DRAFT

ENGINEERING HANDBOOK
FOR HAZARDOUS WASTE INCINERATION

November 1980

For

U.S. Environmental Protection Agency
Office of Research and Development
Cincinnati, Ohio 45268

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by

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PREFACE

The Resource Conservation and Recovery Act (RCRA) authorizes the
United States Environmental Protection Agency (EPA) to regulate
owners/operators of facilities that treat hazardous waste in
incinerators. Pursuant to the legislative mandates specified in
RCRA, the EPA has issued regulations to ensure that hazardous
waste incinerators are operated in an environmentally responsible
manner. Briefly, the regulations include an operational perform-
ance standard for destruction criteria, waste analysis, trial
burns, monitoring and inspections, recordkeeping and reporting,
control of fugitive emissions, and closure requirements, as well
as operating criteria, specified on a case-by-case basis.

These site-specific determinations of operating criteria will
be made by permit writers through the exercise of their engin-
eering judgement. As an aid to those permit writers the Agency
has compiled in this manual a summary of existing knowledge
about the operation of hazardous waste incinerators. This manual
should also be of interest to public citizens concerned about
incinerator operations. Finally, the manual may be useful to
facility owners or operators, both as a source of information
for operational decisions, and as a reference for preparation of
permit applications.

The Agency intends to revise this manual regularly to include
results of new research or knowledge. Please contact EPA with
requests for revised copies or with suggested material for
inclusion in future editions.

CONTENTS

CONTENTS (continued)

CONTENTS (continued)

CONTENTS (continued)

CONTENTS (continued)

CONTENTS (continued)

6. ESTIMATING INCINERATION COSTS

   (This Chapter was Undergoing Revisions at the

   Time of Publication of this Document. A Revised

   Chapter 6 will be Available Upon request at a

   Later Date.)

Appendices

A. Subject Index

B. Glossary of Terms

C. Conversion Factors

D. Bibliography

E. Laboratory-Scale Thermal Decomposition Analytical Data

F. Trial Burn Summaries

Reserved for Chapter Six

LIST OF FIGURES

LIST OF TABLES

ACKNOWLEDGEMENT

CHAPTER 1

INTRODUCTION

CHAPTER 1

INTRODUCTION

ions of tons of industrial waste materials are generated each year in the
ed States. A sizable fraction of this waste is considered hazardous (an
nated 57 million metric tons in 1980). In recent years, incineration has
jed as an attractive potential alternative to hazardous waste disposal
ods such as landfill, ocean dumping, and deep-well injection.

neration possesses several advantages as a hazardous waste disposal
nology:

- Toxic components of hazardous wastes can be converted to harmless
  compounds or, at least, to less harmful compounds.

- Incineration provides for the ultimate disposal of hazardous wastes,
  eliminating the possibility of problems resurfacing in the future.

  The volume of hazardous waste is greatly reduced by incineration.

- Heat recovery makes it possible to recover some of the energy
  produced by the combustion process.

s likely that incineration will be a principal technology for the dis-
l of hazardous waste in the future because of the above advantages.

 engineering handbook is a compilation of information available in the
rature and describes current state-of-the-art technology for the incin-
ion of hazardous waste. The handbook is designed to serve as a technical
ource document in the evaluation of hazardous waste incineration operations.
. document is intended to serve as a useful technical resource for Federal,
onal, and state EPA officials; designers of hazardous waste incineration
lities, owners and operators of hazardous waste incineration facilities,
 the general technical community.

 chapter in the handbook addresses a separate topic involved in hazardous
:e incineration. A brief abstract for each chapter is presented in
le 1-1.

 user is encouraged to make use of the references cited in each chapter
additional information is required.

TABLE 1-1. ENGINEERING HANDBOOK FOR HAZARDOUS WASTE
INCINERATION - CHAPTERS AND THEIR CONTENT

Chapter	Abstract

1   **Introduction**

Describes the utility of the handbook. Details the structure of the
handbook, specifying where various types of information are
available.

2   **Current Practices**

Contains basic and general information about the nature and opera-
tions of the various incinerators and air pollution control devices
currently used in hazardous waste disposal. Subject matter includes
process descriptions, diagrams, general operating parameters, and
process advantages and disadvantages. An overview of emerging
incineration technologies is included.

3   **Waste Characterization**

Describes the basic waste analysis required to characterize wastes,
and discusses how this information is used to match the waste to an
appropriate incinerator design and determine operating conditions.
Hazardous wastes listed under Section 3001 of the RCRA regulations
are evaluated as to their suitability for incineration.

4   **Incinerator and Air Pollution Control System Design Evaluation**

Provides detailed information and procedures for evaluation of in-
cinerator and air pollution control device design and operating con-
ditions. Basically, this involves a series of internal consistency
checks designed to determine whether (1) acceptable temperatures,
residence times, oxygen concentrations, and mixing can be achieved
and maintained in the incinerator, (2) the various components of the
system have sufficient capacity to accommodate the quantities of
waste to be burned, (3) appropriate air pollution control device
operating conditions can be maintained, (4) the design includes
process control and automatic shutdown safeguards to minimize re-
lease of hazardous materials in the event of equipment malfunction,
and (5) proper materials of construction are used. Individual eval-
uation procedures are provided for liquid injection and rotary kiln
incinerators, and for several types of wet scrubbers.

(continued)

TABLE 1-1 (continued)

Chapter	Abstract
5	**Overall Facility Design, Operation, and Monitoring** Provides engineering background information on the technical capabilities necessary for the incineration facility to process hazardous waste safely and effectively. The chapter discusses overall facility layouts; equipment requirements common to all facilities; waste receiving equipment, procedures, and storage; personnel safety; emergency procedures and provisions; monitoring procedures and instrumentation; sampling and analysis equipment and methodologies; sources of fugitive emissions and their control; scrubber/quench water handling and disposal; and ash collection systems.
6	**Estimating Incineration Costs** Examines the economic factors involved in the construction of new facilities and the operation of existing facilities. Capital costs for incinerators and air pollution control devices are discussed. The costs involved in changing incinerator operating conditions (temperature, percent excess air, residence time) and the removal efficiency of air pollution control devices are examined. The costs involved in performing trial burns are also addressed in this chapter.
Appendices	Provide a subject index, glossary of terms, tables of conversion factors, bibliography, and summaries of incineration data. Included in the summaries are: results of University of Dayton laboratory-scale experiments, and pilot-scale test results.

CHAPTER 2

CURRENT PRACTICES

CONTENTS

CHAPTER 2

CURRENT PRACTICES

2.1 INTRODUCTION

Incineration has developed over a number of years as a means of disposing of various types of waste materials. Recently, the application of incineration to hazardous waste has been given much attention. From an environmental standpoint, incineration can be the best method of disposing of certain hazardous wastes. Incineration of hazardous wastes does not necessarily have to be carried out at land-based facilities. Shipboard incineration has been used to dispose of chlorinated hydrocarbon wastes. The U.S. Environmental Protection Agency estimates that in 1979 only 5% of the country's total hazardous waste stream was managed by incineration. However, approximately 60% of all the hazardous material can be incinerated successfully [1, 2].

The EPA estimates that in 1979 about 39 million short tons (35 million metric tons) of hazardous wastes were generated in this country by some 270,000 industrial plants and other facilities. The majority of these wastes (65%) were produced in ten states: Texas, Ohio, Pennsylvania, Louisiana, Michigan, Indiana, Illinois, Tennessee, West Virginia, and California. It is expected that the quantities of hazardous waste generated will increase annually by 3%. Based on these figures, incineration is becoming increasingly more important in solving waste problems [3, 4].

Incineration is an engineered process that uses thermal decomposition via oxidation to convert a waste to a less bulky, toxic, or noxious material. A waste must be combustible for incineration to be an applicable disposal means [5]. Two important operating conditions for proper incineration are temperature and residence time. These conditions vary with a waste's chemical structure, physical form, and type of incinerator. Table 2-1 summarizes the typical ranges for the two operating conditions mentioned above in six incineration processes. Other important parameters, oxygen availability and adequate mixing, are covered in Chapter 4. Table 2-2 presents a summary of those physical forms suitable for the six technologies.

The following technologies are covered in this chapter: rotary kiln, liquid injection, fluidized bed, multiple hearth, coincineration, and starved air combustion/pyrolysis. The first five technologies mentioned are presented in Section 2.2, Commercially Available Hazardous Waste Incineration Technologies. The other technology, starved air combustion/pyrolysis, appears in Section 2.3, Emerging Hazardous Waste Incineration Technology. Rotary kiln and liquid injection are at present the most highly developed and most commonly used incinerators for hazardous waste incineration. Both exist throughout the United

TABLE 2-1. PERTINENT INCINERATION PROCESSES AND THEIR TYPICAL
OPERATING RANGES [6]

Process	Temperature range, °F (°C)	Residence time
Rotary kiln[a]	1,500 to 2,900 (820 to 1,600)	Liquids and gases, seconds; solids, hours
Liquid injection[a]	1,200 to 2,900 (650 to 1,600)	0.1 to 2 seconds
Fluidized bed	840 to 1,800 (450 to 980)	Liquids and gases, seconds; solids, longer
Multiple hearth	Drying zone 600 to 1,000 (320 to 540) Incineration 1,400 to 1,800 (760 to 980)	0.25 to 1.5 hours
Coincineration	300 to 2,900 (150 to 1,600)	Seconds to hours
Starved air combustion/pyrolysis	900 to 1,500 (480 to 820)	Tenth of a second to several hours

[a]A highly developed hazardous waste incineration technology; covered in detail in Chapter 4.

TABLE 2-2. APPLICABILITY OF AVAILABLE INCINERATION PROCESSES TO INCINERATION OF HAZARDOUS WASTE BY TYPE [6]

Waste type	Rotary kiln[a]	Liquid injection	Fluidized bed[a]	Multiple hearth	Coincineration	Starved air combustion/ pyrolysis
Solids:						
Granular, homogeneous	X		X	X	X	X
Irregular, bulky (pallets, etc.)	X				X	X[b]
Low melting point (tars, etc.)	X	X[c]	X		X	X
Organic compounds with fusible ash constituents	X			X	X	X
Unprepared, large, bulky material	X					
Gases:						
Organic vapor laden	X[d]	X[d]	X[d]	X[d]	X[d]	X[d]
Liquids:						
High organic strength aqueous wastes often toxic	X[e]	X	X		X	
Organic liquids	X[e]	X	X		X	
Solids/liquids:						
Waste contains halogenated aromatic compounds (2,200°F minimum)	X	X[f]			X	
Aqueous organic sludges	X[g]		X	X	X	

[a]Suitable for pyrolysis operation.

[b]Handles large material on a limited basis.

[c]If material can be melted and pumped.

[d]If properly presented to the incinerator.

[e]If equipped with auxiliary liquid injection nozzles.

[f]If liquid.

[g]Provided waste does not become sticky upon drying.

States in full-scale operations. Due to their widespread and successful use in hazardous waste incineration, they are covered in detail in Chapter 4. Air pollution control devices (APCD) are considered an essential part of most hazardous waste incineration processes due to the possibility of pollutant emissions during incineration. Because they are usually an integral part of the overall incineration design, they are covered in this chapter. Fact sheets have been developed and precede a detailed description for each incineration technology and APCD.

2.2 COMMERCIALLY AVAILABLE HAZARDOUS WASTE INCINERATION TECHNOLOGIES

This section deals with available hazardous waste incineration technologies. Included are fact sheets that contain the information listed in the example below, in the format illustrated.

Fact Sheet--	G, S, L[a]

Description - Brief discussion of technology.

Flow Diagram -

Status - Discusses the technology's applicability to hazardous waste incineration.

Wastes -

Wastes previously incinerated	Potential candidates	Unlikely candidates

Advantages -
Disadvantages -
References -

___

[a]Abbreviations for the types of waste (physical form) applicable to this technology:

G = gas	L = liquid	Slg = sludges
S = solid	Sly = slurry	

2.2.1 Rotary Kiln

2.2.1.1 Fact Sheet--

Description - The rotary kiln is a cylindrical refractory-lined shell that is mounted at a slight incline from the horizontal plane. Rotation of the shell provides for transportation of the waste through the kiln as well as for enhanced mixing of the waste with the combustion air. Applicable for incineration of both liquid and solid hazardous wastes and slurries.

Flow Diagram -
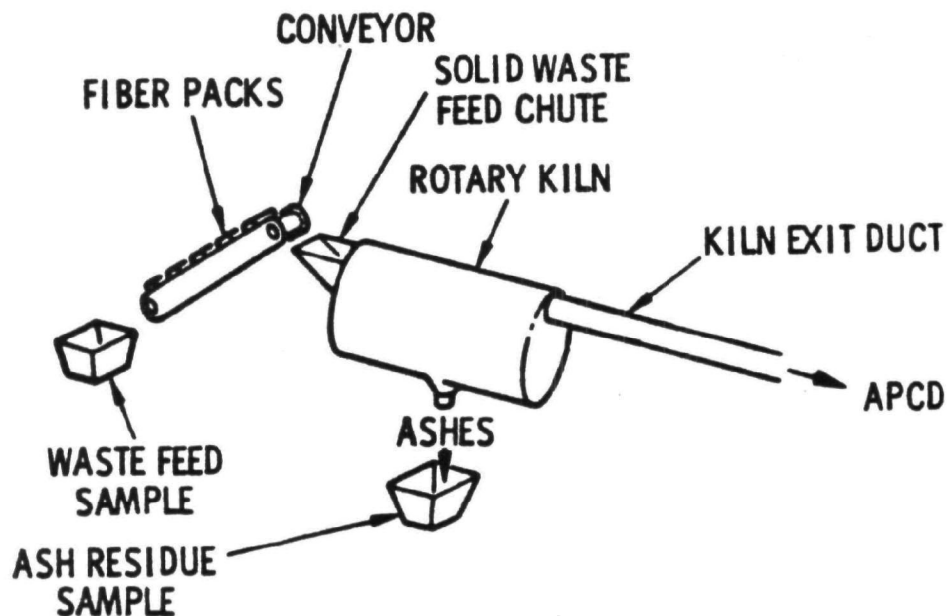
Status - Widespread applicability for hazardous waste incineration. Current technology used by industrial plants to destroy hazardous waste. At present, the rotary kiln is a major type of incinerator used in hazardous waste disposal.

Wastes -

Wastes previously incinerated
PCB wastes in capacitors
Obsolete munitions
Obsolete chemical warfare agents (GB, VX, and mustard)
Polyvinyl chloride waste

Potential candidates

Compounds containing C, H, O Organics containing either phosphorus, silicon, sodium, sulfur, fluorine,
  nitrogen or sulfur Halogenated (bromine, chlorine, iodine) organics

Unlikely candidates

Heavy metals
High-moisture-content waste
Inert material
Inorganic salts
Materials with a high inorganic content; such as: lime sludge from acetylene production by the carbide method; neutralized acid waste from the manufacture of methyl methacrylate; alkylation sludge containing sulfuric acid from petroleum refineries; settled sludge from clarification of wastewaters in the manufacture of paint additives; and lime clay mixtures with absorbed solvents and resins.

Advantages -

(1) Will incinerate a wide variety of liquid and solid wastes.
(2) Will incinerate materials passing through a melt phase.
(3) Capable of receiving liquids and solids independently or in combination.
(4) Feed capability for drums and bulk containers.
(5) Adaptable to wide variety of feed mechanism designs.
(6) Characterized by high turbulence and air exposure of solid wastes.
(7) Continuous ash removal which does not interfere with the waste oxidation.
(8) No moving parts inside the kiln (except when chains are added).
(9) Adaptable for use with a wet gas scrubbing system.
(10) The retention or residence time of the nonvolatile component can be controlled by adjusting the rotational speed.
(11) The waste can be fed directly into the kiln without any preparation such as preheating, mixing, etc.
(12) Rotary kilns can be operated at temperatures in excess of 2,500°F (1,400°C), making them well suited for the destruction of toxic compounds that are difficult to thermally degrade.
(13) The rotational speed control of the kiln also allows a turndown ratio (maximum to minimum operating range) of about 50%.

Disadvantages -

(1) High capital cost for installation.
(2) Operating care necessary to prevent refractory damage; thermal shock is a particularly damaging event.
(3) Airborne particles may be carried out of kiln before complete combustion.
(4) Spherical or cylindrical items may roll through kiln before complete combustion.
(5) The rotary kiln frequently requires additional makeup air due to air leakage via the kiln end seals.
(6) Drying or ignition grates, if used prior to the rotary kiln, can cause problems with melt plugging of grates and grate mechanisms.
(7) High particulate loadings.
(8) Relatively low thermal efficiency.
(9) Problems in maintaining seals at either end of the kiln are a significant operating difficulty.

References - 6-12

2.2.1.2 Detailed Description--
A typical rotary kiln incineration system used for hazardous waste destruction includes the following components [7]:

- Waste feed system
- Rotary kiln incinerator
- Auxiliary fuel feed system
- Afterburner
- Air pollution control device system

The rotary kiln is a cylindrical unit mounted on a slight incline. Kiln dimensions vary with each facility. A typical kiln is 16 ft (5 m) long and 10 ft (3 m) in diameter. Temperatures in the kiln range from 1,500°F to 2,900°F (820°C to 1,600°C). Since rotary kilns are normally totally refractory lined and have no exposed metallic parts, they can operate at high incineration temperatures and experience low corrosion. Residence time may vary from a couple of seconds (gaseous wastes) to a couple of hours (solid wastes). Afterburners, normally used with rotary kilns, are described in Section 2.4.1.

Batch feeding is common in rotary kiln systems. A typical feed capacity for solids is 1,300 lb/hr to 4,400 lb/hr (600 kg/hr to 2,000 kg/hr). Solid wastes, sometimes packed in fiber drums, are fed into the rotary kiln by a conveyor. Liquids and sludges may also be pumped into the kiln. Liquid residues are typically burned in suspension by atomization with stream or air and have a feed capacity of 22 ft^3/hr to 79 ft^3/hr (630 L/hr to 2,250 L/hr). The kiln and the liquid burner (when used) are equipped with natural gas ignitors and gas burners for initial refractory heatup, flame stability, and supplemental heat, if necessary [7].

Atmospheric emissions from the combustion of solid and liquid wastes are generally controlled by a venturi scrubber. Lime is injected to neutralize the scrubber water. Used scrubber water enters settling ponds where it is

analyzed and further treated, if necessary, before discharge. Exhaust gases also pass through absorption trays and a mist eliminator for pollution control before entering the stack.

2.2.2 Liquid Injection

2.2.2.1 Fact Sheet--   L, Sly, Slg

Description - Liquid injection combustors can be used to dispose of virtually any combustible liquid waste (liquid, slurries, sludges). The heart of the liquid injection system is the waste atomization device or nozzle (burner) which atomizes the waste and mixes it with air into a suspension. Combustion takes place in the combustion chamber. Atomization is usually achieved either mechanically using rotary cup or pressure atomization systems, or via gas fluid nozzles using high-pressure air or steam.

Flow Diagram -
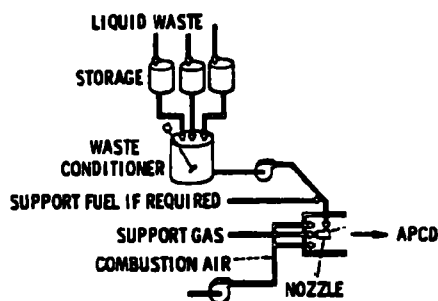
Status - Widespread applicability for hazardous waste incineration. Current technology used by industrial plants to destroy hazardous waste. At present, liquid injection is the most commonly used incinerator for hazardous waste disposal.

Wastes -

Wastes previously incinerated	Potential candidates	Unlikely candidates
Phenols	Organic vapor laden gases	Heavy metals
Still and reactor bottoms	Liquid halogenated (chlorine	High-moisture-content
Cyanide and chrome	bromine, iodine) organics	waste
plating wastes	Organic liquids containing	Inert material
Polyester paint	either nitrogen, sulfur	Inorganic salts
Polyvinyl chloride paint	fluorine, phosphorus,	Material with a high
Thinners	silicon, or sodium	inorganic content
Solvents		(see Section 2.2.1
Off-specification isoprene		for a more detailed
PCB's		list)
Separator sludges		
Detergent sludges		
Digester sludges		

Wastes previously incinerated (continued)

Latex paint
Polymers
Resins
Hexachlorocyclopentadiene
Organophosphate pesticides
Waste from polymer polyol production
Dodecyl mercaptan wastes
Fluorinated herbicide wastes
Ethylene glycol manufacture residue
Waste residues from alkyl benzene production
Perchloroethylene manufacture still bottoms
Alkyl and aryl sulfonic acid wastes
Still bottom from acetaldehyde production
Nitrochlorobenzene

Advantages -

(1) Capable of incinerating a wide range of liquid wastes.
(2) No continuous ash removal system is required other than for air pollution control.
(3) Capable of a fairly high turndown ratio.
(4) Fast temperature response to changes in the waste fuel flowrate.
(5) Virtually no moving parts.
(6) Low maintenance costs.

Disadvantages -

(1) Only wastes which can be atomized through a burner nozzle can be incinerated.
(2) Heat content of waste burned must maintain adequate ignition and incineration temperatures or a supplemental fuel must be provided.
(3) Burners susceptible to pluggage (burners are designed to accept a certain particle size; therefore, particle size is a critical parameter for successful operation).
(4) Burner may or may not be able to accept a material which dries and cakes as it passes through the nozzles.

References - 3, 5, 6, 8, 9, 11-13

2.2.2.2 Detailed Description--
The typical liquid injection incinerator includes the following components:

- Waste burner system
- Auxiliary fuel system
- Air supply system
- Combustion chamber
- Air pollution control device system

The use of a burner nozzle characterizes liquid injection incinerators. Liquid wastes are fed and atomized into the combustion chamber through the burner nozzle. Having a large surface area, the atomized particles vaporize quickly, forming a highly combustible mix of waste fumes and combustion air which ignites and is combusted as it proceeds through the combustion chamber. Typical combustion chamber residence time and temperature ranges are 0.5 to 2 seconds and 1,300°F to 3,000°F (700°C to 1,650°C), respectively. Typical liquid feed rates are as high as 200 ft^3/hr (5,600 L/hr).

The combustion chamber is a refractory-lined cylinder. Burners are normally located in the chamber in such a manner that the flames do not impinge on the refractory walls. The combustion chamber wall can be actively cooled by process air prior to its entry into the combustion zone, thus preheating the air to between 300°F (150°C) and 700°F (370°C).

Liquid waste fuel is transferred from drums into a feed tank. The tank is pressurized with nitrogen, and waste is fed to the incinerator using a remote control valve and a compatible flowmeter. The fuel line is purged with N_2 after use. A recirculation system is used to mix the tank contents [15].

