2	5	HCl	WHB/QC/SV/S/DM	1	
Vulcan Materials Co: Wichita, KS	On-Site	N	N	N	N	30	3	HCl	WHB/ACS/HS/CS	1	

* Site meets major source criteria due to emission of single compound > 10 tons/yr (total compounds < 25 tons/yr).

** 365 operating days/year assumption would denote this value as Y

TABLE 4-2. MAJOR SOURCE DETERMINATION SUMMARY FOR CEMENT AND LWA KILNS
(315 operating days/year assumption)

Facility	Type	Major Source (incl. HCl/Ci2)		Major Source (No HCl/Ci2)	No. of Organic Compounds Considered	No. of Metals Compounds Considered	Chlorine Compounds Considered	APCD	# of Kilns On-Ste	Comments
		Max.	Ave.							
Ash Grove: Chanute, KS	Cement Kiln	Y	Y	N	26	7	HCl/Ci2	ESP	2	Data for 1 kiln applied to 2nd identical kiln.
Ash Grove: Foreman, AR (w/o Toluene outlier)	Cement Kiln	Y	Y	Y	28	7	HCl/Ci2	ESP	3	Data entered for 3 individual kilns. Toluene outlier included. Toluene outlier not included.
Ash Grove: Louisville, NE	Cement Kiln	Y	Y	N	28	7	HCl/Ci2	ESP	2	Data for 1 kiln applied to 2nd identical kiln.
Continental: Hannibal, MO	Cement Kiln	Y	Y	N	20	7	HCl/Ci2	ESP	1	
Essroc Corp.: Logansport, IN	Cement Kiln	Y	Y	N	4	6	HCl/Ci2	ESP	2	Data for 1 kiln applied to 2nd identical kiln.
Essroc Corp.: Dorado, PR	Cement Kiln	N	N	N	4	7	HCl/Ci2	FF	1	
Giant Cement: Harleyville, SC	Cement Kiln	Y	Y	N	0	9	HCl/Ci2	FF	4	Data entered for 2 kilns. Data for 1 kiln applied to 2 other identical kilns.
Heartland Cement: Independence, KS	Cement Kiln	Y	Y*	N	0	7	HCl/Ci2	FF	4	All kilns exit to common stack. All kilns operating during test.
Holnam Inc.: Artesia, MS	Cement Kiln	Y	Y	N	1	7	HCl/Ci2	ESP	1	
Holnam Inc.: Clarksville, MO	Cement Kiln	Y	Y	Y	19	7	HCl/Ci2	ESP	1	
Holnam Inc.: Holly Hill, SC	Cement Kiln	Y	Y	N	2	9	HCl/Ci2	ESP	2	Data entered for 2 individual kilns.
Keystone Cement: Bath, PA	Cement Kiln	Y*	Y*	N	1	8	HCl/Ci2	ESP	2	Data entered for 2 individual kilns.