Normally a gas (for example, propane) preheats the incinerator system to an equilibrium temperature of approximately 1,500°F (815°C) before introduction of the waste liquid.

Atmospheric emissions from the combustion of liquid wastes are often controlled by a high energy venturi scrubber system. Gases leaving the combustion chamber pass through this scrubber into a separator tank (often equipped with a demister). Quenching the exhaust gas is required before it is sent to the venturi scrubber. Scrubbing water mixed with a caustic solution is commonly used in the venturi. Such liquids are injected at the venturi inlet and mixed with the combustion gas at velocities of approximately 100 ft/s to 400 ft/s (30 to 120 m/s) in the venturi throat. Spent scrubber water is collected in a separator tank, then usually transferred to a holding tank. The water-saturated, scrubbed effluent gases are discharged up the stack [14].

2.2.3 Fluidized Bed

2.2.3.1 Fact Sheet--   G, S, L, Sly, Slg

Description - The fluidized bed incinerator consists of a refractory-lined vessel containing inert granular material. Gases are blown through this material at a rate sufficiently high to cause the bed to expand and act as a fluid. The gases are injected through nozzles that permit flow up into the bed and restrict downflow of the bed material. Waste feed, which can be in any form, enters the reactor either above or within the bed. Preheating of the bed to startup temperatures is accomplished by a burner located above and impinging down on the bed.

Flow Diagram -
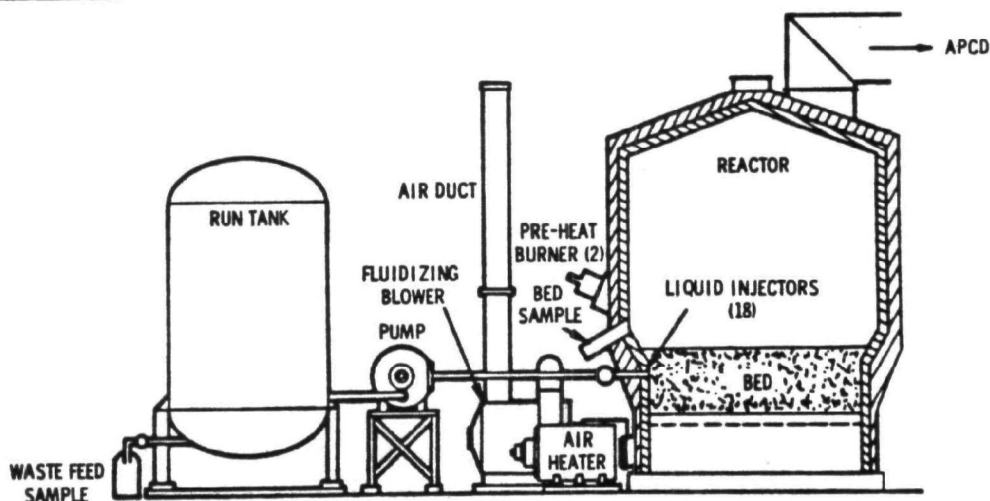
Status - Has primarily been used for municipal and industrial waste incineration. Significant potential for hazardous waste incineration.

Wastes -

Wastes previously incinerated	Potential candidates	Unlikely candidates
Off-specification phenol	Halogenated (bromine, chlorine, iodine) hydrocarbons	Heavy metals
Waste from toluene diamine production from dinitrotoluene		High-moisture-content waste
Organic wastes from pharmaceutical manufacture	Organics containing either sulfur, nitrogen, phosphorus, silicon, fluorine, or sodium	Inert material
		Inorganic salts
Organic peroxide manufacturing wastes		Materials with a high inorganic content (see Section 2.2.1 for a more detailed list)
Ethylene bromide manufacturing wastes		
Methyl methacrylate		
Phenol waste		

Wastes previously incinerated (continued)

Amiben® manufacture liquid wastes
Corboryl manufacture waste
Ethylene manufacturing wastes
Tetraethyl orthosilicate wastes
Urethane manufacture wastes

Advantages -

(1) General applicability for the disposal of combustible solids, liquids, and gaseous wastes.
(2) Simple design concept, requiring no moving parts in the combustion zone.
(3) Compact design due to high heating rate per unit volume (100,000 to 200,000 Btu/hr-ft^3 (900,000 to 1,800,000 kg-cal/hr-m^3) which results in relatively low capital costs.
(4) Relatively low gas temperatures and excess air requirements which tend to minimize nitrogen oxide formation and contribute to smaller, lower cost emission control systems.
(5) Long incinerator life and low maintenance costs.
(6) Large active surface area resulting from fluidizing action enhances the combustion efficiency.
(7) Fluctuation in the feed rate and composition are easily tolerated due to the large quantities of heat stored in the bed.
(8) Provides for rapid drying of high-moisture-content material, and combustion can take place in the bed.
(9) Proper bed material selection suppresses acid gas formation; hence, reduced emission control requirements.
(10) Provides considerable flexibility for shockload of waste; i.e., large quantities of waste being dumped in the bed at a single time.

Disadvantages -

(1) Difficult to remove residual materials from the bed.
(2) Requires fluid bed preparation and maintenance.
(3) Feed selection must avoid bed degradation caused by corrosion or reactions.
(4) May require special operating procedures to avoid bed damage.
(5) Operating costs are relatively high, particularly power costs.
(6) Possible operating difficulties with materials high in moisture content.
(7) Formation of eutectics is a serious problem.
(8) Hazardous waste incineration practices have not been fully developed.
(9) Not well suited for irregular, bulky wastes, tarry solids, or wastes with a fusible ash content.

References - 6, 8, 9, 11-13, 15, 16

2.2.3.2 Detailed Description--

A representative fluidized bed reactor will have the following basic system components [16]:

- Fluidized bed reactor
- Fluidizing air blower
- Waste feed system
- Auxiliary fuel feed system
- Air pollution control device system

A typical reactor has an inside diameter of 26 ft (8 m) and an elevation of 33 ft (10 m). Silica beds are commonly used and have a depth of 3 ft(1 m) at rest and extending up to 6.5 ft (2 m) in height when fluidizing air is passed through the bed. Waste and auxiliary fuel are injected radially into the bed and reacted at temperatures from 840°F to 1,500°F (450°C to 810°C). Further reaction occurs in the volume above the bed at temperatures up to 1,800°F (980°C). A typical residence time for liquid hazardous waste is 12 to 14 seconds [16].

Reactor heat release rates of up to 15 million kcal/hr and, waste, input feed rates of up to 48 ft^3/hr (1,360 L/hr) for liquids over 10,000 Btu/lb (5,560 kcal/kg) in heat content, and up to 270 ft^3/hr (7,570 L/hr) for liquids with a heat content of 3,000 Btu/lb (1,670 kcal/kg), are reported [16].

Liquid wastes can be pumped directly from a tank truck into the reactor by a recirculating pump system. Wastes are injected radially into the reactor bed through a nozzle. Flow rates are determined by recording waste liquid level changes in the calibrated tanker as a function of time [16].

Auxiliary fuel is often fed radially into the bed through a number of bed nozzles manifolded around the reactor circumference [16].

Atmospheric emissions from the combustion of liquid hazardous wastes have been controlled by a venturi scrubber. Recirculating water is injected into the venturi to scrub particulate matter from the combustion gas stream and quench the gas temperature from 1,500°F to 175°F (~820°C to ~80°C) prior to emission into the atmosphere through the stack. Spent scrubber liquid is sent to a wastewater treatment plant for processing [16].

2.2.4 Multiple Hearth

2.2.4.1 Fact Sheet--   S, Slg

<u>Description</u> - A typical multiple hearth furnace includes a refractory-lined steel shell, a central shaft that rotates, a series of solid flat hearths, a series of rabble arms with teeth for each hearth, an air blower, fuel burners mounted on the walls, an ash removal system, and a waste feeding system. Side ports for tar injection, liquid waste burners, and an afterburner may also be included.

Sludge and/or granulated solid combustible waste is fed through the furnace roof by a screw feeder or belt and flapgate. The rotating air-cooled central shaft with air-cooled rabble arms and teeth plows the waste material across the top hearth to drop holes. The waste falls to the next hearth and then the next until discharged as ash at the bottom. The waste is agitated as it moves across the hearths to make sure fresh surface is exposed to hot gases.

<u>Flow Diagram</u> -
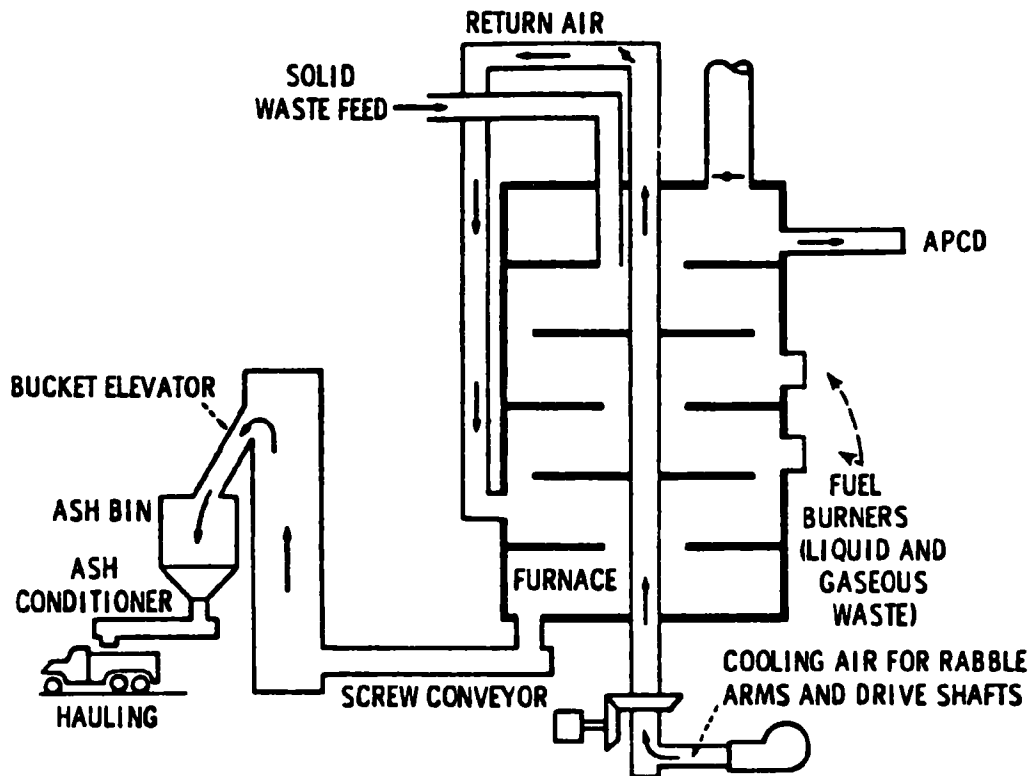
<u>Status</u> - This technology has moderate applicability for hazardous waste in-cineration. A pilot-scale study has been conducted (jointly incinerating PCB's and sewage sludge) [12].

Wastes -

Wastes previously incinerated	Potential candidates
Isophthalic acid and terephthalic acid still bottoms Solid residue from manufacture of aromatic amines Reactor bottoms from PVC manufacture Chemical sludge Oil refinery sludge Pharmaceutical wastes Still bottoms	Halogenated (bromine, chlorine, iodine) organic solids or sludges Organic solids or sludges containing either sodium, silicon, sulfur, phosphorus, nitrogen, or fluorine

Unlikely candidates

Heavy metals
Inert materials
Inorganic salts
Materials with a high inorganic
  content (see Section 2.2.1
  for a more detailed list)

Advantages -

(1) The retention or residence time in multiple hearth incinerators is usually higher for low volatile material than in other incinerator configurations.
(2) Large quantities of water can be evaporated.
(3) A wide variety of wastes with different chemical and physical properties can be handled.
(4) Multiple hearth incinerators are able to utilize many fuels including natural gas, reformer gas, propane, butane, oil, coal dust, waste oils, and solvents.
(5) Because of its multizone configuration, fuel efficiency is high and typically improves with the number of hearths used.
(6) Fuel burners can be added to any of the hearths to maintain a desired temperature profile.
(7) Multiple hearth incinerators are capable of a turndown ratio of 35%.
(8) High fuel efficiency is allowed by the multizone configuration.

Disadvantages -

(1) Due to the longer residence times of the waste materials, temperature response throughout the incinerator when the burners are adjusted is usually very slow.
(2) It is difficult to control the firing of supplementary fuels as a result of this slow response.
(3) Maintenance costs are high because of the moving parts (rabble arms, main shaft, etc.) subjected to combustion conditions.

<u>Disadvantages</u> - (continued)

(4) Multiple hearth incinerators are susceptible to thermal shock resulting from frequent feed interruptions and excessive amounts of water in the feed. These conditions can lead to early refractory and hearth failures.
(5) If used to dispose of hazardous wastes, a secondary combustion chamber probably will be necessary and different operating temperatures might be necessary.
(6) Not well suited for wastes containing fusible ash, wastes which require extremely high temperature for destruction, or irregular bulky solids.

<u>References</u> - 1, 3, 6, 8, 11-13

2.2.4.2 <u>Detailed Description</u>--

The multiple hearth incinerator (commonly called Herreshoff furnace) is a flexible unit which has been utilized to dispose of sewage sludges, tars, solids, gases, and liquid combustible wastes. This type of unit was initially designed to incinerate sewage plant sludges in 1934. In 1968, there were over 125 installations in operation with a total capacity of 17,000 tons/d (wet basis) for this application alone [3].

Furnaces range from 6 ft to 25 ft (1.8 m to 7.6 m) in diameter and from 12 ft to 75 ft (3.6 m to 23 m) in height. The diameter and number of hearths are dependent on the waste feed, the required processing time, and the type of thermal processing employed. Generally, the uppermost hearth is used as an afterburner. Normal incineration usually requires a minimum of six hearths, while pyrolysis applications require a greater number [6].

Normally, waste material enters the furnace by dropping through a feed port located in the furnace top. Rabble arms and teeth, attached to a vertically positioned center shaft, rotate counterclockwise to spiral the waste across the face of the hearth to the drop holes. The waste drops from hearth to hearth through alternating drop holes located either along the periphery of the hearth or adjacent to the central shaft. Ultimately, the residual ash falls to the furnace floor. Air and combustion products flow countercurrently to the feed from the bottom to the top of the combustion chamber [6].

The rabble arms and teeth located on the central shaft all rotate in the same direction; additional agitation of the waste (back rabbling) is accomplished by reversing the angles of the rabble teeth. Waste retention time is controlled by the design of the rabble tooth pattern and the rotational speed of the central shaft [3].

Liquid and/or gaseous combustible wastes may be injected into the unit through auxiliary burner nozzles. This utilization of liquid and gaseous waste represents an economic advantage because it reduces secondary fuel requirements, thus lowering operating costs [3].

One coincineration study conducted demonstrated that DDT and 2,4,5-T could be destroyed in a multiple hearth incinerator. DDT powder (75% AI), DDT in

kerosene (20% AI), and Weedon® solution (20% 2,4,5-T), were incinerated in a 30 in. (76 cm) six-hearth pilot-scale furnace. The pesticides were mixed with sludge containing about 20% by weight solids in the ratio of 0.02 g/g pesticides to sludge. Incineration was conducted on all the pesticides with the afterburner at 1,400°F (760°C), at 1,750°F (955°C), and shut off. Results showed that the destruction efficiencies of 2,4,5-T were above 99.95% with and without the afterburner operating. In almost all cases the highest pesticide losses (including DDT, DDD, DDE, and 2,4,5-T) were in the scrubber water. No tetra-chlorodioxin was detected in the 2,4,5-T formulation or in the incinerator off-gas [13].

The report concluded that DDT and 2,4,5-T can be safely destroyed by coincin-eration with sewage sludge in a multiple hearth furnace and that the internal hearth temperatures should be maintained in excess of 1,000°F to 1,100°F (550°C to 600°C) in order to minimize the formation of DDE [13]. Additional information on coincineration is given in Section 2.2.5.

2.2.5 Coincineration

2.2.5.1 Fact Sheet--

Description - Coincineration generally refers to the joint incineration of hazardous waste, in any form, with refuse and/or sludge. This is not a unique technology; any existing incineration process can be used for this special case of mixing waste streams to obtain better destruction of a particularly intractable waste material.

Status - Hazardous waste coincineration has been performed in a rotary kiln pyrolyzer and a multiple hearth incinerator. This technique is used to supply needed Btu's when the principal waste to be burned possesses insufficient heat content to be autogenic.

Wastes - Any thermally destructible waste is a potential candidate for coincineration. Currently, incineration of the following wastes has been performed:

Wastes previously incinerated	Incinerator
Kepone	Rotary kiln pyrloyzer
DDT	Multiple hearth
2,4,5-T	Multiple hearth
PCB	Multiple hearth

Advantages -

(1) Will potentially incinerate any thermally destructible hazardous waste.
(2) Incorporates the advantages of the type of incinerator used.
(3) Provides for the incineration of two different wastes simultaneously in the same facility, thus increasing return on investment.
(4) Provides potential for hazardous waste incineration in existing incineration facilities.

Disadvantages -

(1) Incorporates the disadvantages of the type of incineration used.

References - 18

2.2.5.2 Detailed Description--
Two types of incinerators have been tested for coincineration of hazardous wastes: a rotary kiln pyrolyzer and a multiple hearth incinerator. The rotary kiln pyrolyzer test unit used for Kepone incineration contained the following components [19]:

- Waste feed system
- Afterburner
- Rotary kiln pyrolyzer
- Air pollution control device system

Kepone-contaminated sludge was simulated by the mechanical mixing of appropriate amounts of Kepone solution in acetic acid into sludge in the feed tank. The latter was a cylindrical vessel, 33 in. (86 cm) in diameter and 24 in. (60 cm)

high fitted with a pneumatic stirrer. The 3.9-in. (10 cm) outlet port in the conical bottom of the feed tank was fitted with a screen and connected to a two-stage, variable speed pump. The discharge line was fitted with a pressure relief valve and with provisions to inject sludge from the feed tank or water from the mains. The feed line, which entered the kiln within the kiln discharge line, was water jacketed to prevent caking within the feed line. At the end of a run, the feed line was flushed with water [18].

The rotary kiln pyrolyzer was 5 ft (1.52 m) in diameter and 10 ft (3.0 m) in length fitted with rotary seal charge and discharge connections so as to minimize the leakage of gases into or out of the kiln. It was heated directly by the hot gases from a 0.923-J/s burner to maintain a nominal temperature of 900°F (500°C). Normally this kiln was batch fed through cover doors on the side, but for the purposes of the coincineration experiments the sludge feed was accomplished through a water-cooled feed line which entered the kiln through the discharge pipe. The maximum feed rate was a nomimal 100 lb/hr (45 kg/hr). Cake buildup within the kiln was prevented by 10 rows of link chain within the kiln [18].

The afterburner, with a residence chamber volume of 8.4 x 10' ft^3 (2.4 m^3), was fired by two 0.147-J/s throat mix burners and an auxiliary gas supply. The incinerator was equipped with a temperature controller and a high limit safety shutoff instrument. In this configuration, the maximum temperature that could be sustained was 2,300°F (1,260°C) with residence times in the order of several seconds [18].

The multiple hearth test unit used for pesticide and PCB incineration contained the following components [13]:

- Waste feed system
- Multiple hearth incinerator
- Air pollution control device system

The PCB's were fed in the form of a solution in kerosene from a burette into the sludge cake feed screw at a rate of 0.05 lb/hr (22.5 g/hr). The test PCB was a preparation Aroclor 1254 which is a combination of some 14 to 16 PCBs [13].

The DDT feed was accomplished by a hopper arrangement placed over the screw-feed mechanism used to conduct the dewatered sludge from the centrifuge to the top hearth of the furnace. The mechanical properties of the powdered DDT preparation used were such that the simple gravity feed device was not particularly satisfactory; one might elect to go to a more elaborate vibratory feed system in practice. The feed device used did not effect a constant feed rate, which was less serious than might be supposed [13].

The furnace was equipped with a scum line feeding into the third hearth. The injection of 2,4,5-T solution was accomplished by gravity feeding the metered solution into the scum flow. Incinerating temperature was 1,175°F (635°C) and afterburner temperature was 1,200°F (650°C) [13].

2.3 EMERGING HAZARDOUS WASTE INCINERATION TECHNOLOGY

This section deals with a technology that is in a research and development stage and is not necessarily recommended for application. A fact sheet for this emerging technology is presented, each followed by a more detailed description of the technology's operating parameters. The technology discussed is starved air combustion/pyrolysis.

2.3.1 Starved Air Combustion/Pyrolysis

2.3.1.1 Fact Sheet--   S, Slg

Description - Starved air combustion utilizes equipment and process flows similar to those for normal incineration, but in this process less than the theoretical amount of air for complete combustion is supplied. When the process is neither purely pyrolytic nor purely oxidative, it is called starved air combustion or thermal gasification. Pyrolysis is the thermal decomposition of solids or sludges in the absence of oxygen.

Flow Diagram -
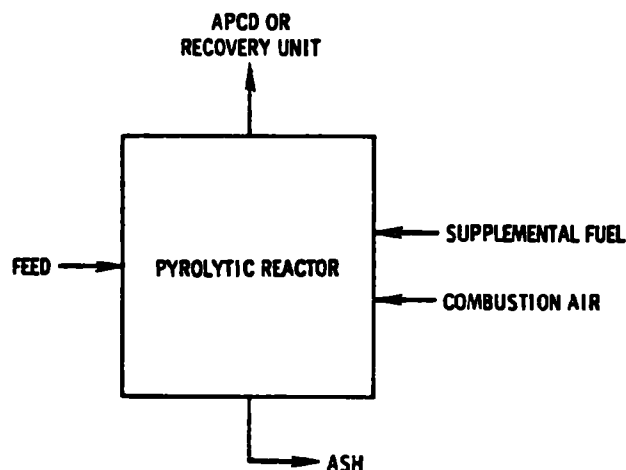
Status - Minimal use in hazardous waste incineration. Potentially applicable to wastes with purely organic (C,H,O) content.

Wastes -

Wastes previously incinerated	Potential candidates
API separator bottoms	C-, H-, and O-containing compounds
Tars from the production of styrene	
Rubber manufacturing waste sludge	
Tars from production of phthalic anhydride	
Spent filter aids	

Organics containing either nitrogen, sulfur, sodium, silicon, phosphorus, fluorine, bromine, chlorine, or iodine

Materials with a high inorganic content (see Section 2.2.1 for a more detailed list)

Inorganic salts

Heavy metals

Inert material

Materials with a high moisture content

Advantages -

(1) Potential for byproduct recovery.
(2) Reduction of sludge volume without large amounts of supplementary fuel.
(3) Thermal efficiency is higher than for normal incineration due to the lower quantity of air required for this process.
(4) Reduced air emissions are sometimes possible.
(5) Converts carbonaceous solids into a gas which is more easily combustible.
(6) Allows for the suppression of particulate emissions.
(7) Allows for some treatment of the hot fuel gas stream prior to combustion to suppress the formation of acid gases.

Disadvantages -

(1) Potential source of carcinogenic decomposition product formation.
(2) Not capable of functioning very well on sludgey or caking material alone unless cake-breaking capabilities are included in the design.

References - 3, 6, 8, 19, 10, 25

2.3.1.2 Detailed Description--

The terms "starved air combustion" and "pyrolysis," while often used inter-changeably, are not one and the same. Starved air combustion uses less than the stoichiometric amount of oxygen required for complete combustion. Pyrolysis is defined as the thermal decomposition of a compound in the absence of oxygen.

Pyrolytic conversion processes are generally custom engineered according to input volumes and types of waste being treated [1]. With respect to waste carbonaceous material, pyrolysis represents a means of converting the unwanted waste into a usable commodity with economic value. Modifications to the pyrolysis process involve treatment of converter effluents. The pyrolysis oils may be sent through a hydrotreating unit and converted to industrial fuel oil. The pyrolysis effluent gas may be cooled and the resultant condensate separated into its components (namely, acetic acid, methanol, furfural, acetone, butyric acid, propionic acid, methyl ethyl ketone, light fuel oil, and other water soluble volatile organics) through the use of conventional separation techniques. The cooled wet gas may be dried and utilized as fuel gas. The char-like pyrolysis residue can be further treated and converted into activated carbon [1].

Other variations include the pyrolyzer itself, which may be incorporated into a specific incinerator unit (i.e., rotary kiln, molten salt, etc.). A typical rotary kiln pyrolyzer, for instance, is a sealed, airtight retort cylinder with an insulated shell. The retort is mounted on a slight incline and rotates. Kiln dimensions are covered in Section 2.2.1. Without oxygen, the wastes in the retort chamber cannot burn; they are broken down (pyrolyzed) into steam, carbon oxides, volatile vapors, and charcoal. Gases formed during pyrolysis are combusted in an afterburner.

Operational temperatures will vary with waste type, incinerator type, and desired products. Operating temperatures are usually in the 1,200°F ± 300°F (650°C ± 150°C) range, with the lower operating temperature generally resulting in greater residue (coke), tar, and light oil yields, and lower gas yields. Residence times will range from a fraction of a second (for flash pyrolysis) to hours (for solids) [1].

2.4 AIR POLLUTION CONTROL DEVICES (APCD)

Air pollutants from the incineration of hazardous wastes may arise both as a result of imcomplete combustion and from the products of combustion of constituents present in the wastes and combustion air. The products of incomplete combustion include carbon monoxide, carbon, hydrocarbons, aldehydes, amines, organic acids, polycyclic organic matter (POM), and any other waste constituents or their partially degraded products that escape thermal destruction in the incinerator. In well designed and operated incinerators, these incomplete combustion products are emitted in insignificant amounts. The primary overall end products of combustion are in most cases carbon dioxide (CO_2) and water vapor (H_2O), but there are also a multitude of other products formed, depending on the composition of the waste material incinerated and combustion conditions. Hydrogen chloride (HCl) and small amounts of chlorine (Cl_2), for example, are formed from the incineration of chlorinated hydrocarbons. Hydrogen fluoride (HF) is formed from the incineration of organic fluorides, and both hydrogen bromide (HBr) and bromine (Br_2) are formed from the incineration of organic bromides. Sulfur oxides, mostly as sulfur dioxide (SO_2), but also including 1% to 5% sulfur trioxide (SO_3), are formed from the sulfur present in the waste material and auxiliary fuel. Phosphorus pentoxide (P_2O_5) is formed from the incineration of organophosphorus compounds. In addition, nitric oxide (NO) is formed by thermal fixation of nitrogen from the combustion air and from nitrogen compounds present in the waste material. Particulate emissions include particles of mineral oxides and salts from the mineral constituents in the waste material, as well as fragments of incompletely burned combustible matter.

Organic pollutants emitted as a result of incomplete combustion of waste material are often present in effluents from the primary combustion chamber at low concentration levels well under the lower flammability limit. The control of the emission of these organic pollutants can be handled by continued combustion at high temperatures using afterburners (also termed secondary combustion chambers).

Scrubbers are also used to control pollutant emissions. They operate by removing pollutants from the gas stream, instead of changing the pollutants, as afterburners do. Afterburners and four types of scrubbers are covered in this section, as are electrostatic precipitators (ESP) and wet electrostatic precipitators (WEP). The fact sheets presented for each control device addresses operating principles, status with hazardous waste incinerators, suitable waste streams, advantages, and disadvantages. Following each fact sheet a more detailed description of the control device is presented.

2.4.1 Afterburners

2.4.1.1 Fact Sheet--

Description - Afterburners are simple combustors employed to destroy (by oxidation) gaseous hydrocarbons not destroyed in the incinerator. Three types of afterburners are described here: direct flame, thermal, and catalytic. Direct flame and thermal afterburners are similar, but they destroy organic vapors by different methods. A high percentage of the vapors pass directly through the flame in a direct flame unit. In a thermal unit the vapors remain in a high temperature oxidizing atmosphere long enough for oxidation reactions to take place. Catalytic devices incorporate a catalytic surface to accelerate the oxidation reactions.

Diagram -
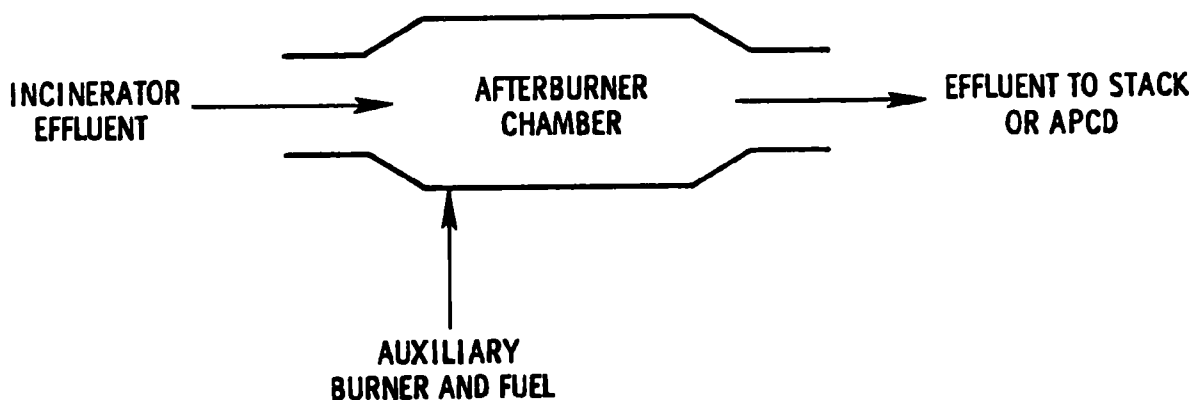
Status - Thermal afterburners are usually an integral part of rotary kilns used in hazardous waste incineration. Thermal afterburners are also used with: liquid injection incinerators in a few instances; pyrolysis units when chemicals are not being recycled; and conincineration units where the incinerator used normally requires an afterburner. Catalytic afterburners are a proven technology for nonhazardous gaseous material.

Applicable Waste Streams - Thermal afterburners are suitable for any gaseous material that is also suitable for incineration or which has been produced by auxiliary equipment; i.e., a rotary kiln. Catalytic afterburners are applicable to the destruction of combustible materials in low concentrations (they are not applicable to chlorinated hydrocarbons due to the HCl formation).

Advantages -

Thermal or Direct Flame

(1) Destroys those pollutants that were not destroyed in the primary incineration.

(2) Allows more flexibility in incinerator operation.

Catalytic

(1) Carries out combustion at relatively low temperatures (more economical to operate than other afterburners).

(2) Clean heated gas produced is well suited for waste heat recovery units.

Disadvantages -

Thermal or Direct Flame

(1) Auxiliary fuel requirements.

(2) Afterburner costs.

Catalytic

(1) Burnout of the catalyst occurs at temperatures exceeding 1,500°F.

(2) Catalyst systems are susceptible to poisoning agents, activity suppressants, and fouling agents.

(3) Occasional cleaning and eventual replacement of catalyst is required.

(4) Maintenance costs are high.

2.4.1.2 **Detailed Description**--Thermal afterburners, used commonly with rotary kilns, provide exposure of the organic vapors to a high temperature oxidizing atmosphere to ensure vapor destruction. Temperatures ranging from 1,200°F to 2,400°F (650°C to 1,300°C) are generally required for successful operation of these devices. Hydrocarbon levels can usually be satisfactorily reduced at temperatures below about 1,400°F (760°C), but higher temperatures may be required to simultaneously oxidize the CO [5]. The following temperatures are often used as guidelines [5]:

> To oxidize hydrocarbons: 900-1,200°F
> To oxidize carbon monoxide: 1,200 - 1,450°F

Depending on the type of pollutant in the gas stream, residence times ranging from 0.2 s to 6.0 s are required for complete combustion. The residence time in most practical afterburner systems is dictated primarily by chemical kinetic considerations. To ensure good mixing, afterburners are operated at high velocity gas flows. Gas velocities in afterburners range from 25 to 50 ft/s. A typical afterburner will be 32 ft (10 m) long, 13 ft (4 m) high, and 13 ft (4 m) wide [5].

From a chemical viewpoint, two main types of reactions occur in afterburner systems: oxidation and pyrolysis reactions. In general, the detailed mechanisms for the oxidation and pyrolysis of even the simplest organic compounds are not completely understood, but it is well established that the reactions occur in many complicated sequential and concurrent steps involving a multitude of chemical intermediates [5].

An auxiliary fuel is fired to supply the heat to warm the gases in a temperature that will promote oxidation of the organic vapors. Usually a portion of the gas stream supplied the oxygen necessary for organic vapor oxidation.

Both gaseous and liquid fuels are used to fire afterburners. Gaseous fuels
have the advantage of permitting firing in multiple jet (or distributed)
burners. Oil firing has the disadvantage of producing sulfur oxides (from
sulfur in the oil) and normally produces higher nitrogen oxides emissions [5].

Catalytic afterburners are applied to gaseous wastes containing low concentra-
tions of combustible materials and air. Usually noble metals such as platinum
and palladium are the catalytic agents. A catalyst is defined as a material
which promotes a chemical reaction without taking a part in it. The catalyst
does not change nor is it used up. However, it may become contaminated and
lose its effectiveness [1].

The catalyst must be supported in the hot waste gas stream in a manner that
will expose the greatest surface area to the waste gas so that the combustion
reaction can occur on the surface, producing nontoxic effluent gases of carbon
dioxide, nitrogen, and water vapor. Most of the combustion occurs during flow
through the catalyst bed which operates at maximum temperatures of 810°C to
870°C (1,500°F to 1,600°F). The ability to carry out combustion at relatively
low temperatures while achieving high destruction efficiencies is a major
advantage of the catalytic incinerator for gaseous wastes [1].

Residence time for catalytic oxidation is about 1 second [1].

Due to the form of the waste material to be treated (dilute and in the gaseous
state), the catalytic afterburner is best suited for use at the processing
site where the waste material is generated [1].

Generally, catalytic afterburners are considered for operation with waste con-
taining hydrocarbon levels that are less than 25% of the lower explosice
limit. When the waste gas contains sufficient heating value to cause concern
about catalyst burnout, the gas may be diluted by atmospheric air to ensure
operating temperatures within the operating limits of the catalyst. Burned
gases are discharged through a stack to the atmosphere if they are not sent to
a waste heat recovery unit [6].

2.4.2 Gas-Atomized Spray Scrubber (Venturi)

2.4.2.1 Fact Sheet--

Description - Gas atomized spray scrubbers utilize the kinetic energy of a moving gas stream to atomize the scrubbing liquid into droplets. Typical of these devices are the venturi scrubbers and orifice scrubbers. In the venturi scrubber, liquid is injected into the high velocity gas stream either at the inlet to the converging section or at.the venturi throat. In the process, the liquid is atomized by the formation and subsequent shattering of attenuated, twisted filaments and thin, cup like films. These initial filaments and films have extremely large surface areas available for mass transfer.

Orifice scrubbers are similar to venturi scrubbers, however, the orifice in this type creates more turbulence than is provided by the venturi type.

Diagram -

GAS
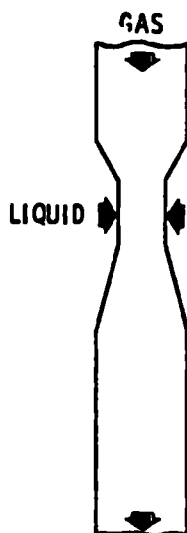
LIQUID

Status - Venturi scrubbers are a major air pollution control device for hazardous waste incineration. They are commonly used with rotary kilns and liquid injection incinerators. The venturi scrubber has also been used with fluidized bed incinerators.

Applicable Waste Streams - Suitable for particles, and fairly effective in removing noxious gases that are highly soluble (HCL, HF.) or reactive with the scrubber solution (SO_2, NO_x, HCN).

Advantages -

(1) Simultaneous gas absorption and dust removal.
(2) Suitable for high temperature, high moisture.
(3) Particulate removal efficiency is high.
(4) Scaling not usually a problem.

Disadvantages -

(1) Corrosion and erosion problems.
(2) Dust is collected wet and the wastewater will have to be treated.
(3) Moderate to high pressure drop; large amount of energy needed.
(4) Requires downstream mist eliminator.

References - 24

2.4.2.2 Detailed Description--

One of the most predominant air pollution control devices for hazardous waste incinerators is a venturi scrubber. A typical venturi scrubber is a duct with a constricted area (throat). Generally, liquid is introduced into the venturi at the throat. Incinerator exhaust gas enters the venturi at a velocity of approximately 100 to 400 ft/s (30 to 120 m/s). The moving gas atomizes the liquid into fine filaments and droplets which allow a large surface area for mass transfer. It is the gas/liquid contact that permits removal of gaseous contaminants.

Prior to passage of the incinerator exhaust gas into the venturi, the gas is quenched to reduce the temperature. While it is recognized that the quench systems when utilized will effect some degree of particle removal, the primary function of these units is to reduce flue gas volume and downstream materials and operating problems through gas cooling. As a result of quenching, inlet temperatures for venturi scrubbers range from 110°F to 300°F (60°C to 150°C).

Some hazardous waste incineration facilities employ sequential venturi and plate type or packed bed scrubbers. For these systems, a gas quench is optional since the venturi may be utilized to effect gas cooling by the mechanism of adiabatic expansion of the gases. Such systems are capable of handling a variety of incineration gas compositions and dust loadings. Plate towers or packed beds, when used in conjunction with gas-atomized spray scrubbers, serve the dual function of eliminating the entrainment of liquid droplets from upstream and further reducing the emission levels of gaseous contaminants.

Incinerating hazardous waste may produce effluent gases with corrosive contaminants, such as HCl. It is possible to neutralize the acid with a caustic solution. The scrubbing solution is determined by the waste burned and its exhaust gas. In addition to corrosion, erosion is a particular problem in venturi scrubbers. This is due to the high gas velocities and particulate loadings encountered during normal duty. Throat and elbow areas are generally subject to the most wear. Acid-resistant tile liners, polymeric liners, and Inconel 625 are often used for scrubber construction.

Venturi scrubbers have been used to control emissions of SO_2, HF, and HCl. Several of the primary operating parameters that will affect the removal of these gaseous contaminants are pressure drop, liquid-to-gas ratio, contact time, and gas flow rate. Pressure drops in venturi scrubbers for controlling gaseous emissions from incineration of hazardous wastes are typically in the 30- to 50-in. water gage (WG) (7.5 to 12.5-kPa) range [24]. It is necessary to use the correct pressure drop to ensure efficient removal. A higher than needed pressure drop will result in wasted energy; a lower than needed pressure drop will result in a lower removal efficiency. As a prime operating parameter, the pressure drop should be as low as possible yet yield the needed removal efficiency.

The liquid-to-gas ratio is a design and operating parameter of prime importance. It is needed in the determination of the scrubber diameter, and has an effect on the unit dimensions. Normal liquid-to-gas ratios for venturi scrubbers are 5 to 20 gal/1,000 acf (0.7 to 2.7 L/m^3) [24].

Higher efficiencies are attained by allowing the gas and liquid phases to be in contact for a longer period of time. The contact time required for gas absorption is a function of the rate of mass transfer. The mass transfer rate, in general, is dependent upon four separate resistances: gas-phase resistance, liquid-phase resistance, chemical reaction resistance, and a solids dissolution resistance for scrubbing liquids containing solid reactants. For absorption of gaseous contaminants that are highly soluble or chemically reactive with the scrubbing liquid, such as the absorption of HCl by caustic solution, the contact time required for 99% removal is extremely short (of the order of 0.4 to 0.6 s). The less reactive and less soluble pollutants require a longer contact time [24].

The rate at which a flue gas from waste incineration must be processed by a particle control device depends primarily on the waste composition, the quantity of excess combustion air used, the initial gas temperature, and the method(s) by which the gas has been cooled, if cooling is used. Hence these parameters, in conjunction with control device size or geometry, will dictate the velocity at which the gas will pass the particle collection elements [24].

It has been shown that the pressure drop across a venturi is proportional to the square of gas velocity and directly proportional to the liquid-to-gas ratio. Therefore, within limits, increasing gas velocity will result in increasing pressure drop, other parameters being equal [24]. Typical gas velocities employed commercially are 100 to 390 ft/s (30 to 120 m/s). The low end of this range, 100 to 150 ft/s (30 to 45 m/s), is typical of power plant applications, while the upper end of the range has been applied to lime kilns and blast furnaces [24].

Particle cut diameter (diameter of particles in which there is a 50% collection) is a frequently used parameter for describing the particle collection performance of venturi scrubbers. One reason for this is because plots of collection efficiency versus particle diameter tend to be rather steep in the region where inertial impaction is the predominant collection mechanism. High energy venturi scrubbers provide the highest wet scrubber efficiency with cut diameters in the 1.17 in x 10^5 to 1.95 in. x 10^5 (0.3 to 0.5 µm) range [24].

2.4.3 Packed Bed Scrubber

2.4.3.1 Fact Sheet--

Description - Contaminants are removed in packed bed scrubbers by a gas absorption process that depends on intimate gas/liquid contact. These scrubbers are vessels filled with randomly oriented packing material such as saddles and rings. The scrubbing liquid is fed to the top of the vessel, with the gas flowing in either concurrent, countercurrent, or crossflow modes. As the liquid flows through the bed, it wets the packing material and thus provides interfacial surface area for mass transfer with the gas phase.

Diagram -
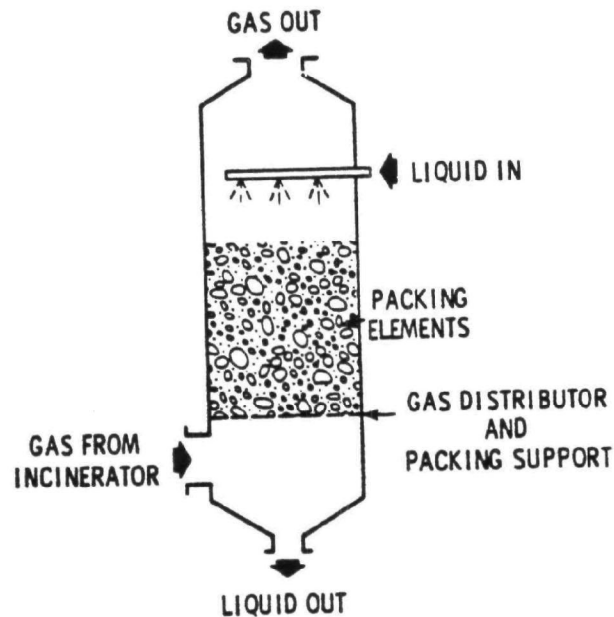
Status - Packed bed scrubbers are a major air pollution control device for hazardous waste incinerators. Predominant use of this APCD has been with liquid injection incinerators, due to their typically low effluent particulate loadings. When packed beds are used to control gaseous emissions from rotary kilns and fluidized bed incinerators, venturi scrubbers are usually incorporated upstream as the primary APCD.

Applicable Waste Streams - Most suitable for the removal of noxious gases in streams containing low or no particulate loading.

Advantages -

(1) High removal efficiency for gaseous and aerosol pollutants.
(2) Low to moderate pressure drop.
(3) Engineering principles controlling the performance of packed bed scrubbers are well developed and understood.
(4) Availability of corrosion-resistant packings to withstand corrosive materials.

Disadvantages -

(1) Low efficiency for fine particles.
(2) Not suitable for high temperature or high dust loading applications.
(3) Requires downstream mist eliminator.
(4) Potential scaling and fouling problems.
(5) Possible damage to the scrubber if scrubber solution pumps fail.

References - 24

2.4.3.2 Detailed Description--
Packed bed scrubbers are used in hazardous waste incineration facilities because of their high removal efficiency for gaseous emissions. Designed properly, a packed bed scrubber will remove >99% of the halogens from inciner- ator exhaust gases. The inherent nature of the design does not, however, allow for removal of particulates from exhaust gases with high particulate loadings. Unless prior treatment is used, this type of waste stream will cause clogging in the packed bed scrubber [24].

The packed bed scrubber is a vessel filled with packing material. The scrub- bing liquid is fed into the top of the vessel, with gas flowing in either a cocurrent, countercurrent, or crosscurrent mode. As the liquid flows through the bed, it wets the packing material and provides interfacial surface area for mass transfer with the gas phase [24].

Differences between packed bed scrubbers include the flow mode, the packing material, and the depth of packing. The choice of flow mode is dependent upon the particular application. Crossflow scrubbing is generally applied to situations where the bed depth is less than 6 ft, and countercurrent design is applied at bed depths of 6 ft or more [24].

Packing material varies in shape and type. Shapes used include rings, spiral rings, and saddles. Packing materials are usually made of ceramic or some other material that will withstand corrosion from acids [24].

The primary parameters that affect scrubber design and the removal of gaseous emissions are discussed below. These include pressure drop, liquid-to-gas ratio, contact time, and gas flow rate [24].

Packed beds used for gaseous emission control in hazardous waste incineration facilities usually have a pressure drop range from 2.0 to 7.2 in. WG (0.5 to 1.8 kPa). The total pressure drop across the packed bed is directly propor- tional to the depth of packing and affects the gaseous removal efficiency in the packed bed scrubber. Normal liquid-to-gas ratios in packed beds vary from 6 to 75 gal/1000 acf, (0.8 to 10 L/m^3, with most units operating between 22 and 52 gal/1000 acf (3 and 7 L/m^3) [24].