Lanfarge Corp.: Alpena, MI	Cement Kiln	Y	Y	N	0	5	HCl/Ci2	FF	5	Data for 1 kiln applied to 2nd identical kiln. 3 kilns not in operation.
Lanfarge Corp.: Demopolis, AL	Cement Kiln	Y*	N	N	0	5	HCl/Ci2	ESP	1	
Lanfarge Corp.: Fredonia, KS	Cement Kiln	Y	Y	N	1	5	HCl/Ci2	ESP	2	Data entered for 2 individual kilns.
Lanfarge Corp.: Paulding, OH	Cement Kiln	Y	N**	N	0	5	HCl/Ci2	ESP	2	Data for 1 kiln applied to 2nd identical kiln.
Lone Star Ind.: Cape Girardeau, MO	Cement Kiln	Y	Y	N	3	7	HCl/Ci2	FF	1	
Lone Star Ind.: Greencastle, IN	Cement Kiln	N	N	N	23	7	HCl/Ci2	ESP	1	
Medusa Cement: Wampum, PA	Cement Kiln	Y	Y	N	1	7	HCl/Ci2	ESP	3	Data entered for 2 kilns. Data for 1 kiln applied to another identical kiln.
National Cement Co.: Lebec, CA	Cement Kiln	N	N	N	1	8	HCl/Ci2	FF	1	
Norlite Corp.: Cohoes, NY	LWA	Y	Y*	N	4	9	HCl/Ci2	FF	2	Data for 1 kiln applied to 2nd identical kiln.
North Texas Cement: Midlothian, TX	Cement Kiln	Y*	Y*	N	3	5	HCl/Ci2	ESP	3	Data for 1 kiln applied to 2 other identical kilns.
River Cement: Festus, MO	Cement Kiln	Y	Y	N	9	7	HCl/Ci2	ESP	2	2 kilns exit to common stack. Both kilns operating during test.
Sollite Corp.: Anovnia, VA	LWA	Y	Y	N	0	7	HCl/Ci2	FF	2	Data entered for 2 individual kilns.
Sollite Corp.: Brooks, KY	LWA	Y	Y	N	0	7	HCl/Ci2	FF	1	
Sollite Corp.: Cascade, VA	LWA	Y	Y	N	16	7	HCl/Ci2	FF	3	Data entered for 3 individual kilns.
Sollite Corp.: Green Cove, FL	LWA	Y	Y	N	0	7	HCl/Ci2	FF	1	
Sollite Corp.: Norwood, NC	LWA	Y	Y	N	0	7	HCl/Ci2	FF	4	Data entered for 4 individual kilns.
Southdown, Inc.: Fairborn, OH	Cement Kiln	N	N	N	0	5	HCl/Ci2	FF	1	
Southdown, Inc.: Knoxville, TN	Cement Kiln	Y	Y	N	1	5	HCl/Ci2	FF	1	
Southdown, Inc.: Kosmosdale, KY	Cement Kiln	Y*	Y*	N	10	5	HCl/Ci2	FF	1	
Texas Industries: Midlothian, TX	Cement Kiln	Y	Y	N	0	5	HCl/Ci2	ESP	4	Data for 1 kiln applied to 3 other identical kilns.