In gas absorption devices, higher efficiencies are attained by allowing the gas and liquid phases to be in contact for a longer period of time. Removal efficiencies for gaseous contaminants in packed beds are directly related to the depth of packing, which in turn determines the contact time [24].

The contact time required for gas absorption is a function of the rate of mass transfer. The mass transfer rate, in general, is dependent upon four separate resistances: gas-phase resistance, liquid-phase resistance, chemical reaction resistance, and a solids dissolution resistance for scrubbing liquids containing solid reactants [24].

In the design of gas absorption devices, the cross-sectional area for gas-liquid contact is determined by the superficial gas velocity selected. The greater the gas velocity selected, the smaller will be the scrubber diameter but the larger will be the pressure drop [24].

There are two additional factors to be considered in the selection of gas velocity. First, the gas velocity through the scrubber should allow sufficient residence time for gas-liquid contact. Second, in a countercurrent packed bed, the gas velocity should not exceed the flooding velocity. At the flooding point, the pressure-drop-versus-gas-rate curve becomes almost vertical, and a liquid layer starts to build up on top of the packing. The flooding poing represents the upper limiting conditions of pressure drop and fluid rates for practical tower operation (Figure 2-1). A margin of 30% to 40% of the flooding velocity should be allowed in designing these scrubber types. The most common gas velocities in packed beds range from 7 to 10 ft/s (2.1 to 3.0 m/s) [24].
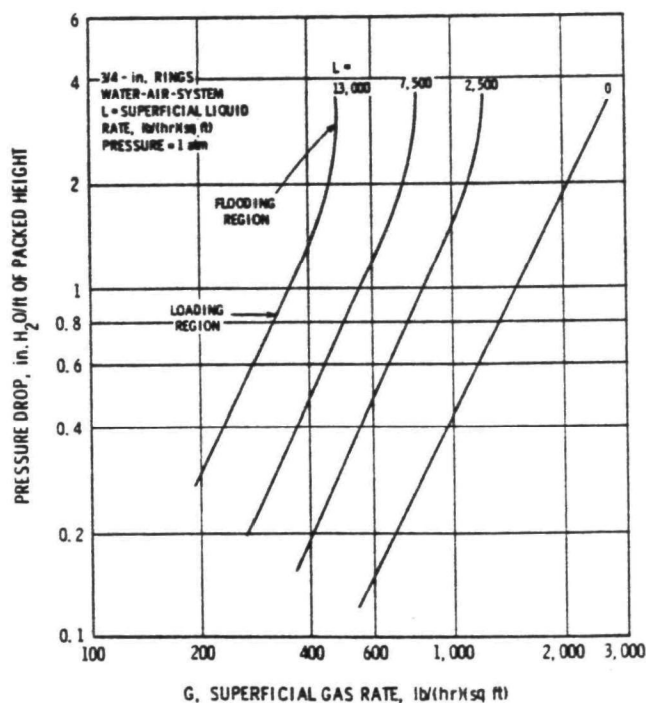
Figure 2-1. Packed tower pressure drop as function
of gas rate and liquid rate.

As in the case with other wet scrubbers, mist eliminators are often used downstream of the packed bed scrubber for proper pollution control. When a wet scrubber follows or precedes a packed scrubber, mist eliminators are often not used. A packed bed scrubber is often sequential to a venturi in a hazardous waste incineration facility.

Most commonly, packed scrubbers are used with liquid injection incinerators because of the low particulate loading in the exhaust gas. The particulates in gas streams tend to clog up the bed and decrease removal efficiency.

2.4.4 Spray Tower

2.4.4.1 Fact Sheet--

Description - Spray towers remove contaminants by a gas absorption process. The scrubbing liquid is atomized by high pressure spray nozzles into small droplets, then directed into a chamber that gases pass through in either countercurrent, cocurrent, or crossflow direction. In this case, the scrubbing liquid is the dispersed phase and gas is the continuous phase. Since mass transfer occurs at the liquid droplet surface, gas absorption is enhanced by finer droplets; i.e., by the increased droplet surface area.

Diagram -
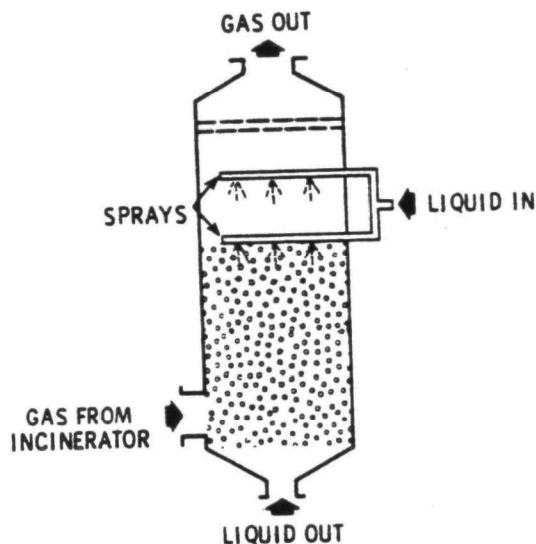
Status - Potential as an APCD for hazardous waste incinerators, although particulate efficiency is lower than that of a high energy venturi and absorption efficiency is lower than that of a packed bed scrubber.

Applicable Waste Streams - Spray towers are suitable for gas streams with particles and gaseous pollutants.

Advantages -

(1) Simultaneous gas absorption and dust removal.
(2) Suitable for high temperature, high moisture, and high dust loading applications.
(3) Simple design.
(4) Rarely have problems with scaling.

Disadvantages -

(1) High efficiency may require high pump discharge pressures.
(2) Dust is collected wet.
(3) Nozzles are susceptible to plugging.
(4) Requires downstream mist eliminator.

<u>Disadvantages</u> - (continued)

(5) Structure is large and bulky.
(6) Lower particulate collection efficiency than a high pressure venturi.
(7) Lower absorption efficiency than a packed tower.

<u>References</u> - 24

2.4.4.2 <u>Detailed Description</u>--
Preformed spray towers are chambers in which a liquid is atomized by high pressure spray nozzle. The gas stream usually enters the bottom of the chamber and flows countercurrent to the liquid, although both cocurrent and cross-current modes have been used. The gas may travel in a single path or may be directed by a series of baffles. The atomized liquid forms droplets and mass transfer occurs at the droplet surface. The finer the droplets, the more gas absorption is enhanced. Impurities which are soluble in the scrubbing liquid are removed by the gas absorption process.

Several of the primary operating parameters that will affect the removal of gaseous contaminants in preformed towers are discussed here. These include the pressure drop, liquid-to-gas ratio, contact time, and gas flow rate. A normal pressure drop for a preformed spray tower is 0.5 to 4 in. WG (0.125 to 0.996 kPa) [24].

Liquid-to-gas ratios are strongly dependent upon the control device and the specific application. Under normal operating conditions, preformed spray towers employ liquid-to-gas ratios in the range of 0.0299 gal/acf (4 to 14 L/m^3) [26].

In gas absorption devices, higher efficiencies are attained by allowing the gas and liquid phases to be in contact for a longer period of time. The contact time required for gas absorption is a function of the rate of mass transfer. The mass transfer rate, in general, is dependent upon four separate resistances: gas-phase resistance, liquid-phase resistance, chemical reaction resistance, and a solids dissolution resistance for scrubbing liquids containing solid reactants. For absorption of gaseous contaminants that are highly soluble or chemically reactive with the scrubbing liquid, such as the absorption of HCl by caustic solution, the contact time required for 99% removal is extremely short (of the order of 0.4 to 0.6 s). The rate at which flue gas from a waste incinerator must be processed by a particle control device depends primarily on the waste composition, the quantity of excess combustion air used, the initial gas temperature, and the method(s) by which the gas has been cooled, if cooling is used. Hence these parameters, in conjunction with the control device size or geometry, will dictate the velocity at which the gas will pass the particle collection elements. Because inertial impaction is the principal particle collection mechanism it is beneficial to operate with a high relative velocity between the gas and the collection element. Practical relative velocity limitations occur as a result of the increased operating costs associated with high pressure drops, flooding, or other considerations. The most common gas velocities in spray towers range from 7 to 10 ft/s (2.1 to 3.0 m/s) [24].

2.4.5 Plate Scrubber

2.4.5.1 Fact Sheet--

Description - A plate scrubber is a type of wet scrubber that relies on a gas absorption process for the removal of contaminants. The basic design is a vertical cylindrical column with a number of plates or trays inside. The scrubbing liquid is introduced at the top plate and flows successively across each plate as it moves downward to the liquid outlet at the tower bottom. Gas comes in at the bottom of the tower and passes through openings in each plate before leaving through the top. Gas absorption is promoted by the breaking up of the gas phase into little bubbles which pass through the volume of liquid in each plate.

Diagram -
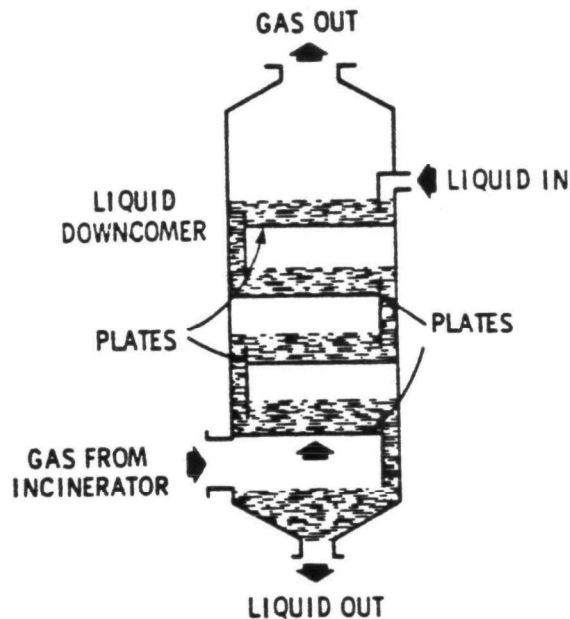
Status - Not as common as packed bed towers or venturi scrubbers for the control of air pollution from hazardous waste incineration. Capable of controlling gaseous emissions from liquid injection incinerators.

Applicable Waste Streams - Most suitable for the removal of noxious gases with low particulate loadings.

Advantages -

(1) Simultaneous gas absorption and dust removal.
(2) High removal efficiency for gaseous and aerosol pollutants.
(3) Low to moderate pressure drop.
(4) Mass transfer increases with multiple plates.
(5) Handles high liquid rates.

Disadvantages -

(1) Low efficiency for fine particles.
(2) Not suitable for high temperature or high dust loading applications.
(3) Requires downstream mist eliminator.
(4) Limestone scrubbing solution causes scaling.
(5) Not suitable for foamy scrubbing liquid.

References - 25

2.4.5.2 Detailed Description--

Plate scrubbers, like all wet scrubbers, remove gaseous contaminants in a gas absorption process that depends on intimate gas/liquid contact. The basic design of a plate scrubber is a vertical cylindrical column with a number of plates or trays inside. Each plate has openings which can be in the form of perforations or slots. The scrubbing liquid is introduced at the top plate and flows across it, then down to the next plate. A downcomer, located on alternate sides of each successive plate, permits the downward movement of the liquid. The scrubbing liquid, exits along with the pollutants at the liquid outlet located at the tower bottom.

Incinerator gas enters the bottom of the tower and passes up through the plate openings before exiting at the top. The gas has enough velocity to prevent the liquid from flowing through the holes in the plates. Gas absorption is promoted by the breaking up of the gas phase into little bubbles which pass through the volume of liquid in each plate.

At hazardous waste incineration facilities, plate towers with two sieve trays are typically used as an absorber/mist eliminator in conjunction with a high energy venturi scrubber.

The primary operating parameters that will affect the removal of gaseous contaminants such as SO_2 are discussed here. These include the pressure drop, liquid-to-gas ratio, contact time, and gas flow rate.

Total pressure drop across the plate towers is similar to that of packed beds, and in the 2.0 to 7.2 in. WG (0.5 to 1.8 kPa range). In plate towers pressure drop is not used as an operating parameter to estimate removal efficiency. Rather, the number of plates is the primary parameter that determines removal efficiency [24].

The liquid-to-gas ratio is a design and operating parameter of prime importance. It is needed in the determination of the scrubber diameter, and has an effect on the height of a transfer unit. A high liquid-to-gas ratio will lead to the requirement of a larger diameter, but at the same time will also reduce the height of a transfer unit. Normal liquid-to-gas ratios in plate towers vary from 6 to 75 gal/1000 acf, (0.8 to 10 L/m^3) with most units operating at between 22 and 52 gal/1000 acf (3 and 7 L/m^3) [24].

Higher efficiencies are attained by allowing the gas and liquid phases to be in contact for a longer period of time. Greater depths of liquid on the trays lead to higher tray efficiency through longer contact time. An increase in the number of plates and the column height also improves removal efficiency.

In the design of gas absorption devices, the cross-sectional area for gas-liquid contact is determined by the superficial gas velocity selected. The greater the gas velocity selected, the smaller will be the scrubber diameter but the larger will be the pressure drop.

There are two additional factors that must be considered in the selection of gas velocity. First, the gas velocity through the scrubber should allow sufficient residence time for gas-liquid contact. Second, in countercurrent plate towers, the gas velocity should not exceed the flooding velocity (the upper limiting conditions of pressure drop and fluid rates for practical operation). A margin of 30% to 40% of the flooding velocity should be allowed in designing these scrubber types. The most common gas velocities in plate towers, range from 7 to 10 ft/s (2.1 to 3.0 m/s) [24].

Parameters that affect the particle collection performance of a plate scrubber include pressure drop, liquid-to-gas ratio, gas velocity, dust loading, and particle size distribution. High particulate loadings and fine particles are unfavorable conditions.

Plate towers are appropriate when particle size is not less than $1\mu m$. Unlike absorption efficiency, particle collection efficiency will not necessarily improve with an increased number of plates, but decreased perforation diameter does increase particle collection efficiency. The other parameters have been discussed previously and will not be addressed [26].

2.4.6 Electrostatic Precipitator (ESP)

2.4.6.1 Fact Sheet--

Description - Electrostatic precipitation is a process by which particles suspended in a gas are electrically charged and separated from the gas stream under the action of an electric field. Particles are collected on plates where subsequent removal is effected by periodically rapping or rinsing.

Diagram -

CLEAN GAS OUT

NEGATIVE ELECTRODE CONNECTED TO ELECTRICAL POWER SOURCE
NEGATIVELY CHARGED WIRE
GROUNDED COLLECTING PLATE WITH POSITIVE CHARGE
DIRTY GAS IN
HOPPER TO DISCHARGE
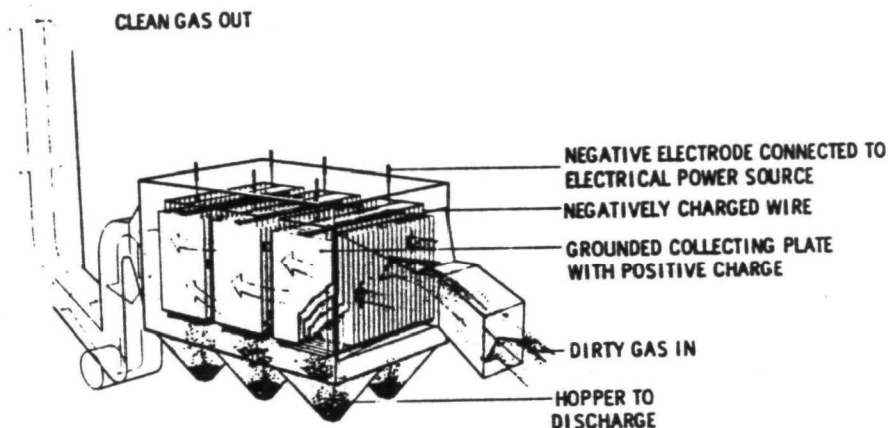
Reprinted by permission

Status - Electrostatic precipitators have been widely used in conjunction with utility boilers and with municipal and industrial incinerators. Dry ESP's are not capable of removing acid gases and, therefore, facilities burning halogenated wastes must employ wet scrubbing of acid halides if ESP's are used for particulate emission control.

Applicable Waste Streams - Effective for the collection of fine particles (less than 3.9×10^{5} in. [1 µm] in diameter), but unable to capture noxious gases. Performs poorly on particles with high electrical resistivity.

Advantages -

(1) Dry dust collection.
(2) Low pressure drop and operating cost.
(3) Efficient removal of fine particles.
(4) Collection efficiency can be improved when stream is treated (i.e., highly conducting dust treated with SO_2).

Disadvantages -

(1) Relatively high capital cost.
(2) Sensitive to changes in flow rate.
(3) Particle resistivity affects removal and economics.

<u>Disadvantages</u> - (continued)

(4) Not capable of removing gaseous pollutants.
(5) Fouling potential with tacky particles.

<u>References</u> - 27

2.4.6.2 <u>Detailed Description</u>--
Electrostatic precipitation is a process by which particles suspended in a gas
are electrically charged and separated from the gas stream. In this process,
negatively charged gas ions are formed between emitting and collecting elec-
trodes by applying a sufficiently high voltage to the emitting electrodes to
produce a corona discharge. Suspended particulate matter is charged as a
result of bombardment by the gaseous ions and migrates toward the grounded
collecting plates due to electrostatic forces. Particle charge is neutralized
at the collecting electrode where subsequent removal is effected by periodical-
ly rapping or rinsing. A majority of industrial EPS's used today are the
single-stage, wire and plate type; charging and collection take place in the
same section of the ESP. Two-stage ESP;s, often called electrostatic filters,
utilize separate sections for particle charging and collecting, and are not
generally employed for controlling particulate emissions from combustion
sources.

Electrostatic precipitators have been widely used in conjunction with utility
boilers and with municipal and industrial incinerators. ESP's have been
employed by European facilities where hazardous wastes are incinerated, al-
though the wastes generally do not contain highly chlorinated compounds. When
halogenated wastes are incinerated, careful waste blending is employed to
protect ESP's from corrosion, so that HCl concentrations do not exceed 1,000
ppm and usually average 300 ppm [27]. Dry ESP's are not capable of removing
acid gases and, therefore, facilities burning halogenated wastes must employ
two-stage gas cleaning if ESP's are used for particulate emission control.

ESP components that are in direct contact with the process gas stream include
the shell, electrodes, high voltage frames, rapper rods and gas distribution
plates. On the basis of mild steel construction, such components constitute
approximately 68% of the total precipitator weight and account for 45% of the
total unit cost [27]. Hence, the applications requiring exposure to corrosive
gas streams have substantial impact on ESP design and ultimate cost. Lead
linings, used in acid mist ESP's, are not generally suitable for use in incin-
erator gas treatment due to poor resistance to attack by gaseous halogens.
Fiber glass reinforced plastic (FRP) has been successfully utilized for inlet
and outlet plenums as well as collecting electrodes; however, the latter
application requires provision of adequate conductivity to permit current flow
to ground.

ESP's are carefully designed and constructed for maximum electrical safety;
however, normal high voltage precautions must be observed. Design features
such as interlocks between access doors and electrical elements should be
employed. Also, access after deenergizing should be delayed to allow for
static charge drainage.

Compared to those of wet scrubbers, pressure and temperature drops across ESP's are very small. The pressure drop across an ESP is typically below 1.00 in. WG (0.25 kPa) as compared with wet scrubbers which may operate with pressure drops up to 60.2 in. WG (15 kPa). Additionally, ESP's provide, generally higher removal efficiencies for particles smaller than 3.9×10^5 in. (1 μm) in diameter than do wet scrubbers. A standard gas temperature range is up to 700°F (370°C) and the voltage normally applied ranges from 30 kV to 75 kV.

2.4.7 Wet Electrostatic Precipitator (WEP)

2.4.7.1 Fact Sheet--

Description - The wet electrostatic precipitator is a variation of the dry electrostatic precipitator design. Particle collection is achieved by introduction of evenly distributed liquid droplets to the gas stream through sprays located above the electrostatic field sections, and migration of the charged particles and liquid droplets to the collection plates.

Diagram -
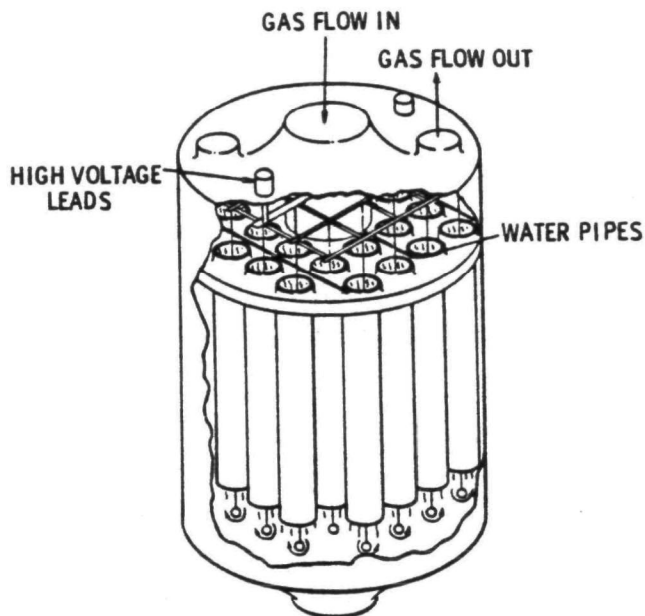
Status - There are presently no WEP installations at hazardous waste incineration facilities.

Applicable Waste Stream - Effective in removal of fine particles and of condensed organic fumes.

Advantages -

(1) Simultaneous gas absorption and dust removal.
(2) Low energy consumption.
(3) No dust resistivity problems.
(4) Efficient removal of fine particles.

Disadvantages -

(1) Low gas absorption efficiency.
(2) Sensitive to changes in flow rate.
(3) Dust collection is wet.

References - 28, 29

2.4.7.2 Detailed Description--

The wet electrostatic precipitator is a variation of the dry electrostatic precipitator design. The two major added features in a WEP system are: (1) a preconditioning step, where inlet sprays in the entry section are provided for cooling, gas absorption, and removal of coarse particles, and (2) a wetted collection surface, where liquid is used to continuously flush away collected materials. Particle collection is achieved by introduction of evenly distributed liquid droplets to the gas stream through sprays located above the electrostatic field sections, and migration of the charged particles and liquid droplets to the collection plates. The collected liquid droplets from a continuous downward-flowing film over the collection plates, and keep them clean by removing the collected particles. To control the carryover of liquid droplets and mists, the last section of the WEP is often operated without penetrate and mists can be collected on baffles.

The WEP overcomes some of the limitations of the dry electrostatic precipitator. The operation of the WEP is not influenced by the resistivity of the particles. Further, since the internal components are continuously being washed with liquid, buildup of tacky particles is controlled and there is some capacity for removal of gaseous pollutants. In general, applications of the WEP fall into two areas: removal of fine particles, and removal of condensed organic fumes. Outlet particulate concentrations are typically in the 2 to 24 mg/m^3 range.

Data on capability of the WEP to remove acid gases are very limited. WEP's have been installed to control HF emissions from Soderberg aluminum reduction cells [27]. With a liquid-to-gas ratio of 5 gal/1000 acf (0.67 L/m^3) and a liquid pH between 8 and 9, fluoride removal efficiencies higher than 98% have been measured. Outlet concentration of HF was found to be less than 1 ppm.

There are no WEP installations at hazardous waste incineration facilities. A potential application is to consider use of the WEP in conjunction with a low pressure drop venturi scrubber upstream, where a major portion of the gaseous contaminants and heavy particles will be removed. The WEP will then serve as a second stage control device for removal of the submicron particles and remaining gaseous pollutants. Because of its limited application history, extensive pilot testing prior to design and installation may be necessary.

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CHAPTER 3

WASTE CHARACTERIZATION

CONTENTS

CHAPTER 3

WASTE CHARACTERIZATION

3.1 INTRODUCTION

Waste characterization is a major factor in assessing the feasibility of
destroying a hazardous waste material by incineration. It affects the design
of the incinerator and its emissions control system and helps determine the
compatibility of a waste with a proposed or available facility. It also plays
a part in determining incinerator operating conditions for complete destruction
of a specific waste.

This chapter discusses the importance of the physical, chemical, and thermo-
dynamic properties of hazardous wastes in evaluating them for incineration and
in selecting a compatible incineration technology type. It also classifies
RCRA Section 3001 hazardous wastes and other hazardous wastes as good, poten-
tial, or poor candidates for incineration, based on technical considerations,
and identifies compatible incineration technology types for these wastes. In
addition, it presents information on sampling and analysis of hazardous wastes
for characterization, and it provides a work sheet to help in evaluating a
waste for incineration.

3.2 WASTE CHARACTERIZATION BACKGROUND INFORMATION

Background information about the hazardous waste(s) is generally available.
Such information may have been generated under Section 3001 (Identification
and Listing of Hazardous Waste), Section 3002 (Standards Applicable to Gener-
ators of Hazardous Waste), or Section 3003 (Standards Applicable to Transporters
of Hazardous Waste) of the RCRA regulations. Additional information can usu-
ally be obtained from studies of the process(es) generating the waste(s).
This background information is helpful in evaluating waste for incineration.

3.2.1 Information Available from Waste Generators

A generator of hazardous waste should be able to provide the Standard Industrial
Classification (SIC) code of the industry from which the waste originates, the
EPA hazardous waste number, and a short description of the waste. The generator
may also provide a detailed description of the process that generates the
waste.

3.2.2 Information Available from Transporters

Federal or state regulations regarding transportation of the waste may give
additional waste characterization information. The manifest that accompanied

3-1

a waste shipment will identify the waste hazard class according to DOT regulations. Also, waste data sheets (forms) that are used prior to discharge of any waste at a disposal operation may be available. These types of information are helpful in evaluating a waste or planning provisions for personnel and environmental safety during storage and handling of the waste at the facility.

3.2.3 Additional Information Sources

Additional information relevant to hazardous waste incineration can be obtained by contacting the following sources:

A. EPA regional offices:

Region I
John F. Kennedy Federal Building
Room 2203
Boston, MA   02203
Telephone: (617) 223-7210

Region II
26 Federal Plaza, Room 1009
New York, NY   10007
Telephone: (212) 264-2525

Region III
Curtis Building
6th & Walnut Streets
Philadelphia, PA   19106
Telephone: (215) 597-9814

Region IV
345 Courtland Street, NE
Atlanta, GA   30308
Telephone: (404) 881-4727

Region V
230 S. Dearborn Street
Chicago, IL   60604
Telephone: (312) 353-2000

Region VI
First International Building
1201 Elm Street
Dallas, TX   75270
Telephone: (214) 767-2600

Region VII
1735 Baltimore Street
Kansas City, MO   64108
Telephone: (816) 374-5493

Region VIII
1860 Lincoln Street
Denver, CO 80203
Telephone: (303) 837-3895

Region IX
215 Fremont Street
San Francisco, CA 94105
Telephone: (415) 556-2320

Region X
1200 6th Avenue
Seattle, WA 98101
Telephone: (206) 442-1220

B. Industrial Environmental Research Laboratory
    U.S. Environmental Protection Agency
    5555 Ridge Avenue
    Cincinnati, OH 45268
    Telephone: (513) 684-4303

C. Office of Solid Waste
    U.S. Environmental Protection Agency
    401 M Street, SW
    Washington, DC 20460
    Telephone: (202) 755-9206

D. State Environmental Protection Departments

Table 3-1 can also be consulted relative to RCRA Section 3001 hazardous wastes and other hazardous wastes which are good, potential, or poor candidates for incineration with appropriate incineration technologies, based on technical considerations. This table was prepared using available background documents for some of the listed waste, trial burn data, and engineering judgment based on chemical formula(s) of compound(s) present in the waste. The following criteria were used to structure engineering judgment:

Waste containing	Incineration category
• Carbon, hydrogen, and/or oxygen	Good
• Carbon, hydrogen, ≤30% by weight chlorine and/or oxygen	Good
• Carbon, hydrogen, and/or oxygen, >30% by weight chlorine, phosphorus, sulfur, bromine, iodine, or nitrogen	Potential
• Unknown percent of chlorine	Potential
• Inorganic compounds	Poor
• Compounds containing metals	Poor

Other factors to be considered in evaluating waste for incineration are:

TABLE 3-1. HAZARDOUS WASTES RATED AS GOOD, POTENTIAL, OR POOR CANDIDATES FOR INCINERATION BY APPROPRIATE TECHNOLOGIES [1-8]

EPA hazardous waste number	Hazardous waste	Candidate for incineration			Incinerator type		
		Good	Potential	Poor	Liquid injection	Rotary kiln	Fluidized bed
Generic							
F001	The spent halogenated solvents used in degreasing, tetrachloroethylene, trichloroethylene, methylene chloride, 1,1,1-trichloroethane, carbon tetrachloride, and the chlorinated fluorocarbons; and sludges from the recovery of these solvents in degreasing operations.	√			√	√	√
F002	The spent halogenated solvents, tetrachloroethylene, methylene chloride, trichloroethylene, 1,1,1-trichloroethane, chlorobenzene, 1,1,2-tri-chloro-1,2,2-trifluoroethane, o-dichlorobenzene, trichlorofluoromethane and the still bottoms from the recovery of these solvents.	√			√	√	√
F003	The spent nonhalogenated solvents, xylene, acetone, ethyl acetate, ethyl benzene, ethyl ether, n-butyl alcohol, cyclohexanone, and the still bottoms from the recovery of these solvents.	√			√	√	√
F004	The spent nonhalogenated solvents, cresols and cresylic acid, nitrobenzene, and the still bottoms from the recovery of these solvents.	√			√	√	√
F005	The spent nonhalogenated solvents, methanol, toluene, methyl ethyl ketone, carbon disulfide, isobutanol, pyridine and the still bottoms from the recovery of these solvents	√			√	√	√
F006	Wastewater treatment sludges from electroplating operations			√			
F007	Spent plating bath solutions from electroplating operations			√			
F008	Plating bath sludges from the bottom of plating baths from electroplating operations.			√			
F009	Spent stripping and cleaning bath solutions from electroplating operations.			√			
F010	Quenching bath sludge from oil baths from metal heat treating operations.			√			
F011	Spent solutions from salt bath pot cleaning from metal heat treating operations.			√			
F012	Quenching wastewater treatment sludges from metal heat treating operations.			√			
F013	Flotation tailings from selective flotation from mineral metals recovery operations.			√			
F014	Cyanidation wastewater treatment tailing pond sediment from mineral metals recovery operations			√			
F015	Spent cyanide bath solutions from mineral metals recovery operations			√			
F016	Dewatered air pollution control scrubber sludges from coke ovens and blast furnaces.			√			
Wood preservation							
K001	Bottom sediment sludge from the treatment of wastewaters from wood preserving processes that use creosote and/or pentachlorophenol	√				√	√
Inorganic pigments							
K002	Wastewater treatment sludge from the production of chrome yellow and orange pigments			√			
K003	Wastewater treatment sludge from the production of molybdate orange pigments			√			
K004	Wastewater treatment sludge from the production of zinc yellow pigments			√			

(continued)

TABLE 3-1 (continued)

EPA hazardous waste number	Hazardous waste	Good	Potential	Poor	Liquid injection	Rotary kiln	Fluidized bed
Inorganic pigments (cont'd)							
K005	Wastewater treatment sludge from the production of chrome green pigments			✓			
K006	Wastewater treatment sludge from the production of chrome oxide green pigments (anhydrous and hydrated)			✓			
K007	Wastewater treatment sludge from the production of iron blue pigments			✓			
K008	Oven residue from the production of chrome oxide green pigments			✓			
Organic chemicals							
K009	Distillation bottoms from the production of acetaldehyde from ethylene	✓					
K010	Distillation side cuts from the production of acetaldehyde from ethylene	✓					
K011	Bottom stream from the wastewater stripper in the production of acrylonitrile	✓					
K012	Still bottoms from the final purification of acrylonitrile in the production of acrylonitrile	✓			✓	✓	✓
K013	Bottom stream from the acetonitrile column in the production of acrylonitrile	✓					
K014	Bottoms from the acetronitrile purification column in the production of acrylonitrile	✓			✓	✓	
K015	Still bottoms from the distillation of benzyl chloride						
K016	Heavy ends or distillation residues from the production of carbon tetrachloride	✓				✓	✓
K017	Heavy ends (still bottoms) from the purification column in the production of epichlorohydrin	✓				✓	✓
K018	Heavy ends from fractionation of ethyl chloride production	✓					
K019	Heavy ends from the distillation of ethylene dichloride in ethylene dichloride production	✓				✓	✓
K020	Heavy ends from the distillation of vinyl chloride in vinyl chloride monomer production	✓				✓	✓
K021	Aqueous spent antimony catalyst waste from fluoromethanes production		✓				
K022	Distillation bottom tars from the production of phenol/acetone from cumene	✓				✓	✓
K023	Distillation light ends from the production of phthalic anhydride from naphthalene	✓			✓	✓	✓
K024	Distillation bottoms from the production of phthalic anhydride from naphthalene	✓				✓	✓
K025	Distillation bottoms from the production of nitrobenzene by the nitration of benzene	✓					
K026	Stripping still tails from the production of methyl ethyl pyridines	✓					
K027	Centrifuge residue from toluene diisocyanate production						
K028	Spent catalyst from the hydrochlorinator reactor in the production of 1,1,1-trichloroethane				✓		
K029	Waste from the product stream stripper in the production of 1,1,1-trichloroethane	✓					

(continued)

3-5

TABLE 3-1 (continued)

EPA hazardous waste number	Hazardous waste	Candidate for incineration			Incinerator type		
		Good	Potential	Poor	Liquid injection	Rotary kiln	Fluidized bed
Organic chemicals (cont'd)							
K030	Column bottoms or heavy ends from the combined production of trichloro-ethylene and perchloroethylene	✓				✓	✓
Pesticides							
K031	By-products salts generated in the production of MSMA and cacodylic acid		✓				
K032	Wastewater treatment sludge from the production of chlordane	✓					
K033	Wastewater and scrub water from the chlorination of cyclopentadiene in the production of chlordane	✓					
K034	Filter solids from the filtration of hexachlorocyclopentadiene in the production of chlordane		✓				
K035	Wastewater treatment sludges generated in the production of creosote	✓					
K036	Still bottoms from toluene reclamation distillation in the production of disulfoton	✓					
K037	Wastewater treatment sludges from the production of disulfoton	✓					
K038	Wastewater from the washing and stripping of phorate production	✓					
K039	Filter cake from the filtration of diethylphosphorodithoric acid in the production of phorate	✓				✓	✓
K040	Wastewater treatment sludge from the production of phorate	✓	✓				
K041	Wastewater treatment sludge from the production of toxaphene	✓					
K042	Heavy ends or distillation residues from the distillation of tetrachloro-benzene in the production of 2,4,5-T	✓					
K043	2,6-Dichlorophenol waste from the production of 2,4-D	✓					
Explosives							
K044	Wastewater treatment sludges from the manufacturing and processing of explosives		✓			✓	✓
K045	Spent carbon from the treatment of wastewater containing explosives	✓					
K046	Wastewater treatment sludges from the manufacturing, formulation and loading of lead-based initiating compounds		✓		✓	✓	✓
K047	Pink/red water from TNT operations	✓				✓	✓
Petroleum refining							
K048	Dissolved air flotation (DAF) float from the petroleum refining industry	✓				✓	✓
K049	Slop oil emulsion solids from the petroleum refining industry	✓					
K050	Heat exchanger bundle cleaning sludge from the petroleum refining industry		✓			✓	✓
K051	API separator sludge from the petroleum refining industry	✓				✓	✓
K052	Tank bottoms (leaded) from the petroleum refining industry	✓				✓	✓
Leather tanning finishing							
K053	Chrome (blue) trimmings generated by the following subcategories of the leather tanning and finishing industry, hair pulp/chrome tan/retan/wet finish, hair save/chrome tan/retan/wet finish; retan/wet finish, no beamhouse; through-the-blue, and shearling		✓				

TABLE 3-1 (continued)

EPA hazardous waste number	Hazardous waste	Candidate for incineration			Incinerator type		
		Good	Potential	Poor	Liquid injection	Rotary kiln	Fluidized bed
Leather tanning finishing (cont'd)							
K054	Chrome (blue) shavings generated by the following subcategories of the leather tanning and finishing industry: hair pulp/chrome tan/retan/wet finish; hair save/chrome tan/retan/wet finish; retan/wet finish; no beamhouse; through-the-blue, and shearling		✓				
K055	Buffing dust generated by the following subcategories of the leather tanning and finishing industry: hair pulp/chrome tan/retan/wet finish; hair save/chrome tan/retan/wet finish; retan/wet finish; no beamhouse; and through-the-blue		✓				
K056	Sewer screenings generated by the following subcategories of the leather tanning and finishing industry. hair pulp/chrome tan/retan/wet finish; hair save/chrome tan/retan/wet finish; retan/wet finish; no beamhouse; through-the-blue; and shearling		✓				
K057	Wastewater treatment sludges generated by the following subcategories of the leather tanning and finishing industry; hair pulp/chrome tan/retan/wet finish, hair save/chrome tan/retan/wet finish; retan/wet finish; no beamhouse; through-the-blue and shearling		✓				
K058	Wastewater treatment sludges generated by the following subcategories of the leather tanning and finishing industry: hair pulp/chrome tan/retan/wet finish; hair save/chrome tan/retan/wet finish; and through-the-blue		✓				
K059	Wastewater treatment sludges generated by the following subcategory of the leather tanning and finishing industry: hair save/nonchrome tan/retan/wet finish		✓				
Iron and steel							
K060	Ammonia still lime sludge from coking operations		✓				
K061	Emission control dust/sludge from the electric furnace production of steel		✓				
K062	Spent pickle liquor from steel finishing operations		✓				
K063	Sludge from lime treatment of spent pickle liquor from steel finishing operations		✓				
Primary copper							
K064	Acid plant blowdown slurry/sludge resulting from the thickening of blowdown slurry from primary copper production		✓				
Primary lead							
K065	Surface impoundment solids contained in and dredged from surface impoundments at primary lead smelting facilities		✓				
Primary zinc							
K066	Sludge from treatment of process wastewater and/or acid plant blowdown from primary zinc production		✓				
K067	Electrolytic anode slimes/sludges from primary zinc production		✓				
K068	Cadmium plant leach residue (iron oxide) from primary zinc production		✓				

TABLE 3-1 (continued)

EPA hazardous waste number	Hazardous waste	Candidate for incineration			Incinerator type		
		Good	Potential	Poor	Liquid injection	Rotary kiln	Fluidized bed
Secondary lead							
K069	Emission control dust/sludge from secondary lead smelting			✓			
Discarded commercial chemical products, off-specification species, containers, and spill residues thereof							
P001	3-(alpha-Acetonylbenzyl)-4-hydroxycoumarin and salts	✓			✓	✓	✓
P002	1-Acetyl-2-thiourea		✓		✓	✓	✓
P003	Acrolein	✓			✓		✓
P004	Aldrin		✓		✓	✓	✓
P005	Allyl alcohol	✓			✓	✓	✓
P006	Aluminum phosphide			✓			✓
P007	5-(Aminomethyl)-3-isoxazolol		✓			✓	✓
P008	4-Aminopyridine		✓			✓	✓
P009	Ammonium picrate		✓				
P010	Arsenic acid			✓			
P011	Arsenic pentoxide			✓			
P012	Arsenic trioxide			✓			
P013	Barium cyanide		✓		✓	✓	✓
P014	Benzenethiol			✓			
P015	Beryllium dust			✓			
P016	Bis(chloromethyl) ether		✓		✓	✓	✓
P017	Bromoacetone		✓			✓	✓
P018	Brucine	✓			✓	✓	✓
P019	2-Butanone peroxide	✓			✓	✓	✓
P020	2-sec-butyl-4,6-dinitrophenol			✓			
P021	Calcium cyanide	✓			✓	✓	✓
P022	Carbon disulfide		✓		✓	✓	✓
P023	Chloroacetaldehyde	✓				✓	
P024	p-Chloroaniline	✓				✓	
P025	1-(p-Chlorobenzoyl)-5-methoxy-2-methylindole-3-acetic acid		✓			✓	
P026	1-(o-Chlorophenyl) thiourea		✓		✓	✓	
P027	3-Chloropropionitrile	✓				✓	
P028	alpha-Chlorotoluene	✓					
P029	Copper cyanide			✓			
P030	Cyanides	✓				✓	✓
P031	Cyanogen	✓				✓	✓
P032	Cyanogen bromide		✓			✓	✓
P033	Cyanogen chloride		✓			✓	
P034	2-Cyclohexyl-4,6-dinitrophenol	✓				✓	
P035	2,4-Dichlorophenoxyacetic acid (2,4-D)		✓				
P036	Dichlorophenylarsine	✓				✓	•
P037	Dieldrin	✓				✓	
P038	Diethylarsine			✓			
P039	O,O-Diethyl-S-[2-(ethylthio)ethyl] ester of phosphorothioic acid	✓	✓		✓	✓	✓
P040	O,O-Diethyl-O-(2-pyrazinyl) phosphorothioate	✓			✓	✓	✓

(continued)

TABLE 3-1 (continued)

EPA hazardous waste number	Hazardous waste	Candidate for incineration			Incinerator type		
		Good	Potential	Poor	Liquid injection	Rotary kiln	Fluidized bed
	Discarded commercial chemical products, off-specification species, containers, and spill residues thereof (cont'd)						
P041	O,O-Diethyl phosphoric acid, O-p-nitrophenyl ester		✓		✓	✓	✓
P042	3,4-Dihydroxy-alpha-(methylamino)-methyl benzyl alcohol	✓			✓	✓	✓
P043	Di-isopropylfluorophosphate		✓		✓		✓
P044	Dimethoate		✓			✓	✓
P045	3,3-Dimethyl-1-(methylthio)-2-butanone-O-[(methylamino)carbonyl] oxime		✓			✓	✓
P046	alpha, alpha-dimethylphenethylamine	✓			✓	✓	✓
P047	4,6-Dinitro-o-cresol and salts		✓			✓	✓
P048	2,4-Dinitrophenol		✓			✓	✓
P049	2,4-Dithiobiuret		✓			✓	✓
P050	Endosulfan		✓			✓	
P051	Endrin		✓		✓	✓	
P052	Ethylcyanide	✓			✓	✓	✓
P053	Ethylenediamine	✓			✓	✓	✓
P054	Ethyleneimine	✓			✓	✓	✓
P055	Ferric cyanide			✓			
P056	Fluorine			✓			
P057	2-Fluoroacetamide		✓			✓	✓
P058	Fluoroacetic acid, sodium salt			✓			
P059	Heptachlor	✓				✓	
P060	1,2,3,4,10,10-Hexachloro-1,4,4a,5,8,8a-hexahydro-1,4:5,8-endo, endo-dimethanonaphthalene		✓			✓	✓
P061	Hexachloropropene		✓		✓	✓	✓
P062	Hexaethyl tetraphosphate		✓			✓	✓
P063	Hydrocyanic acid	✓			✓	✓	✓
P064	Isocyanic acid, methyl ester	✓			✓	✓	✓
P065	Mercury fulminate			✓			
P066	Methomyl		✓			✓	✓
P067	2-Methylaziridine	✓			✓	✓	✓
P068	Methyl hydrazine	✓			✓	✓	✓
P069	2-Methyllactonitrile		✓		✓	✓	✓
P070	2-Methyl-2-(methylthio)propionaldehyde-o-(methylcarbonyl) oxime		✓			✓	✓
P071	Methyl parathion		✓			✓	✓
P072	1-Naphthyl-2-thiourea		✓			✓	✓
P073	Nickel carbonyl			✓			
P074	Nickel cyanide			✓			
P075	Nicotine and salts		✓			✓	✓
P076	Nitric oxide			✓			
P077	p-Nitroaniline		✓			✓	✓
P078	Nitrogen dioxide			✓			
P079	Nitrogen peroxide			✓			
P080	Nitrogen tetroxide			✓			
P081	Nitroglycerine	✓			✓	✓	✓
P082	N-Nitrosodimethylamine		✓			✓	✓
P083	N-Nitrosodiphenylamine		✓			✓	✓

(continued)

TABLE 3-1 (continued)