* Site meets major source criteria due to emission of single compound > 10 tons/yr (total compounds < 25 tons/yr).

** 365 operating days/year assumption would denote this value as Y

REFERENCES

- Air Pollution Control Consultant, "Ceramic Monolith Filter Removes Particulate From Hot Gases," *The Air Pollution Control Consultant*, pp. 1.10-1.11, September/October 1992.
- Andersson, C., and B. Weimer, "Mercury Emission Control - Sodium Sulfide Dosing at the Hogdalen Plant in Stockholm," *Proceedings of the 2nd Annual International Specialty Conference on Municipal Waste Combustion*, Air and Waste Management Association, VIP-19, pp. 664-674, Tampa, FL, April 1991.
- Barton, R., G. Hassel, W.S. Lanier, and W.R. Seeker, *State-of-the-Art Assessment of Medical Waste Thermal Treatment*, EPA Contract No. 68-03-3365, June 1990.
- Barton, R., W.R. Seeker, and H. Bostian, "The Behavior of Metals in Municipal Sludge Incinerators," *Trans IChemE*, Vol. 69, Part B, pp. 29-36, February 1991.
- Baturay, A., and J. Bruno, "Reduction of Metal Emissions from Sewage Sludge Incinerators with Wet Electrostatic Precipitators," *Proceedings of the 83rd Annual Meeting of the Air and Waste Management Association*, Pittsburgh, PA, 90-30.8, June 24-29, 1990.
- Benoit, M., E. Hansen, et al., U.S. Patent No. 4,850,290, "Method for Energy Recovery from Solid Hazardous Wastes," July 25, 1989.
- Blizard, G. and R. Tidona, "Design, Installation and Start-Up of a Rotary Kiln Hospital Waste Incineration System with Heat Recovery and SDA/FF APC System," *Proceedings of the 1992 Incineration Conference*, Albuquerque, NM, May 1992.
- Blumbach, J., and L. Nethé, "Sorbalit - A New Economic Approach Reducing Mercury and Dioxin Emissions," *Proceedings of 85th Annual Air and Waste Management Association Meeting*, Kansas City, MO, 92-41.09, June 21-26 1992.
- Bonner, T., et al., *Hazardous Waste Incineration Engineering*, Noyes Data Corporation, 1981.
- Boos, R., R. Budin, et al., "PCDD- and PCDF Destruction by A SCR-Unit in a Municipal Waste Incinerator," *Chemoshpere*, Vol. 25, No. 3, pp. 375-382, 1993.
- Braun, H., and A. Gerig, "Mercury Emission Monitoring on Municipal Waste Combustion," *Proceedings of the Municipal Waste Combustion International Specialty Conference*, Air and Waste Management Association, VIP-19, Tampa, FL, April 1991.
- Brna, T., "Toxic Metal Emissions from MWCs and Their Control," *Proceedings of the Municipal Waste Combustion International Specialty Conference*, Air and Waste Management Association, VIP-19, Tampa, FL, pp. 145-161, April 1991.
- Brown, B., and K. Felsvang, "Control of Mercury and Dioxin Emissions from United States and European Municipal Waste Incinerators by Spray Dryer Absorption Systems," *Proceedings of the Municipal Waste Combustion International Specialty Conference*, Air and Waste Management Association, VIP-19, Tampa, FL, pp. 675-705, April 1991.
- Buonicore, A.J., and W.T. Davis, (editors), *Air Pollution Control Engineering Manual*, Air and Waste Management Association, Van Nostrand Reinhold, New York, 1992.

Buonicore, A., L. Theodore, R. McKinney, and G. Tchobanoglous, "Waste Management," *Perry's Chemical Engineer's Handbook - 6th Edition*, R. Perry, Editor, McGraw Hill, New York, pp. 26-31, 1984.

Buonicore, A., "Experience With Air Pollution Control Equipment on Hazardous Waste Incinerators," *83rd Annual Meeting of the Air and Waste Management Association*, Pittsburgh, PA, 90-33.2, June 24-29, 1990.

Calvert, product literature, San Diego, CA, phone (619) 272-0050, 1992.

Ceilote, product literature, Berea, OH, 44017, phone (216) 243-0700, 1992.

Cheremisenoff, P.N., "Pollution Engineering Guide to Fine Particulate Control in Air Pollution," Pudvan Publishing Co., Northbrook IL, 1988.

Christiansen, O., and B. Brown, "Control of Heavy Metals and Dioxins from Hazardous Waste Incinerators by Spray Dryer Absorption Systems and Activated Carbon Injection," *Proceedings of 85th Annual Air and Waste Management Association Meeting*, Kansas City, MO, 92-41.06, June 21-26, 1992.

Clarke, L., and L. Sloss, *Trace Elements: Emissions from Coal Combustion and Gasification*, International Energy Agency Coal Research, IEACR/49, London, July 1992.

Clarke, M., "The Nation's First Mercury Emissions Standard: An Assessment of New Jersey's Standard for Municipal Waste Combustors," *Proceedings of the 86th Annual Air and Waste Management Association Meeting*, Denver, CO, 93-RP-154.01, June 13-18, 1993.

Clarke, M., "A Review of Activated Carbon Technologies for Reducing MSW Incinerator Emissions," *Proceedings of the Municipal Waste Combustion International Specialty Conference*, Air and Waste Management Association, VIP-19, Tampa, FL, pp. 975-994, April 1991.

Christiansen, O., and B. Brown, "Control of Heavy Metals and Dioxins from Hazardous Waste Incinerators by Spray Dryer Absorption Systems and Activated Carbon Injection," *Proceedings of 85th Annual Air and Waste Management Association Meeting*, Kansas City, MO, 92-41.06, June 21-26, 1992.