EPA hazardous waste number	Hazardous waste	Candidate for incineration			Incinerator type		
		Good	Potential	Poor	Liquid injection	Rotary kiln	Fluidized bed
Discarded commercial chemical products, off-specification species, containers, and spill residues thereof (cont'd)							
P084	N-Nitrosomethylvinylamine		✓			✓	✓
P085	Octamethylpyrophosphoramide		✓		✓	✓	✓
P086	Oleyl alcohol condensed with 2 moles ethylene oxide	✓			✓	✓	✓
P087	Osmium tetroxide			✓			
P088	7-Oxabicyclo[2.2.1]heptane-2,3-dicarboxylic acid	✓			✓	✓	✓
P089	Parathion		✓		✓	✓	
P090	Pentachlorophenol		✓				
P091	Phenyl dichloroarsine			✓			
P092	Phenylmercury acetate		✓			✓	✓
P093	N-Phenylthiourea		✓		✓	✓	✓
P094	Phorate		✓			✓	✓
P095	Phosgene		✓			✓	✓
P096	Phosphine			✓			
P097	Phosphorothioic acid, O,O-dimethyl ester, O-ester with N,N-dimethyl benzene sulfonamide		✓		✓	✓	✓
P098	Potassium cyanide			✓			
P099	Potassium silver cyanide			✓			
P100	1,2-Propanediol	✓			✓	✓	✓
P101	Propionitrile	✓			✓	✓	✓
P102	2-Propyn-1-ol	✓					
P103	Selenourea			✓			
P104	Silver cyanide			✓			
P105	Sodium azide			✓			
P106	Sodium cyanide			✓			
P107	Strontium sulfide		✓			✓	✓
P108	Strychnine and salts		✓			✓	✓
P109	Tetraethyldithiopyrophosphate		✓				
P110	Tetraethyl lead			✓			
P111	Tetraethylpyrophosphate		✓		✓	✓	✓
P112	Tetranitromethane		✓				
P113	Thallic oxide			✓			
P114	Thallium selenite			✓			
P115	Thallium (1) sulfate		✓			✓	✓
P116	Thiosemicarbazide		✓			✓	✓
P117	Thiuram		✓			✓	✓
P118	Trichloromethanethiol		✓				
P119	Vanadic acid, ammonium salt			✓			
P120	Vanadium pentoxide			✓			
P121	Zinc cyanide			✓			
P122	Zinc phosphide	✓			✓		
U001	Acetaldehyde	✓			✓	✓	✓
U002	Acetone	✓			✓	✓	✓
U003	Acetonitrile		✓		✓		✓

(continued)

TABLE 3-1 (continued)

EPA hazardous waste number	Hazardous waste	Candidate for incineration			Incinerator type		
		Good	Potential	Poor	Liquid injection	Rotary kiln	Fluidized bed
Discarded commercial chemical products, off-specification species, containers, and spill residues thereof (cont'd)		✓			✓	✓	✓
U004	Acetophenone	✓					
U005	2-Acetylaminoflourene		✓		✓	✓	✓
U006	Acetyl chloride				✓		
U007	Acrylamide	✓			✓	✓	✓
U008	Acrylic acid	✓			✓	✓	✓
U009	Acrylonitrile						
U010	6-Amino-1,1a,2,8,8a,8b-hexahydro-8-(hydroxymethyl)8-methoxy-5-methylcarba-mate azirino(2',3':3,4) pyrrolo(1,2-a)indole-4, 7-dione (ester)		✓			✓	✓
U011	Amitrole	✓			✓	✓	✓
U012	Aniline			✓			
U013	Asbestos		✓			✓	✓
U014	Auramine		✓			✓	
U015	Azaserine		✓		✓	✓	
U016	Benz[c]acridine		✓		✓	✓	
U017	Benzal chloride	✓			✓	✓	✓
U018	Benz[a]anthracene	✓			✓	✓	✓
U019	Benzene	✓			✓	✓	
U020	Benzenesulfonyl chloride				✓	✓	✓
U021	Benzidine	✓			✓	✓	✓
U022	Benzo[a]pyrene		✓		✓	✓	
U023	Benzotrichloride				✓	✓	✓
U024	Bis(2-chloroethoxy)methane		✓		✓		
U025	Bis(2-chloroethyl) ether	✓			✓	✓	✓
U026	N,N-Bis(2-chloroethyl)-2-naphthylamine		✓		✓	✓	✓
U027	Bis(2-chloroisopropyl) ether				✓	✓	✓
U029	Bromomethane				✓	✓	✓
U030	4-Bromophenyl phenyl ether	✓			✓	✓	✓
U031	n-Butyl alcohol			✓			
U032	Calcium chromate				✓	✓	✓
U033	Carbonyl fluoride				✓	✓	
U034	Chloral				✓	✓	✓
U035	Chlorambucil				✓	✓	
U036	Chlordane	✓			✓	✓	✓
U037	Chlorobenzene	✓			✓	✓	✓
U038	Chlorobenzilate	✓					
U039	p-Chloro-m-cresol				✓	✓	✓
U040	Chlorodibromomethane				✓	✓	✓
U041	1-Chloro-2,3-epoxypropane				✓	✓	✓
U042	Chloroethyl vinyl ether				✓	✓	✓
U043	Chloroethene				✓	✓	✓
U044	Chloroform				✓	✓	✓
U045	Chloromethane				✓	✓	

(continued)

TABLE 3-1 (continued)

EPA hazardous waste number	Hazardous waste	Candidate for incineration			Incinerator type		
		Good	Potential	Poor	Liquid injection	Rotary kiln	Fluidized bed
Discarded commercial chemical products, off-specification species, containers, and spill residues thereof (cont'd)							
U089	Diethylstilbestrol	✓				✓	✓
U090	Dihydrosafrole	✓			✓	✓	✓
U091	3,3'-Dimethoxybenzidine	✓				✓	✓
U092	Dimethylamine		✓			✓	✓
U093	p-Dimethylaminoazobenzene	✓				✓	✓
U094	7,12-Dimethylbenz[a]anthracene	✓				✓	✓
U095	3,3'-Dimethylbenzidine	✓			✓	✓	✓
U096	alpha-alpha-Dimethylbenzylhydroperoxide		✓			✓	✓
U097	Dimethylcarbamoyl chloride		✓		✓	✓	✓
U098	1,1-Dimethylhydrazine	✓				✓	✓
U099	1,2-Dimethylhydrazine	✓				✓	✓
U100	Dimethylnitrosoamine	✓				✓	✓
U101	2,4-Dimethylphenol	✓			✓	✓	✓
U102	Dimethyl phthalate		✓			✓	✓
U103	Dimethyl sulfate		✓			✓	✓
U104	2,4-Dinitrophenol		✓			✓	✓
U105	2,4-Dinitrotoluene		✓			✓	✓
U106	2,6-Dinitrotoluene	✓			✓	✓	✓
U107	Di-n-octyl phthalate	✓			✓	✓	✓
U108	1,4-Dioxane		✓			✓	✓
U109	1,2-Diphenylhydrazine		✓			✓	✓
U110	Dipropylamine		✓			✓	✓
U111	Di-n-propylnitrosamine	✓			✓	✓	✓
U112	Ethyl acetate	✓				✓	✓
U113	Ethyl acrylate	✓			✓	✓	✓
U114	Ethylenebisdithiocarbamate	✓				✓	✓
U115	Ethylene oxide		✓			✓	✓
U116	Ethylene thiourea	✓			✓	✓	✓
U117	Ethyl ether	✓				✓	✓
U118	Ethylmethacrylate		✓			✓	✓
U119	Ethyl methanesulfonate	✓				✓	✓
U120	Fluoranthene		✓			✓	✓
U121	Fluorotrichloromethane	✓				✓	✓
U122	Formaldehyde	✓			✓	✓	✓
U123	Formic acid	✓			✓	✓	✓
U124	Furan	✓			✓	✓	✓
U125	Furfural	✓			✓	✓	✓
U126	Glycidylaldehyde		✓			✓	✓
U127	Hexachlorobenzene		✓			✓	✓
U128	Hexachlorobutadiene		✓			✓	✓
U129	Hexachlorocyclohexane	✓			✓	✓	✓
U130	Hexachlorocyclopentadiene	✓				✓	✓

(continued)

TABLE 3-1 (continued)

EPA hazardous waste number	Hazardous waste	Candidate for incineration			Incinerator type		
		Good	Potential	Poor	Liquid injection	Rotary kiln	Fluidized bed
Discarded commercial chemical products, off-specification species, containers, and spill residues thereof (cont'd)							
U046	Chloromethyl methyl ether		√		√	√	√
U047	2-Chloronaphthalene	√			√	√	
U048	2-Chlorophenol	√			√	√	√
U049	4-Chloro-o-toluidine hydrochloride	√			√	√	√
U050	Chrysene	√			√	√	√
U051	Cresote	√				√	√
U052	Cresols	√			√	√	√
U053	Crotonaldehyde	√			√	√	√
U054	Cresylic acid	√			√	√	√
U055	Cumene	√			√	√	√
U056	Cyclohexane	√			√	√	√
U057	Cyclohexanone	√				√	√
U058	Cyclophosphamide		√			√	√
U059	Daunomycin		√			√	
U060	DDD		√			√	
U061	DDT		√			√	
U062	Diallate	√				√	√
U063	Dibenz[a,h]anthracene	√				√	
U064	Dibenzo[a,i]pyrene		√		√	√	
U065	Dibromochloromethane		√		√	√	
U066	1,2-Dibromo-3-chloropropane		√			√	√
U067	1,2-Dibromoethane		√			√	√
U068	Dibromomethane	√				√	√
U069	Di-n-butyl phthalate		√		√	√	√
U070	1,2-Dichlorobenzene		√		√	√	
U071	1,3-Dichlorobenzene		√			√	
U072	1,4-Dichlorobenzene		√			√	
U073	3,3'-Dichlorobenzidine		√		√		√
U074	1,4-Dichloro-2-butene		√			√	√
U075	Dichlorodifluoromethane		√		√	√	√
U076	1,1-Dichloroethane		√		√	√	√
U077	1,2-Dichloroethane		√		√	√	√
U078	1,1-Dichloroethylene		√		√	√	√
U079	1,2-trans-dichloroethylene		√		√	√	√
U080	Dichloromethane		√			√	√
U081	2,4-Dichlorophenol		√			√	√
U082	2,6-Dichlorophenol		√		√	√	√
U083	1,2-Dichloropropane		√			√	√
U084	1,3-Dichloropropane	√			√	√	√
U085	Diepoxybutane	√			√	√	√
U086	1,2-Diethylhydrazine		√		√	√	√
U087	O,O-DiethylS-methyl ester of phosphorodithioic acid	√			√	√	√
U088	Diethyl phthalate						

(continued)

TABLE 3-1 (continued)

EPA hazardous waste number	Hazardous waste	Candidate for incineration			Incinerator type		
		Good	Potential	Poor	Liquid injection	Rotary kiln	Fluidized bed
Discarded commercial chemical products, off-specification species, containers, and spill residues thereof (cont'd)							
U089	Diethylstilbestrol	✓				✓	✓
U090	Dihydrosafrole	✓			✓	✓	✓
U091	3,3'-Dimethoxybenzidine	✓				✓	✓
U092	Dimethylamine	✓				✓	✓
U093	p-Dimethylaminoazobenzene		✓			✓	✓
U094	7,12-Dimethylbenz[a]anthracene	✓				✓	
U095	3,3'-Dimethylbenzidine	✓			✓	✓	✓
U096	alpha-alpha-Dimethylbenzylhydroperoxide	✓			✓	✓	✓
U097	Dimethylcarbamoyl chloride		✓				
U098	1,1-Dimethylhydrazine		✓		✓	✓	✓
U099	1,2-Dimethylhydrazine		✓		✓	✓	✓
U100	Dimethylnitrosoamine		✓				✓
U101	2,4-Dimethylphenol	✓			✓	✓	✓
U102	Dimethyl phthalate	✓				✓	✓
U103	Dimethyl sulfate		✓				✓
U104	2,4-Dinitrophenol		✓			✓	✓
U105	2,4-Dinitrotoluene		✓			✓	✓
U106	2,6-Dinitrotoluene		✓			✓	
U107	Di-n-octyl phthalate	✓			✓	✓	✓
U108	1,4-Dioxane	✓			✓	✓	✓
U109	1,2-Diphenylhydrazine		✓			✓	
U110	Dipropylamine		✓		✓	✓	✓
U111	Di-n-propylnitrosamine		✓		✓	✓	✓
U112	Ethyl acetate	✓			✓	✓	
U113	Ethyl acrylate	✓			✓	✓	✓
U114	Ethylenebisdithiocarbamate		✓			✓	✓
U115	Ethylene oxide	✓				✓	
U116	Ethylene thiourea		✓		✓	✓	✓
U117	Ethyl ether	✓			✓	✓	✓
U118	Ethylmethacrylate	✓				✓	
U119	Ethyl methanesulfonate		✓		✓	✓	✓
U120	Fluoranthene	✓				✓	✓
U121	Fluorotrichloromethane		✓			✓	
U122	Formaldehyde	✓				✓	✓
U123	Formic acid	✓			✓	✓	✓
U124	Furan	✓				✓	
U125	Furfural	✓			✓	✓	✓
U126	Glycidylaldehyde	✓			✓	✓	
U127	Hexachlorobenzene		✓			✓	
U128	Hexachlorobutadiene		✓			✓	✓
U129	Hexachlorocyclohexane		✓		✓	✓	
U130	Hexachlorocyclopentadiene		✓		✓	✓	✓

(continued)

TABLE 3-1 (continued)

EPA hazardous waste number	Hazardous waste	Candidate for incineration			Incinerator type		
		Good	Potential	Poor	Liquid injection	Rotary kiln	Fluidized bed
Discarded commercial chemical products, off-specification species, containers, and spill residues thereof (cont'd)							
U131	Hexachloroethane	✓				✓	✓
U132	Hexachlorophene	✓				✓	✓
U133	Hydrazine	✓			✓	✓	✓
U134	Hydrofluoric acid			✓		✓	✓
U135	Hydrogen sulfide	✓				✓	✓
U136	Hydroxydimethyl arsine oxide			✓			
U137	Indeno(1,2,3-cd)pyrene	✓				✓	✓
U138	Iodomethane	✓			✓	✓	✓
U139	Iron Dextran			✓			
U140	Isobutyl alcohol	✓			✓	✓	✓
U141	Isosafrole	✓				✓	✓
U142	Kepone	✓				✓	✓
U143	Lasiocarpine	✓				✓	✓
U144	Lead acetate		✓				
U145	Lead phosphate		✓				
U146	Lead subacetate	✓				✓	✓
U147	Maleic anhydride	✓				✓	✓
U148	Maleic hydrazide	✓				✓	✓
U149	Malononitrile	✓				✓	✓
U150	Melphalan	✓				✓	✓
U151	Mercury		✓				
U152	Methacrylonitrile	✓			✓	✓	✓
U153	Methanethiol	✓				✓	✓
U154	Methanol	✓			✓	✓	✓
U155	Methapyrilene	✓			✓	✓	✓
U156	Methyl chlorocarbonate	✓				✓	✓
U157	3-Methylcholanthrene	✓				✓	✓
U158	4,4'-Methylene-bis-(2-chloroaniline)	✓			✓	✓	✓
U159	Methyl ethyl ketone	✓				✓	✓
U160	Methyl ethyl ketone peroxide	✓				✓	✓
U161	Methyl isobutyl ketone	✓				✓	✓
U162	Methyl methacrylate	✓				✓	✓
U163	N-Methyl-N'-nitro-N-nitrosoguanidine	✓				✓	✓
U164	Methylthiouracil	✓				✓	✓
U165	Naphthalene	✓				✓	✓
U166	1,4-Naphthoquinone	✓				✓	✓
U167	1-Naphthylamine	✓				✓	✓
U168	2-Naphthylamine	✓				✓	✓
U169	Nitrobenzene	✓			✓	✓	✓
U170	4-Nitrophenol	✓				✓	✓
U171	2-Nitropropane	✓				✓	✓
U172	N-Nitrosodi-n-butylamine	✓			✓	✓	✓
U173	N-Nitrosodiethanolamine	✓			✓	✓	✓

(continued)

3-15

TABLE 3-1 (continued)

EPA hazardous waste number	Hazardous waste	Candidate for incineration			Incinerator type		
		Good	Potential	Poor	Liquid injection	Rotary kiln	Fluidized bed
Discarded commercial chemical products, off-specification species, containers, and spill residues thereof (cont'd)			✓		✓	✓	✓
U174	N-Nitrosodiethylamine		✓		✓		
U175	N-Nitrosodi-n-propylamine		✓				✓
U176	N-Nitroso-n-ethylurea		✓			✓	✓
U177	N-Nitroso-n-methylurea		✓				
U178	N-Nitroso-n-methylurethane		✓			✓	
U179	N-Nitrosopiperidine		✓			✓	✓
U180	N-Nitrosopyrrolidine		✓				
U181	5-Nitro-o-toluidine	✓				✓	✓
U182	Paraldehyde		✓			✓	
U183	Pentachlorobenzene		✓		✓		✓
U184	Pentachloroethane		✓			✓	
U185	Pentachloronitrobenzene	✓				✓	✓
U186	1,3-Pentadiene		✓			✓	✓
U187	Phenacetin	✓				✓	
U188	Phenol		✓			✓	✓
U189	Phosphorous sulfide	✓					
U190	Phthalic anhydride		✓			✓	✓
U191	2-Picoline		✓				✓
U192	Pronamide		✓			✓	✓
U193	1,3-Propane sultone		✓				✓
U194	n-Propylamine		✓		✓	✓	✓
U196	Pyridine	✓				✓	✓
U197	Quinones		✓				✓
U200	Reserpine	✓				✓	✓
U201	Resorcinol		✓		✓	✓	✓
U202	Saccharin	✓				✓	
U203	Safrole			✓			
U204	Selenious acid			✓			
U205	Selenium sulfide		✓			✓	✓
U206	Streptozotocin		✓		✓	✓	✓
U207	1,2,4,5-Tetrachlorobenzene		✓		✓	✓	✓
U208	1,1,1,2-Tetrachloroethane		✓		✓	✓	✓
U209	1,1,2,2-Tetrachloroethane		✓			✓	✓
U210	Tetrachloroethane		✓			✓	✓
U211	Tetrachloromethane		✓				✓
U212	2,3,4,6-Tetrachlorophenol	✓			✓	✓	✓
U213	Tetrahydrofuran				✓		
U214	Thallium acetate				✓		
U215	Thallium carbonate				✓		
U216	Thallium chloride				✓		
U217	Thallium nitrate	✓			✓	✓	✓
U218	Thioacetamide	✓				✓	✓
U219	Thiourea						

(continued)

TABLE 3-1 (continued)

EPA hazardous waste number	Hazardous waste	Candidate for incineration			Incinerator type		
		Good	Potential	Poor	Liquid injection	Rotary kiln	Fluidized bed
Discarded commercial chemical products, off-specification species, containers, and spill residues thereof (cont'd)							
U220	Toluene	✓			✓	✓	✓
U221	Toluenediamine		✓			✓	✓
U222	o-Toluidine hydrochloride		✓		✓	✓	✓
U223	Toluene diisocyanate		✓		✓	✓	
U224	Toxaphene		✓		✓	✓	
U225	Tribromomethane		✓			✓	✓
U226	1,1,1-Trichloroethane		✓			✓	
U227	1,1,2-Trichloroethane		✓			✓	
U228	Trichloroethane		✓			✓	✓
U229	Trichlorofluoromethane		✓			✓	
U230	2,4,5-Trichlorophenol		✓			✓	
U231	2,4,6-Trichlorophenol		✓			✓	
U232	2,4,5-Trichlorophenoxyacetic acid		✓			✓	
U233	2,4,5-Trichlorophenoxypropionic acid alpha, alpha, alpha-Trichlorotoluene		✓			✓	✓
U234	Trinitrobenzene		✓			✓	
U235	Tris(2,3-dibromopropyl) phosphate		✓			✓	✓
U236	Trypan blue		✓			✓	✓
U237	Uracil mustard		✓			✓	✓
U238	Urethane	✓			✓	✓	✓
U239	Xylene	✓			✓	✓	✓
Other hazardous wastes							
SIC code number							
2865	Vacuum still bottoms from the production of maleic anhydride	✓				✓	✓
2865	Distillation residues from fractionating tower for recovery of benzene and chlorobenzenes		✓			✓	
2865	Vacuum distillation residues from purification of 1-chloro-4-nitrobenzene		✓			✓	✓
2865	Still bottoms or heavy ends from methanol recovery in methyl methacrylate production	✓				✓	✓
2869	Heavy ends and distillation from production of carbaryl	✓				✓	✓
2869	Residues from the production of hexachlorophenol, trichlorophenol and 2,4,5-T		✓			✓	✓
2869	Heavy ends from distillation of ethylene dichloride in vinyl chloride production		✓			✓	✓
2869	Solid waste discharge from ion exchange column in production of acrylonitrile		✓			✓	✓
2869	Bottom stream from quench column in acrylonitrile production of acrylonitrile		✓		✓	✓	✓
2869	Still bottoms from aniline production	✓				✓	✓
2869	Tars from manufacture of bicycloheptadiene and cyclopentadiene	✓				✓	✓
2869	Still bottom from production of furfural	✓				✓	✓
2869	Unrecovered triester from production of disulfoton	✓				✓	✓
2295	Waste polyvinyl chloride (PVC) from the manufacture of coated fabrics	✓				✓	✓
2869	Still bottoms from the production of pentachloronitrobenzene	✓				✓	

(continued)

TABLE 3-1 (continued)

EPA hazardous waste number	Hazardous waste	Candidate for incineration			Incinerator type		
		Good	Potential	Poor	Liquid injection	Rotary kiln	Fluidized bed
Other hazardous wastes (cont'd)							
SIC code number							
2869	Process clean out sludges from production of 1,1,1-trichloroethane		✓			✓	✓
2869	Heavy ends and light ends from the production of methyl acrylate	✓				✓	✓
2822	Polyvinyl chloride sludge from the manufacture of polyvinyl chloride		✓			✓	✓
2869	Still bottoms from the purification of fluoromethanes in the production of fluoromethanes		✓			✓	✓
2869	Heavy ends and light ends from the production of ethyl acrylate	✓				✓	✓
2869	Heavy ends from the production of glycerine from allyl chloride	✓					
2869	Heavy ends from the distillation of acetic anhydride in the production of acetic anhydride	✓				✓	✓
2869	Light ends from the distillation of acetaldehyde in the production of acetic anhydride	✓			✓	✓	✓
	· Reactor cleanup wastes from the chlorination, dehydrochlorination or oxychlorination of aliphatic hydrocarbons		✓		✓	✓	✓
	· Fractionation bottoms from the separation of chlorinated aliphatic hydrocarbons	✓			✓	✓	✓
	· Distillation bottoms from the separation of chlorinated aliphatic hydrocarbons	✓			✓	✓	✓
	· Reactor cleanup wastes from the chlorination or oxychlorination of cyclic aliphatic hydrocarbons	✓			✓	✓	✓
	· Fractionation bottoms from the separation of chlorinated cyclic aliphatic hydrocarbons	✓			✓	✓	✓
	· Distillation bottoms from the separation of chlorinated cyclic aliphatic hydrocarbons	✓			✓	✓	✓
	· Batch residues from the batch production of chlorinated polymers	✓			✓	✓	✓
	· Solution residues from the production of chlorinated polymers	✓			✓	✓	✓
	· Reactor cleanup wastes from the chlorination of aromatic hydrocarbon	✓			✓	✓	
	· Fractionation bottoms from the separation of chlorinated aromatic hydrocarbons	✓			✓	✓	
	· Distillation bottoms from the separation of chlorinated aromatic hydrocarbons	✓			✓	✓	
3333	Zinc production: oxide furnace residue and acid plant sludge		✓				
3339	Ferromanganese emissions control, baghouse dusts and scrubwater solids		✓				
3339	Ferrochrome silicon furnace emission control dust or sludge		✓				
3339	Ferrochrome emissions control, furnace baghouse dust, and ESP		✓				
3339	Primary antimony-pyrometallurgical blast furnace slag		✓				
3341	Secondary lead, scrubber sludge from SO₂ emission control, soft lead production		✓				

TABLE 3-1 (continued)

EPA hazardous waste number	Hazardous waste	Candidate for incineration			Incinerator type		
		Good	Potential	Poor	Liquid injection	Rotary kiln	Fluidized bed
Other hazardous wastes (cont'd)							
SIC code number							
3341	Secondary lead-white metal production furnace dust				√		
3341	Secondary copper-pyrometallurgical, blast furnace slag				√		
3341	Secondary copper-electrolytic refining wastewater treatment sludge				√		
3341	Secondary aluminum dross smelting-high salt slag plant residue				√		
3341	Zinc-cadmium metal reclamation, cadmium plant residue				√		
3691	Lead acid storage battery production wastewater treatment sludges				√		
3691	Lead acid storage battery production cleanup wastes from cathode and anode paste production				√		
3691	Nickel cadmium battery production wastewater treatment sludges				√		
3691	Cadmium silver oxide battery production wastewater treatment sludges				√		
3691	Mercury cadmium battery production wastewater treatment sludges				√		
3692	Magnesium carbon battery production chromic acid wastewater treatment sludges				√		
2816	Ash from incinerated still bottoms (paint and pigment production)				√		
2819	Arsenic bearing wastewater treatment sludges from production of boric acid				√		
2834	Arsenic or organo-arsenic containing wastewater treatment sludges from production of veterinary pharmaceuticals				√		
2851	Wastewater treatment sludges from paint production				√		
2851	Air pollution control sludges from paint production				√		
2869	By-product salts in production of MSMA				√		
2869	By-product salts in production of cacodylic acid				√		
2869	Lead slag from lead alkyl production				√		
3312	Steel Finishing: Alkaline cleaning waste • Waste pickle liquor • Cyanide-bearing wastes from electrolytic coating • Chromate and dichromate wastes from chemical treatment • Descaling acid				√		
3322	Lead/phenolic sand-casting waste from malleable iron foundries				√		
3331	Primary copper smelting and refining electric furnace slag, converter dust, acid plant sludge, and reverberatory dust (T)				√		
3332	Primary lead blast furnace dust				√		
3339	Primary antimony-electrolytic sludge				√		
3339	Primary tungsten-digestion residue				√		
1094	Waste rock and overburden from uranium mining				√		
1099	Chlorinator residues and clarifier sludge from zirconium extraction				√		
1475	Overburden and slimes from phosphate surface mining				√		
2874	Waste gypsum from phosphoric acid production				√		
2819-2874	Slag and fluid bed prills from elemental phosphorus production				√		
2812	Sodium calcium sludge from production of chlorine by Down Cell process						
2812	Mercury bearing brine purification muds from mercury cell process in chlorine production				√		

(continued)

3-19

TABLE 3-1 (continued)

EPA hazardous waste number	Hazardous waste	Candidate for incineration			Incinerator type		
		Good	Potential	Poor	Liquid injection	Rotary kiln	Fluidized bed
Other hazardous wastes (cont'd)							
SIC code number							
2816	Mercury bearing wastewater treatment sludges from the production of mercuric sulfide pigment			√			
2816	Chromium bearing wastewater treatment sludges from the production of TiO₂ pigment by the chloride process			√			
2816	Arsenic bearing sludges from purification process in the production of antimony oxide			√			
2816	Antimony bearing wastewater treatment sludge from production of antimony oxide			√			
3312	Iron making: Ferromaganese blast furnace dust • Ferromanganese blast burnace sludge • Electric furnace dust and sludge			√			

ᵃUse this table for indicative guidance only. For decision making, read the material presented in the text.

- Moisture content
- Potential pollutants present in incinerator effluents
- Inert content
- Heating value and auxiliary fuel requirements
- Potential health and environmental effects
- Physical form
- Corrosiveness
- Quality
- Known carcinogenic content
- PCB content.

Table 3-1 should be used with caution. The information is indicative rather than conclusive. Conclusive decisions can be made only after studying the actual physical, chemical, and thermodynamic characteristics of the material(s) along with trial burn data (if available), and comparing expected behavior with the known behavior of a similar material (similar composition or physical, chemical, and thermodynamic characteristics) undergoing thermal destruction.

The incineration technology ratings in Table 3-1 are influenced by the physical form of the waste. In general, liquid wastes can be incinerated by a liquid injection incinerator, rotary kiln, or fluidized bed incinerator. Waste in gas, liquid, solid, and mixture forms can be incinerated by either a rotary or fluidized bed incinerator. The kinematic viscosity of the liquid waste has to be considered in determining its suitability for incineration by liquid injection incinerators.

Liquid injection, and rotary kiln incinerators are widely used to dispose of hazardous wastes. There is substantial research going on fluidized bed incinerators and they appear to be promising in disposing of hazardous wastes. Multiple hearths and multiple chambers incinerators have moderate applicability for incineration of hazardous wastes. They are widely used for the destruction of solids (municipal refuse) and sludges (sewage sludges). If the ash resulting from incineration of a waste is fusible, multiple hearths incinerators are not well suited for its disposal. Multiple hearth incinerators are not capable of operating at elevated temperatures - so that if a temperature over 2000°F is needed for destruction, multiple hearths incinerators are not applicable. Multiple hearths and multiple chambers incinerators have limited applicability to hazardous wastes, so they are not included in Table 3-1.

It may be possible to blend different wastes or wastes and fuel oils to change poor or potential candidates into good candidates for incineration. Such blending may also change the characteristics of a waste, making it incinerable in a different incineration type than is identified in Table 3-1. It is also possible that some wastes identified in Table 3-1 as good or potential candidates may turn out to be poor candidates for incineration if mixed with or contaminated by poor incineration candidates like metals (arsenic, chromium, etc.). Therefore, such factors as blending and waste contamination should be considered on a case-by-case basis in making decisions. As mentioned earlier, Table 3-1 should be used with caution for indicative guidance rather than conclusive decisions.

3.3 WASTE SAMPLING [9]

It is important that a representative sample of the waste be collected and properly handled in determining waste characteristics. Sampling situations vary widely and therefore no universal sampling procedure can be recommended. However, it is important to incorporate quality assurance procedures as necessary components in any waste sampling plan.

Sampling procedures require a plan of action to maximize safety of sampling personnel, minimize sampling time and cost, reduce errors in sampling, and protect the integrity of the samples after sampling. The following steps are essential in this plan of action:

1. Prior to collecting a sample, check the manifest to see whether dangerous emissions can be expected and to make sure that what is sampled resembles what is described in the manifest.

2. Ask the generator for background information on the waste.

3. Determine what should be sampled (truck, barrel, pond, etc.).

4. Select the proper sampler (Coliwasa, scoop, bucket, etc.).

5. Select the proper sample container and closure (glass, plastic, etc.).

6. Design an adequate sampling plan that includes the following:

   (a) Choice of the proper sampling point. (b) Determination of the number of samples to be taken. (c) Determination of the volumes of samples to be taken.

7. Observe proper sampling precautions (safety of personnel, protective gear).

8. Handle samples properly (sample preservation).

9. Identify samples and protect them from tampering.

10. Record all sample information in a field notebook.

11. Fill out chain of custody record.

12. Fill out sample analysis request sheet.

13. Deliver or ship the samples to the laboratory for analysis.

Various samplers and their applicabilities; sample containers and their compatibility with wastes; sampling points, number of samples and sample volume requirements; personnel protective gear and other safety precautions; sample preservation requirements; sampling procedures for various situations; and sample handling (labeling, field logging, chain of custody, analysis request form and sample shipping) are discussed in detail in "Samplers and Sampling

Procedures for Hazardous Waste Streams" (EPA-600/2-80-018, January 1980).
This source can be consulted prior to sampling.

Chain of custody procedures recommended by EPA's National Field Investigation
Center are described below:

1. The laboratory director designates one full-time employee (usually the
   laboratory supervisor) as a sample custodian and one other person as an
   alternate. In addition, the laboratory sets aside a "sample storage
   security area." This is a clean, dry, isolated room which can be
   securely locked.

2. All samples are handled by the minimum number of persons.

3. All incoming samples are received only by the custodian or, in his absence,
   the alternate, who indicates receipt by signing the sample transmittal
   sheets and, as appropriate, sample tags, accompanying the samples and re-
   taining the sheets as permanent records.

4. Immediately upon receipt, the custodian places the sample in the sample
   room, which is locked at all times except when the samples are removed or
   replaced by the custodian. To the maximum extent possible, only the
   custodian is permitted in the sample room.

5. The custodian ensures that heat-sensitive or light-sensitive samples, or
   other sample materials having unusual physical characteristics, or
   requiring special handling, are properly stored and maintained.

6. Only the custodian, or in his absence, the alternate, distributes samples
   to, or divides them among, personnel performing tests. The custodian
   enters into a permanent log book the laboratory sample number, time and
   date, and the name of the person receiving the sample. The receiver also
   signs the entry.

7. Laboratory personnel are then responsible for the care and custody of the
   sample until analytical tests are completed. Upon completion of tests un-
   used portion of the sample together with all identifying tags and labora-
   tory records are returned to the custodian, who records the appropriate
   entries in the log book. These, and other records are retained as
   appropriate.

8. The analyst records in his laboratory notebook or worksheet the name of
   the person from whom the sample was received, whether it was sealed, iden-
   tifying information describing the sample (by origin and sample identifi-
   cation number), the procedures performed, and the results of the testing.
   If deviations from approved analytical procedures occur, the analyst is
   prepared to justify this decision under cross-examination. The notes are
   signed and dated by the person performing the tests. If that person is not
   available as a witness at time of trial the government may be able to
   introduce the notes in evidence under the Federal Business Records Act.

Samples, tags, and laboratory records of tests may be destroyed only upon the written order of the laboratory director, who ensures that this information is no longer required.

The Field Sampling Chain of Custody Form should be completed by the field sampling team and included with the shipping container when sent to the contractor's laboratory. A separate form should be included with each box of samples, listing the samples contained in that box. A sample of a completed form is included for reference (Figure 3-1).

A copy of chain of custody procedures can be obtained by contacting:

> National Field Investigation Center
> U.S. Environmental Protection Agency
> Denver Federal Center
> Building #53, Box 25227
> Denver, Colorado 80225
> Telephone: (303) 234-4650

Other reference materials that can be consulted before developing a sampling plan are listed below.

1. Sampling petroleum and petroleum products; Method ASTM D270.

2. Sampling industrial chemicals; Method ASTM E300.

3. Benedetti-Pichler, A. A. Theory and principles of sampling for chemical analysis. In: Walfer, E. J.; and Bell, G., eds. Physical methods in chemical analysis, Vol. 3. New York, Academic Press, Inc., 1956.

4. Preparing coal samples for analysis; Method ASTM D2013.

5. Sampling coke for analysis; Method ASTM D345.

6. Guidelines establishing test procedures for the analysis of pollutants, proposed regulations. Federal Register. 44(233):69464-69575, 1979 December 3.

7. Procedures for level 2 sampling and analysis of organic materials. Research Triangle Park, NC; U.S. Environmental Protection Agency; 1979 February. 164 p. EPA-600/7-79-033.

8. Test Methods for Evaluating Solid Waste - Physical/Chemical Methods; SW-646-1980.

9. Hazardous Waste and Consolidated Permit Regulations, Federal Register. 45(98):33063-33285. 1980 May 19.

3.4 BASIC ANALYSIS OF WASTE [10, 12]

This section discusses the basic physical and chemical information about a waste that may be required in determining its feasibility for incineration and

LEADER	NAME OF SURVEY OR ACTIVITY	DATE OF COLLECTION	SHEET
Melvin	Priority Pollutant Survey 523.10	9/12/84	1 of 1

DESCRIPTION OF SHIPMENT

TYPE OF SAMPLE   Water Samples

TOTAL NUMBER SAMPLE CONTAINERS   10

CONTENTS OF SHIPMENT

FIELD SAMPLE NO.	NO. OF CONTAINERS/FIELD NO.			ANALYSES REQUIRED - CHECK WHERE APPROPRIATE						
	PLASTIC	GLASS	VOA	CYANIDE	PHENOLS	ASBESTOS	PESTICIDES	METALS	VOA	SEMI-
0876	1			✓						
0895		2					✓			
1992	1							✓		
3862	1	·				✓				
3812			3						✓	
6413		1			✓					
6863		1								

PERSONNEL CUSTODY RECORD					
RELINQUISHED BY (SAMPLER)	RECEIVED BY	DATE	TIME	REASON	
H. Melvin	Harpy Airlines	10/1/84	1600	Delivery to lab	
SEALED UNSEALED	X SEALED UNSEALED				
RELINQUISHED BY	RECEIVED BY	DATE	TIME	REASON	
Airline	Vendor	10/3/84	900		

Figure 3-1. Field sampling chain of custody form.

its compatibility for a given incineration facility and in designing an incineration facility. Basic hazardous waste data helpful in selecting an incineration system are as follows:

- Type(s) of waste: Physical form - liquid, gas, solid, or mixture

- Ultimate analysis: C, H, O, N, S, P, Cl, F, Br, I, ash, moisture

- Heating value: Btu/lb

- Solids: Size, form, and quantity

- Liquids: Viscosity as a function of temperature, specific gravity

- Sludges: Density, viscosity, and percent solids

- Slurries: Density, viscosity, and percent solids

- Gases: Density

- Special characteristics: Toxicity, corrosiveness, and other unusual features

- Disposal rate: Peak, average, and minimum (present and future)

- Trace metals: As, Ba, Cd, Cr, Pb, Hg, Se, Ag

- Major organic compound groups: e.g., aromatics, aliphatics, etc.

It may not be necessary to follow the complete, elaborate analysis protocol for each shipment of waste from the same source, unless the material is entirely different from earlier shipments. How often the shipments should be sampled, and for what parameters samples should be analyzed, should be determined on a case-by-case basis using best engineering judgment by the user of this handbook.

In matching different wastes with commercial incineration facilities, the physical form (solid, liquid, etc.) of the wastes is very important. The criteria used for matching different wastes to the various incineration facilities are:

    (1) Physical form:

        Gas, liquid, slurry, sludge, or solid

    (2) Temperature range required for destruction:

        (a) >2,000°F (>1,087°C)
        (b) 1,400-2,000°F (757-1,087°C)
        (c) 700-1,400°F (367-757°C)
        (d) <700°F (<367°C)

(3) Off-gases:

    (a) Essentially oxides of carbon and nitrogen, and
        water vapor

    (b) Halogen, sulfur, phosphorus or volatile metal
        species

(4) Ash:

    Nonfusible, fusible, or metallic

(5) Heating value:

    (a) 10,000 Btu/lb (>23 MJ/kg)
    (b) 5,000-10,000 Btu/lb (12-23 MJ/kg)
    (c) 5,000 Btu/lb (<12 MJ/kg)

Liquid injection, fluidized bed, and rotary kiln incinerators are widely used to dispose of hazardous waste. A particular incinerator may be better suited for incineration of a particular type of waste based on the physical characteristics of the waste. Solids, sludges, and slurries of high viscosity liquids can be disposed in rotary kiln or fluidized bed incinerators, but not in a liquid injection incinerator. If the ash resulting from the incineration of a waste is fusible, fluidized bed incinerators are not well suited for its disposal. Furthermore, fluidized bed incinerators are not capable of operating at elevated temperatures, so if a temperature over 2,000°F (1,087°C) is needed for destruction, rotary kilns or liquid injection incinerators are applicable. Fluidized bed incinerators are generally not operated at temperatures above 1,500°F.

The percentages of carbon, hydrogen, oxygen, nitrogen, sulfur, halogens, and phosphorus in the waste, as well as its moisture content, need to be known to calculate stoichiometric combustion air requirements and to predict combustion gas flow and composition. The presence of halogenated and sulfur-bearing waste can result in the formation of HCl, HF, H_2S, and SO_2 in the incinerator gases. These must be removed with suitable scrubbing equipment before discharge to the atmosphere. Also, in the incineration of organic wastes containing chlorine, sufficient hydrogen should be provided by either the waste or auxiliary fuel for the chlorine to form HCl and not Cl_2. Nitrogen oxides are produced during high temperature combustion by reaction between nitrogen and oxygen in the air. Their formation can be reduced by reducing combustion temperature or excess air, but such controls may cause the formation of other pollutants. Nitrogen content of waste material is generally low, but the presence of nitrogen-containing materials (nitrates, ammonium compounds, etc.) can greatly increase the NO_x emissions.

Trace metals (arsenic, barium, cadmium, chromium, mercury, lead, selenium, and silver) are a potential cause for concern in incinerator emissions. Analyses for them should be performed unless it is known that they are or are not present in the waste. Wastes containing significant amounts of metals will generally be poor candidates for incineration. Such wastes will require postcombustion emission control of a special type, and the effluent or solid waste from the emission control device must in turn be treated as a hazardous

waste, although considerably reduced in volume and weight from the original hazardous waste.

Ash content of the waste should be determined to evaluate the potential for excessive slag formation as well as potential particulate emissions from the incinerators. Kinematic viscosity and the size and concentration of solids in a liquid waste are the most important physical properties to consider in evaluating a liquid waste incinerator design. The physical handling system and burner atomization techniques are dependent on viscosity and solid content of the waste. Chemically complex sludges may contain such elements as Na, K, Mg, P, S, Fe, Al, Ca, Si, O_2, N_2, C and H_2. Several chemical reactions can be expected to take place in the high temperature oxidizing atmosphere of an incineration operation of chemically complex sludges. Resulting ash may contain Na_2SO_4, Na_2CO_3, NaCl, etc. Pure Na_2SO_4 has a melting point of 1,623°F. Pure Na_2CO_3 has a melting point of 1,564°F. However, mixtures of these two compounds have melting points lower than either one of the two by themselves. At 47% Na_2SO_4 - 53% Na_2CO_3, the melting point is 1,552°F. Sodium chloride has a melting point of 1,472°F. In combination with Na_2CO_3, sodium chloride will lower the melting point of the mixture. At 62 mole % Na_2CO_3, the eutectic melting point is 1,172°F. Likewise, mixtures of NaCl and Na_2SO_4 form low melting mixture with the eutectic melting point of 1,154°F for a 65 mole % Na_2SO_4 mixture. When all three of these compounds are present, a mixture melting point as low as 1,134°F is possible. So sludges containing substantial amounts of sodium can cause defluidization of fluidized bed by forming low melting eutectic mixtures. Furthermore, if the particles of the fluidized bed are silica-sand, Na_2SO_4 will react with the silica to form a viscous sodium-silicate glass, which will cause rapid defluidization.

The heating value of a waste corresponds to the quantity of heat released when the waste is burned, commonly expressed as Btu/lb. It should be considered in establishing an energy balance for the combustion chamber and in assessing the need for auxiliary fuel firing. As a rule of thumb, a minimum heating value of about 8,000 Btu/lb is required to sustain combustion.

Special characteristics of the waste such as extreme toxicity, mutagenicity or carcinogenicity, corrosiveness, fuming, odor, pyrophoric properties, thermal instability, shock sensitivity, and chemical instability should also be considered in incinerator facility design. Thermal or shock instability are of particular concern from a combustion standpoint, since wastes with these properties pose an explosion hazard. Other special properties relate more directly to the selection of waste handling procedures and air pollution control requirements.

Chapter 4 discusses detailed procedures for evaluating the design and compatibility of incinerators with the basic physical, chemical, and thermodynamic properties of the waste.

3.5 SUPPLEMENTAL ANALYSIS OF WASTE

In addition to its basic analysis, supplemental analysis of waste to identify and quantify its major chemical components will be helpful in evaluating waste for incineration. This information will help to determine whether or not the

waste is similar to others that have been successfully incinerated previously, in a similar facility or in the existing facility. The necessary supplemental information may be available from sources described in Section 3.2. For example, the waste generator may have previously analyzed the waste stream or may have a sufficiently thorough understanding of the process generating the waste to adequately characterize it.

The supplemental analyses that may be necessary to determine whether a waste can be effectively incinerated and/or whether a trial burn is required are the following:

- Level 1 organic analysis
- Specific organic analysis
- Trace metal scan
- Thermal decomposition unit analysis

3.6 ANALYSIS TEST METHODS

All the physical, chemical, and thermodynamic analyses of the waste should be conducted following ASTM, EPA, or EPA-sponsored equivalent methods. The May 19, 1980 Federal Register (pages 33130 and 33131) identifies approved measurement techniques for each organic chemical and inorganic species (heavy metals) listed in Section 3001 of RCRA (May 19, 1980 Federal Register). Additional reference materials that can be consulted for analytical guidance are listed below:

1. ASTM books.

2. Test methods for evaluating solid waste. Washington, DC; U.S. Environmental Protection Agency; 1980 May. EPA SW-846.

3. Lentzen, D. E.; Wagoner, D. E.; Estes, E. D.; and Gutknecht, W. F. IERL-RTP procedures manual: level 1 environmental assessment, second edition. Research Triangle Park, NC; U.S. Environmental Protection Agency; 1978 October. 279 p. EPA 600/7-78-201.

4. Guidelines establishing test procedures for the analysis of pollutants, proposed regulations. Federal Register. 44(233):69464-69575, 1979 December 3.

5. Procedures for level 2 sampling and analysis of organic materials. Research Triangle Park, NC; U.S. Environmental Protection Agency; 1979 February. 164 p. EPA-600/7-79-033.

6. Standard methods for the examination of water and wastewater, 14th ed. Washington, American Public Health Association, 1976. 1193 p.

7. Methods for chemical analysis of water and wastes. Cincinnati, OH; U.S. Environmental Protection Agency; 1979 March. 463 p. EPA-600/4-79-020.

8. Hauser, R.; and Cummins, R. L. Increasing sensitivity of 3-methyl-2-benzothiazolone hydrazone test for analyses of aliphatic aldehydes in air. Analytical Chemistry. 56:679, 1964.

9. Kraak, J. C.; and Huber, J. F. K. Separation of acidic compounds by high-pressure liquid-liquid chromatography involving ion-pair formation. Journal of Chromatography. 102:331-351, 1974.

10. Smythe, L. E. Analytical chemistry of pollutants. In: Bockris, J. O'M., ed. Environmental chemistry. New York, Plenum, 1977.

Thermal decomposition unit analysis is briefly discussed in Section 3.7.