Crosley, S., and R. Kedl, "Laboratory Measurements of Metal Adsorption from Simulated Incinerator Flue Gases: Sorbent Selection for Cesium Capture," *Proceedings of the 1992 Incineration Conference*, Albuquerque, NM, pp. 605-609, May 11-15, 1992.

Dalton, D., R. Gillins, T. Harris, T., and A. Wollerman, "An Assessment of Off-Gas Treatment Technologies for Application to Thermal Treatment of Department of Energy Wastes," Prepared for U.S. DOE under contract DE-AC05-84OR21400, DOE/MWIP-1, September 1992.

DeWees, W., C. Davis, S. McClintock, A. Cone, H. Bostian, E. Crumpler, and S. Steinsberger, "Sampling and Analysis of Municipal Wastewater Sludge Incinerator Emissions for Metals, Metal Species, and Organics," *83rd Annual Meeting of the Air and Waste Management Association*, Pittsburgh, PA, 90-26.7, June 24-29, 1990.

Dellinger, H., D. Pershing, and A. Sarofim, "Evaluation of the Origin, Emissions, and Control of Organic and Metal Compounds from Cement Kilns Co-fired With Hazardous Wastes," Scientific Advisory Board on Cement Kiln Recycling, June 8, 1993.

Dempsey, C., and T. Oppelt, "Incineration of Hazardous Waste: A Critical Review," *Journal of the Air and Waste Management Association*, Vol. 43, p. 35, January 1993.

Donnelly, J., and F. Felsvang, "Joy/Niro SDA MSW Gas Cleaning Systems New Developments," *Proceedings of the 82nd Annual Air and Waste Management Association Meeting*, Anaheim, CA, 89-109.6, June 25-30, 1989.

Durkee, K., and J. Eddinger, "Status of EPA Regulatory Development Program for Medical Waste Incinerators — Results of Emission Test Program," *Proceedings of the 1992 Incineration Conference*, Albuquerque, NM, pp. 447-456, May 11-15, 1992.

Eddings, E., and J. Lighty, "Fundamental Studies on Metal Behavior During Solids Incineration," *Combustion Science and Technology*, Vol. 85, pp. 375-385, 1992.

EER (Energy and Environmental Research Corporation), *Air Pollution Control and Monitoring Technologies for Rocky Flats Fluidized Bed Unit: State of the Art Assessment*, EPA Contract No. 68-CO-0094, 1993.

Elliott, T.C., *Standard Handbook of Powerplant Engineering*, McGraw-Hill Publishing Co., 1989.

England, G., et al., "Field Evaluation of Humidification for Precipitator Performance Enhancement," *Proceedings of the 7th Symposium on the Transfer and Utilization of Particulate Control Technology*, EPRI/EPA, Vol. 1, May 1989.

EPA (U.S. Environmental Protection Agency), U.S. Patent No. 4,904,283, "Enhanced Fabric Filtration Through Controlled Electrostatically Augmented Dust Deposition," February 27 (1990).

EPA (U.S. Environmental Protection Agency), *Handbook: Operation and Maintenance of Hospital Medical Waste Incinerators*, EPA/625/6-89/024, January 1990.

EPA (U.S. Environmental Protection Agency), *Handbook: Control Technologies for Hazardous Air Pollutants*, EPA/625/6-91/014, June 1991.

EPA Contract 68-D2-0164, "Commercial and On-Site Incinerators, First Draft," EPA Work Assignment 1-9, Prepared by Energy and Environmental Research Corporation, June 1994.

EPA Contract 68-D2-0164, "Cement and Lightweight Aggregate Kiln Major Source Report, Second Draft," EPA Work Assignment 1-10 and 1-11, Prepared by Energy and Environmental Research Corporation, June 1994.

Epner, E., and J. Yackiw, "Locating and Estimating Air Toxic Emissions from Medical Waste Incinerators," EPA No. 68D90054, September 1993.

Expanded Shale Clay and Slate Institute, *Lightweight Concrete - History, Applications and Economics*, Washington, D.C., 1971.

Felsvang, K., R. Gleiser, G. Juip, and K. Nielsen, "Activated Carbon Injection in Spray Dryer/ESP/FF for Mercury and Toxics Control," Trace Elements Transformation in Coal-Fired Power Systems Workshop, Scottsdale, AZ, April 19-21, 1993.

Fouhy, K., "Legislation Scrubs Flue Gas Emissions," *Chemical Engineering*, pp. 31-35, June 1992.

Frankenhaeuser, M., H. Manninen, I. Koho, et al., "Organic Emissions from Co-Combustion of Mixed Plastics with Coal in a Bubbling Fluidized Bed Boiler," *Chemosphere*, Vol. 27, Nos, 1-3, pp. 309-316, 1993.

Frillici, P., R. Li, G. Bacon, and D. Hayes, "Evaluation of Mercury Emission Reduction Alternative for the Fort Dix Resource Recovery Facility," *Proceedings of the 86th Annual AWMA Meeting*, 93-RP-154.03, Denver, CO, June 1993.

Gaige, C., and R. Halil, "Clearing the Air About Municipal Waste Combustors," *Solid Waste and Power*, pp. 12-17, January/February 1992.

Gao, D., and G. Silcox, "Metal Capture by Mineral-based Sorbent Added to the Solids of RotaryKiln Incinerators," 1993 Spring Meeting of the Wester States Section of the Combustion Institute, Salt Lake City, UT, March 1993.

Gennrich, T., "Nextel High Temperature Filter Bags," *Proceedings of The User and Fabric Filtration Conference VI*, Air and Waste Management Association, SP-84, pp. 125-147, Toronto, Ontario, September 1992.

Gooch, J., *A Manual on the Use of Flue Gas Conditioning for ESP Performance Enhancement*, EPRI, CS-4145, August 1985.

Guest, T., "Mercury Control in Canada," 86th Annual Meeting of the Air and Waste Management Association, Denver, CO, 93-WP-109.01, June 21-26, 1993.

Gullet, B., K. Bruce, and L. Beach, "Effect of Sulfur Dioxide on the Formation Mechanism of Polychlorinated Dibenzodioxin and Dibenzofuran in Municipal Waste Combustors," *Environmental Science and Technology*, Vol. 26, No. 10, 1992.

Gullett, B., and W. Jozewicz, "Bench-Scale Sorption and Desorption of Mercury with Activated Carbon," *Proceedings of the Municipal Waste Combustion International Specialty Conference*, Air and Waste Management Association, VIP-32, Williamsburg, VA, pp. 903-917, March 1993.

Gullett, B.K., P.M. Lemieux, J.D. Kilgroe, and J.E. Dunn, "Formation and Prevention of Polychlorinated Dibenzo-p-Dioxin and Poly chlorinated Dibenzofuran During Waste Combustion: The Role of Combustion and Sorbent Parameters," *Environmental Science and Technology*, Vol. 51, No. 2, 1994.

Hagenmaier, K., K. Tichaczek, H. Brunner, and G. Mittelbach, "Application of De-Nox Catalysts for the reduction of Emissions of PCDD/PCDF and Other PICs from Waste Incineration Facilities by Catalytic Oxidation," *Proceedings of the Municipal Waste Combustion International Specialty Conference*, Air and Waste Management Association, VIP-19, Tampa, FL, p. 382, April 1992.

Hartenstein, H., "A Fixed Bed Activated Coke/Carbon Filter as a Final Gas Cleaning StageRetrofitted for a Hazardous Waste Incineration Plant - The First 6 Months of Operating Experience," *Proceedings of 85th Annual Air and Waste Management Association Meeting*, 9248.04, Kansas City, MO, June 21-26, 1992.

Hassel, G., T. McGrath, W.R. Seeker, and D. Taylor, "Capture of Volatile Metals in a FluidizedBedAfterburner," *Proceedings of the Fall Meeting of the Western States Section of the Combustion Institue*, La Holla, CA, October 1990.

Hiraoka, M., N. Takkeda, T. Kasakura, et al., "Catalytic Destruction of PCDDs in Flue Gas," presented at Dioxin '90 EPRI Seminar, Bayreuth, F.R.G., 1990.

Ho, T., C. Chen, H. Hopper, and D. Oberacker, "Metal Capture During Fluidized Bed Incineration of Wastes Contaminated with Lead Chloride," *Combustion Science and Technology*, Vol. 85, pp. 101-116, 1992.

Hyland, G., W. Cramer, G. Faloon, and T. Holder, "State of the Art, Small-Scale Medical Waste Incinerator Operating Case History," *Proceedings of the 1993 Incineration Conference*, Knoxville, TN, pp. 355-362, May 3-7, 1993.

IAEA (International Atomic Energy Agency), *Treatment of Off-Gas From Radioactive Waste Incinerators*, Vienna, Technical Report Series No. 302, 1989.

Jaasund, S.A., "Electrostatic Precipitators: Better Wet Than Dry," *Chemical Engineering*, pp. 159-163, November 23, 1987.

John Zink, product literature, Tulsa, OK, (708) 656-7800, 1992.

Junk, G., J. Richard, *Chemosphere*, Vol. 10, pp. 1237-1241, 1981.

Kilgrove, J., T. Brna, D. White, et al., "Camden County MWC Carbon Injection Test Results," *Proceedings of the Municipal Waste Combustion International Specialty Conference*, Air and Waste Management Association, VIP-32, Williamsburg, VA, pp. 123-142, March 1993.

Krivanek, S., "Mercury Control Technologies for MWC's; The Unanswered Questions," *Proceedings of the Municipal Waste Combustion International Specialty Conference*, Air and Waste Management Association, VIP-32, Williamsburg, VA, pp. 824-840, March 1993.

Lamb, L., C. Brickley, and R. Dykes, *Locating and Estimating Air Toxics Emissions from Sewage Sludge Incinerators*, EPA-450/2-90-009, May 1990.

Lancia, A., D. Musmarra, F. Pepe, and G. Volpicelli, "Adsorption of Mercuric Chloride Vapors from Incinerator Flue Gases on Calcium Hydroxide Particles," *Combustion Science and Technology*, Vol. 93, pp. 277-289, 1993.

Laudal, D., and S. Miller, "Enhanced Fine Particulate Control for Reduced Air-Toxic Emissions," *Proceedings of Managing Hazardous Air Pollutants - State-of-the-Art*, EPRI, Washington, DC, November 1991.

Lea, F.M., *The Chemistry of Cement and Concrete*, Chemical Publishing Co., Inc., New York, NY, 1970.

Lindbauer, R., F. Wurst, and T. Prey, "Combustion Dioxin Suppression in Municipal Solid Waste Incineration with Sulphur Additives," *Chemosphere*, Vol. 25, Nos. 7-10, pp. 1409-1414, 1992.

Lindquist, B., "Gas Cleaning in Connection with Waste Incineration," *Proceedings of the Municipal Waste Combustion International Specialty Conference*, Air and Waste Management Association, VIP-19, Tampa, FL, pp. 300-311, April 1991.

Litt, R., and T. Tewksbury, "Trace Metal Retention When Firing Hazardous Waste in a Fluidized Bed Incinerator," EPA-600/2-84-198, 1984.

Malcolm Pirnie, Inc., TRP Environmental Associates, Inc, and Clement International Corporation, A Report on Mercury Control System for the Lee County Resource Recovery Facility, prepared for the Florida Department of Utilities, Lee County, Florida, April 1992.

Marschall, H., H. Spencer, H., and H. Elliott, "New Oregon Incinerator Demonstrates Process Innovation to Protect Both Air and Water," *Proceedings of Specialty Conference - Thermal Treatment of Municipal, Industrial, and Hospital Wastes II*, Air and Waste Management Association, SP-69, pp. 60-73, Pittsburgh, PA, November 1989.

Mattila, H., T. Virtanen, et al., "Emissions of Polychlorinated Dibenzo-p-dioxins and Dibenzofurans in Flue Gas from Co-Combustion of Mixed Plastics with Coal and Bark," *Chemosphere*, Vol. 25, No. 11, pp. 1599-1609, 1992.

McDonald, J.R., and A.H. Dean, *Electrostatic Precipitator Manual*, Noyes Data Corporation, 1982.

McKeena, J.D., and J.H. Turner, *Fabric Filter - Baghouses I: Theory, Design, and Selection*, ETS International, Inc., 1989.

Morun, B., and F. Schwarzkopf, "Use of High-Surface-Are-Hydrate-Additive in a Two Stage Process," *Proceedings of the 1992 Incineration Conference*, Albuquerque, NM, pp. 133-139, May 11-15, 1992.

Natale, F., K. Callahan, and G. Whalen, "Pilot Plant Testing of a Wet Electrostatic Precipitator at the GCAU Fluid Bed Sludge Incinerator," *83rd Annual Meeting of the Air and Waste Management Association*, Pittsburgh, PA, 90-30.7, June 24-29, 1990.

Ok, G., Y. Hanai, and T. Katou, "Decomposition of Chlorinated Dioxins, Odorous Compounds and NO_x from MSW Incineration Plant by Oxidizing Catalysts," *Chemosphere*, Vol. 26, No. 12, pp. 2167-2172, 1993.

Otani, Y., Emi, H., Kanaoka, C., Uchijima, I., and H. Nishino, "Removal of Mercury Vapor from Air with Sulfur-Impregnated Adsorbents," *Environmental Science and Technology*, Vol. 22, No. 6, pp. 708-711, 1988.

Peray, K.E., *The Rotary Cement Kiln*, 2nd Edition, Chemical Publishing Co., New York, NY, 1986.

Pethnick, F., "High Temperature Baghouse Operation Using a Unique Metallic Fiber Filter Design," *Proceedings of The User and Fabric Filtration Conference VI*, Air and Waste Management Association, SP-84, pp. 99-110, Toronto, Ontario, September 1992.

Pilney, J., G. Gathje, H. Vincent, and G. Jones, "EDV Field Testing at the 3M Corporate Incinerator," *Proceedings of the 1993 Incineration Conference*, Knoxville, TN, pp. 227-231, May 3-7, 1993.

Politi, D., A. Harleston, and E. Mull, "Control of Flue Gas Emissions at the Healthwaste Medical Waste Incineration Facility Bronx, New York: A State of the Art Medical Waste Disposal Facility," *Proceedings of the 1993 Incineration Conference*, Knoxville, TN, pp. 389-394, May 3-7, 1993.

Richman, M., D. Fickling, and J. Hahn, "Mercury Removal Studies at a Municipal Waste Combustor in Marion County, Oregon," *Proceedings of the Municipal Waste Combustion International Specialty Conference*, Air and Waste Management Association, VIP-32, Williamsburg, VA, pp. 918-932, March 1993.

Saxena, S., R. Henry, and W. Podolski, "Particle Removal From High-Temperature, High-Pressure Combustion Gases," *Progress in Energy and Combustion Science*, Vol. 11, No. 3, p. 193, 1985.

Schoner, P., "An Innovative System for the Emission Control of Heavy Metals and Dioxin," *Proceedings of the 1992 Incineration Conference*, Albuquerque, NM, pp. 129-132, May 1992.

Scotto, M., T. Peterson, and J. Wendt, "Hazardous Waste Incineration; The In Situ Capture of Lead by Sorbents in a Laboratory Scale Combustor," *24th International Symposium on Combustion*, pp. 1109-1118, The Combustion Institute, Pittsburgh, PA, 1992.

Sedman, C., and T. Brna, *Municipal Waste Combustion Study: Flue Gas Cleaning Technology*, EPA/530-SW-021d, June 1987.

Shamekhi, R., H. Petersen, and W. Panknin, "Research into Activated Carbon Technology on Harmful Organic Substances, Heavy Metals and NO_x Control," *Proceedings of the 83rd Annual Air and Waste Management Association Meeting*, Pittsburgh, PA, 90-25.1, June 24-29, 1990.

Sheppard, S., "Operating Experience With the Ionizing Wet Scrubber on Hazwaste Incinerators," *Proceedings of the 1992 Incineration Conference*, Albuquerque, NM, pp. 87-92, May 11-15, 1992.

Sprung, S., *Technological Problems in Pyroprocessing Cement Clinker: Cause and Solution*, Berton-Verlag, Dusseldorf, Germany, 1985.

Srinivasachar, S., J. Morency, and B. Wyslouzil, "Heavy Metal Transformations and Capture During Incineration," *85th Annual Meeting of the Air and Waste Management Association*, Kansas City, MO, 92-41.07, June 21-26, 1992.

Steag, telephone conversation on July 25, 1994 with Volker Rummenhohl, (202) 338-8767, 1994.

Stohr, J., J. Furrer, J. Hunsigner, and S. Kreis, "Final Cleaning of Flue Gas from Municipal Waste Incinerators," *Proceedings of the 1993 Incineration Conference*, Knoxville, TN, pp. 203206, May 3-7, 1993.

Theodore, L., and A. Buonicore, *Air Pollution Control Equipment: Selection, Design, Operation, and Maintenance*, Englewood Cliffs, NY, 1982.

Troxler, W., G. Smith, C. Henke, J. Lauber, J. Czapl, and J. Segada, "Ionizing Wet Scrubber Pilot Test Results for Controlling Emissions from a Liquid Hazardous Waste Incinerator," *85th Annual Meeting of the Air and Waste Management Association*, Kansas City, MO, 92-41.05, June 21-26, 1992.

Uberoi, M., and F. Shadman, "Sorbents for the Removal of Lead Compounds from Hot Flue Gases," *AICHE*, Vol. 36, No. 2, pp. 307-309, 1990.

Uberoi, M., and F. Shadman, "High Temperature Removal of Cadmium Compounds Using Solid Sorbents," *Environmental Science and Technology*, Vol. 25, No. 7, pp. 1285-1289, 1991.

Valenti, M., "Tougher Standards for Burning Hazardous Waste," *Mechanical Engineering*, Vol. 115, p. 69, August 1993.

Weitzman, L., "Cement Kilns as Hazardous Waste Incinerators," *Environmental Progress*, Vol. 2, No. 1, pp. 10-14, 1983.

White, D., T. Brna, et al., "Parametric Evaluation of Powdered Activated Carbon Injection of Control of Mercury Emissions form a Municipal Waste Combustor," *Proceedings of 85th Annual Air and Waste Management Association Annual Meeting*, Kansas, MO, 92-40.06, June 1992.

White, D., K. Nebel, and M. Johnston, "Municipal Waste Combustors: A Survey of Mercury Emissions and Applicable Control Technologies," *Proceedings of the Municipal Waste Combustion International Specialty Conference*, Air and Waste Management Association, VIP-19, Tampa, FL, pp. 652-662, April 1991.

White, H., *Industrial Electrostatic Precipitation*, Addison-Wesley Publishing Company, Reading, MA, 1970.

Zievers, E. C., Zievers, J., and Eggerstandt, P., "Cylindrical Porous Ceramic Elements for Hot Gas Filtration in the Chemical Industry," *Proceedings of the 1990 Incineration Conference*, San Diego CA, May 14-18, 1990.

Zievers, E., Zievers, J., Eggerstedt, P., and Aguilar, P., "Porous Ceramics in Medical Waste Incineration," *Proceedings of the 1991 Incineration Conference*, pp. 183-188, Knoxville, TN, May 13-17, 1991.