3.7 THERMAL DECOMPOSITION UNIT ANALYSIS [11]

In the interest of safety, it may be necessary that knowledge of the thermal decomposition properites of a toxic organic substance be obtained before large-scale incineration is conducted.

In response to this need, a laboratory system has been designed and assembled by the University of Dayton Research Institute (UDRI) under EPA sponsorship. This thermal decomposition analytical system (TDAS) is a closed, continuous system which consists of a versatile thermal decomposition unit followed by in-line dedicated gas chromatograph-mass spectrometer-data handling computer (GC-MS-COMP). The objective of this laboratory system is to provide fundamental thermal decomposition data on a wide variety of organic materials - gases, liquids, and solids (including polymers).

Thermal decomposition tests were conducted with the TDAS on polychlorinated biphenyls (PCB's) and on "Hex" wastes. The PCB's were found to have high thermal stability in air. Furthermore, in oxygen-deficient atmospheres their thermal stability is increased by at least 390°F (200°C) over that experienced in air. "Hex" wastes also demonstrated a high degree of thermal stability. Several chlorinated, aromatic compounds were still present after exposure to 1,470°F (800°C). Further increases in temperature to 1,830°F (1,000°C) decomposed all compounds except for low levels of hexachlorobenzene.

Figures 3-2, 3-3, 3-4, and 3-5 illustrate decomposition of hexachlorobiphenyl in air, decomposition of pentachlorobiphenyl in different gaseous atmospheres, the effect of oxygen content on decomposition of pentachlorobiphenyl, and the decomposition profile of Hex wastes, respectively.

The UDRI thermal decomposition analytical system, decomposition experiments, resulting test data and their interpretation are discussed in detail in Appendix E. Also, the following articles can be consulted for more information on TDAS:

1. Rubey, W. A. Design consideration associated with the development of a thermal decomposition analytical system (TDAS). Dayton, OH; University of Dayton Research Institute; 1979 May. Technical Report UDR-TR-79-34 (EPA Grant No. R805 117-01-0).
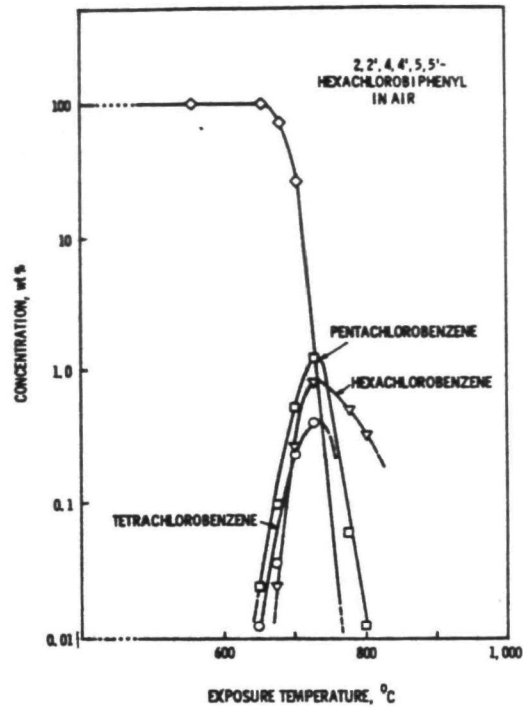
Figure 3-2.   Decomposition of hexachlorobipenyl [11].
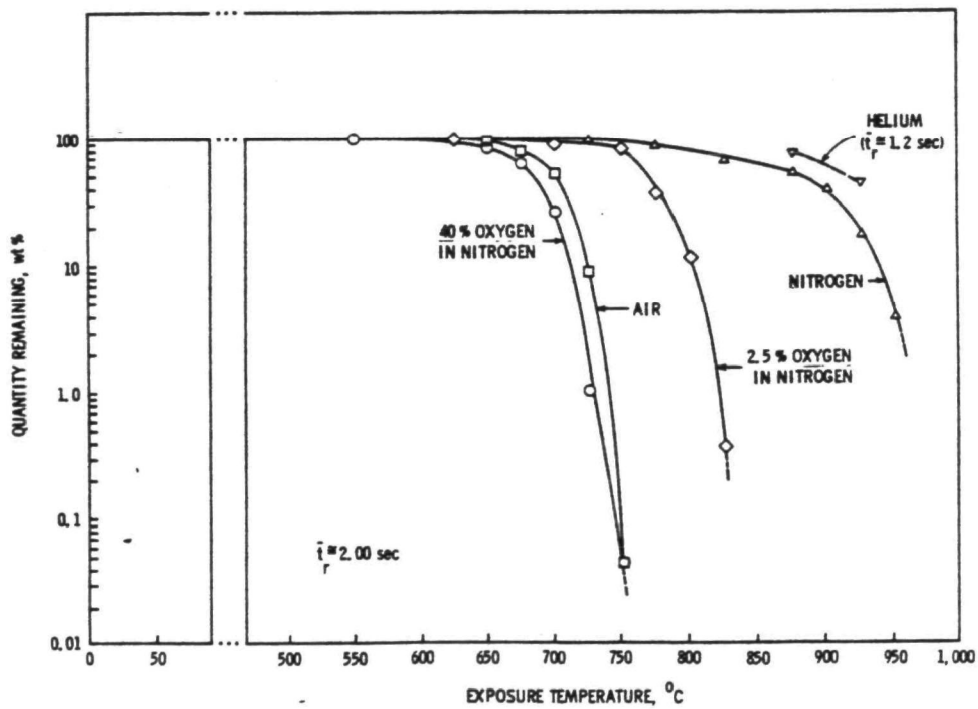
Figure 3-3.   Decomposition of pentachlorobipenyl in
different gaseous atmospheres [11].
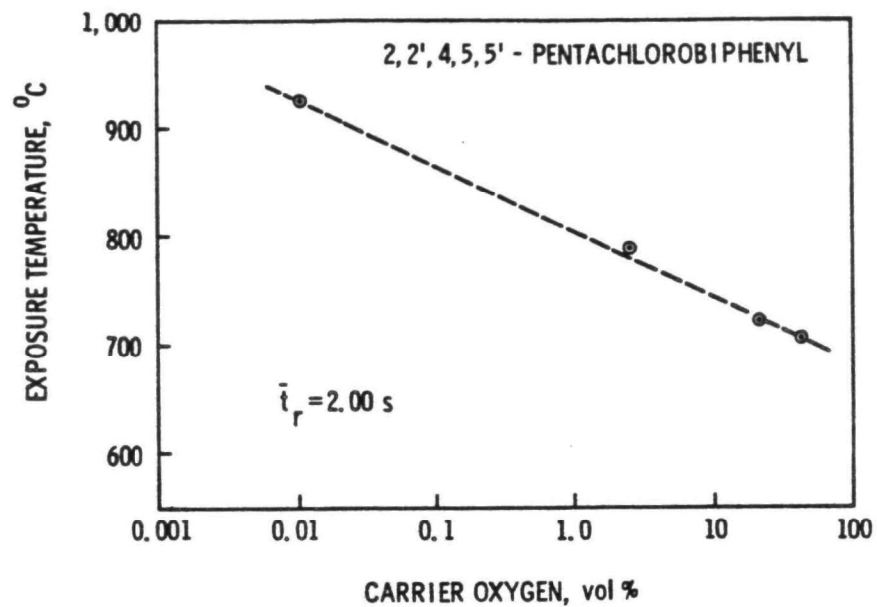
Figure 3-4. Effect of oxygen content on decomposition of pentachlorobiphenyl [11].
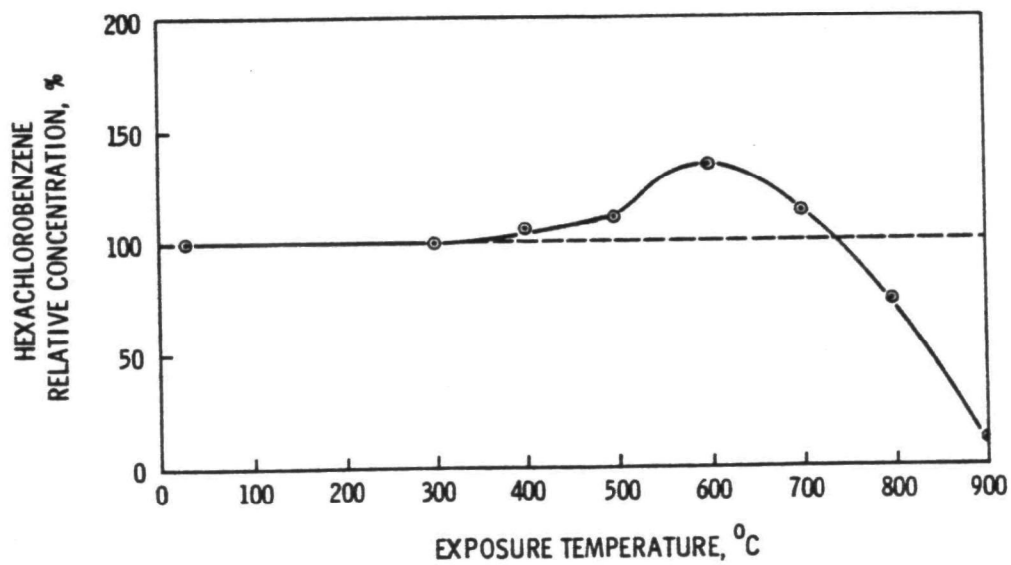
Figure 3-5. Decomposition profile of hexachlorobenzene [11].

3-32

2. Duvall, D. S.; Rubey, W. A.; and Mescher, J. A. High temperature decomposition of organic hazardous waste. Treatment of hazardous waste, proceedings of the sixth annual research symposium. Cincinnati, OH; U.S. Environmental Protection Agency; 1980 March. p. 121-131. EPA-600/9-80-011.

The temperature, residence time, and oxygen required to destroy a given waste by incineration can be determined by thermal decomposition unit analysis or by a pilot- or full-scale trial burn. It is not necessary to generate temperature, residence time, and oxygen requirement data for wastes for which such data already exist. Trial burn data for some wastes are presented in Appendices F and G.

3.8 WORK SHEET

The work sheet presented in this section is designed to help evaluate a waste for incineration in light of the information presented in this chapter for waste characterization.

WORK SHEET

	Yes	No*
1. Background Information		
• Is background information available and known?	—	—
• Is the SIC code of the waste generating source known?	—	—
• Does the waste fall into an EPA hazardous waste classification?	—	—
• If the waste falls into an EPA hazardous waste classification, is the EPA hazardous waste number known?	—	—
• Any special characteristics of the waste known?	—	—
• Are principal waste components and their percentages known?	—	—
• Is the detail of the process generating the waste known?	—	—
• Is the waste hazard class according to DOT regulations known?	—	—
2. Waste Sampling		
• Is the waste sampled with a compatible sampling device?	—	—
• Is the waste collected in a compatible sample container?	—	—

- Was sampling plan adequate to collect repre-
    sentative samples (determination of sampling
    points, number of samples, and samples'
    volumes)?   ___   ___

- Were the samples properly handled (preserva-
    tion, labeling, and shipping)?   ___   ___

- Was pertinent information adequately recorded
    in the field log book?   ___   ___

- Were the chain of custody procedures recom-
    mended by EPA's National Field Investigation
    Centers followed?   ___   ___

3. Basic Analysis Information

- Are data for specific basic analysis known?   ___   ___
    - Physical state of waste at 25°C   ___   ___
    - Single phase   ___   ___
    - Multiphase   ___   ___
    - Vapor pressure   ___   ___
    - Viscosity   ___   ___
    - Specific gravity   ___   ___
    - Melting point   ___   ___
    - Boiling point   ___   ___
    - Flash point   ___   ___
    - Solids (size, form, and quantity)   ___   ___
    - pH   ___   ___
    - Trace metals (As, Ba, Cd, Cr, Hg, Pb, Se, Ag)   ___   ___
    - Net heating value   ___   ___
    - Elemental analysis (C, H, O, N, S, P, Cl, F, Br, I) ___   ___
    - Ash content   ___   ___
    - Moisture content   ___   ___
    - PCB's   ___   ___
    - Presence of
        Carcinogen   ___   ___
        Pesticide   ___   ___
        Odor   ___   ___
    - Toxicity   ___   ___
        Ingestion   ___   ___
        Inhalation   ___   ___
        Dermal   ___   ___
        Eyes   ___   ___
    - Reactivity   ___   ___
    - Fire hazard   ___   ___
    - Radioactivity   ___   ___

4. Supplemental Analysis Information

  · Are the major chemical components of the waste and their
     percentages known?   __   __

  · If waste is known or suspected to contain potentially
     hazardous metals other than those listed in basic analysis
     information, are their percentages known?   __   __

  · Has the waste been tested for thermal decomposition analysis? __   __

  · Are the temperature and residence time necessary for destruc-
     tion as determined by TDAS known?   __   __

  · Are any principal hazardous particle decomposition products
     identified by TDAS?   __   __

  · Has the waste been incinerated before and, if so, in what
     type of incineration technology?   __   __

5. Other Information

  · Are past disposal practices for the waste known?   __   __

  · Are any other wastes similar to the one under consideration
     known for good or potential incineration?   __   __

  · Has the proposed facility and/or technology been used before
     to destroy a similar or like waste?   __   __

  · Are waste generation rates (i.e., peak, average, and minimum)
     known (present and future)?   __   __

  · Are there any trial burn data available for the waste?   __   __

  · Are any potential health and environmental effects of the
     waste known?   __   __

6. Waste Incineration Decision

  · Can a decision be made about waste incineration with the
     available information about the waste and information
     available from this chapter and Chapter 4?   __   __

  · If answer is no to the above question, will any additional
     waste characterization information help to make a decision
     about waste incineration?   __   __

  · If answer is no to the above question, will a trial burn
     be necessary?   __   __

*Any response in the "No" column may indicate the possibility that the informa-
tion provided is not sufficient for a decision, and additional information
may be required.

3.9 REFERENCES

1. Hazardous waste and consolidated permit regulations. Federal Register. 45(98):33121-33133, 1980 May 19.

2. Assessment of industrial hazardous waste practices: leather tanning and finishing industry. Washington, DC; U.S. Environmental Protection Agency; 1976 November. 233 p. EPA SW-131C.

3. Assessment of hazardous waste practices in the petroleum refining industry. Washington, DC; U.S. Environmental Protection Agency; 1976 June. 353 p. EPA SW-129C.

4. Assessment of industrial hazardous waste practices: paint and allied products industry, contract solvent reclaiming operations, and factory application of coatings. U.S. Environmental Protection Agency; 1976. EPA SW-119C.

5. Alternatives for hazardous waste management in the organic chemical, pesticides and explosives industries. Cincinnati, OH; U.S. Environmental Protection Agency; 1977. EPA SW-151C.

6. Assessment of industrial hazardous waste practices: electronic components manufacturing industry. Washington, DC; U.S. Environmental Protection Agency; 1977 January. 207 p. EPA SW-140C.

7. Assessment of industrial hazardous waste practices: special machinery manufacturing industries. Washington, DC; U.S. Environmental Protection Agency; 1977 March. 328 p. EPA SW-141C.

8. Background document, Resource Conservation and Recovery Act; Subtitle C - Identification and listing of hazardous waste; Section 261.31 and 261.32 - Listing of hazardous wastes. Washington, DC; U.S. Environmental Protection Agency; 1980 May 2.

9. Sampling and sampling procedures for hazardous waste streams. Cincinnati, OH; U.S. Environmental Protection Agency; 1980 January. 78 p. EPA-600/2-80-018.

10. Hazardous material incineration design criteria. Cincinnati, OH; U.S. Environmental Protection Agency; 1979 October. 110 p. EPA-600/2-79-198.

11. Duvall, D. S.; Rubey, W. A.; and Mescher, J. A. High temperature decomposition of organic hazardous waste. Treatment of hazardous waste, proceedings of the sixth annual research symposium. Cincinnati, OH; U.S. Environmental Protection Agency; 1980 March. p. 121-131. EPA-600/9-80-011.

12. Becker, K. P.; and C. J. Wall. Waste treatment advances: Fluid bed incineration of wastes. Chemical Engineering Progress. 72:61-68, 1976 October.

CHAPTER 4

INCINERATOR AND AIR POLLUTION CONTROL SYSTEM DESIGN EVALUATION

CONTENTS

CHAPTER 4

INCINERATOR AND AIR POLLUTION CONTROL
SYSTEM DESIGN EVALUATION

4.1 INTRODUCTION

This chapter presents engineering calculations and general "rules of thumb" that can be used to determine whether or not incinerator and air pollution control system design and operating criteria are consistent with good industry practice and sufficient to meet current emission standards. The evaluation procedures are intended to determine if (1) the physical, chemical, and thermodynamic properties of the waste have been properly considered in the incinerator and air pollution control device design; (2) the basic design considerations for these units have been addressed; (3) acceptable temperatures, residence times, oxygen concentrations, and mixing can be achieved and maintained in the incinerator; (4) air pollution control system design and operating criteria are in line with current industry practice and the desired degree of pollutant removal; (5) various components of the incinerator, air pollution control, and gas handling systems have sufficient capacity to handle the quantities of waste to be burned; (6) the design incorporates process control and automatic shutdown capability to minimize the release of hazardous material in the event of equipment malfunction; and (7) appropriate materials of construction are used.

Evaluation procedures are presented for two generic types of incinerators and three generic types of air pollution control devices: liquid injection incinerators, rotary kiln/afterburner incinerators, venturi scrubbers, packed bed scrubbers, and plate (or tray) tower scrubbers. While liquid injection incinerators are used only for disposal of liquid organic wastes, rotary kilns are used to dispose of both liquid and solid wastes. Venturi scrubbers are primarily used for particulate control, while packed bed and plate tower scrubbers are used for acid gas removal. It is believed that more than 90% of the hazardous waste incineration facilities in the United States employ these generic incinerator and air pollution control device designs. Electrostatic precipitators may be used for particulate removal at large incineration facilities. However, these devices are extremely difficult to evaluate from a theoretical standpoint; a compliance test is usually needed to ensure acceptable performance. If other types of incinerators and/or air pollution control devices are being evaluated technical assistance can be requested.

Incinerator and air pollution control system evaluation procedures are presented in Sections 4.3 and 4.4, respectively. Section 4.5 presents worksheets to simplify some of the calculations shown in 4.3 and 4.4.

The following section, 4.2, describes how the destruction and removal efficiency (DRE) of an incinerator/air pollution control system can be calculated for the principal organic hazardous constituent(s) (POHC) of a waste. The current state-of-the-art in combustion modeling does not allow a purely theoretical prediction of destruction and removal efficiency based on design and operating parameters for the incinerator/air pollution control system. Therefore, the DRE calculations presented in Section 4.2 cannot be applied in preliminary design evaluation unless sampling and analysis data are available. However, destruction and removal efficiency calculations are an integral part of the final design evaluation process.

4.2 DESTRUCTION AND REMOVAL EFFICIENCY CALCULATIONS

4.2.1 Definition

Destruction and removal efficiency for an incinerator/air pollution control system is defined by the following formula:

$$DRE = \frac{W_{in} - W_{out}}{W_{in}} (100)$$

where
DRE = destruction and removal efficiency, %

W_{in} = mass feed rate of the principal organic hazardous constituent(s) to the incinerator.

W_{out} = mass emission rate of the principal organic hazardous constituent(s) to the atmosphere (as measured in the stack prior to discharge.

Thus, DRE calculations are based on the combined efficiencies of destruction in the incinerator and removal from the gas stream in the air pollution control system. The (potential) presence of principal organic hazardous constituents in incinerator bottom ash or solid/liquid discharges from air pollution control devices is not accounted for in the DRE calculation as currently defined by EPA.

Part 264, Subpart O regulations for hazardous waste incineration require a DRE of 99.99% for all principal organic hazardous components of a waste unless it can be demonstrated that a higher or lower DRE is more appropriate based on human health criteria. Specification of the principal organic hazardous constituents in a waste is subject to best engineering judgment, considering the toxicity, thermal stability, and quantity of each organic waste constituent. DRE requirements in the Subpart O regulations do not apply to metals or other noncombustible materials.

Destruction and removal efficiencies are normally measured only during trial burns and occasional compliance tests, and are used as a basis for determining whether or not the incinerator/air pollution control system operating conditions are adequate. Sections 4.3 and 4.4 present design evaluation procedures for incinerators and air pollution control devices that are based on state-of-the-art engineering practice. However, any conclusions reached through these

evaluation procedures should be supported by trial burn data demonstrating acceptable destruction and removal efficiency.

4.2.2 Sample Calculation

A liquid injection incinerator equipped with a quench tower, venturi scrubber, and packed bed caustic scrubber has been constructed to burn a mixture of waste oils and chlorinated solvents with the following empirical composition:

73.0 wt % carbon
16.5 wt % chlorine
10.5 wt % hydrogen

The principal organic hazardous components are trichloroethylene, 1,1,1-tri-chloroethane, methylene chloride, and perchloroethylene. Each of these compounds constitutes about 5% of the total waste feed to the incinerator.

During a trial burn, the incinerator was operated at a waste feed rate of 5,000 lb/hr and 50% excess air. The gas flow rate measured in the stack was 19,200 dscfm. Under these conditions, the measured concentrations of the principle organic hazardous components were:

Trichloroethylene - 4.9 µg/dscf
1,1,1-Trichloroethane - 1.0 µg/dscf
Methylene chloride - 49 µg/dscf
Perchloroethylene - 490 µg/dscf

In order to calculate destruction and removal efficiency for each of these compounds using the equation,

$$DRE = \frac{W_{in} - W_{out}}{W_{in}} (100)$$

it is necessary to calculate the mass flow of each component entering and exiting the system. Because each hazardous component constitutes about 5% of the waste and the total waste feed rate was 5,000 lb/hr, W_{in} for each component is:

$$W_{in} = 0.05 \ (5,000 \ lb/hr) = 250 \ lb/hr$$

The mass flow rate of each component exiting the stack is then calculated by the following equation:

$$W_{out} = C_i \ x \ \left[\frac{(19,200 \ dscfm) \ (60 \ min/hr)}{4.54 \times 10^8 \ \mu g/lb} \right]$$

where W_{out} = mass flow rate of component i exiting the stack, lb/hr

C_i = concentration of component i in the stack gas, μg/dscf

Using this equation to calculate W_{out} for each component and the previously cited equation for destruction and removal efficiency, the following results are obtained:

Component	W_{out}, lb/hr	DRE, %
Trichloroethylene	0.0124	99.995
1,1,1-Trichloroethane	0.00254	99.999
Methylene chloride	0.124	99.95
Perchloroethylene	1.24	99.5

These results indicate that the required 99.99% destruction and removal efficiency was achieved in the trial burn for trichloroethylene and 1,1,1-trichloroethane, but not for methylene chloride and perchloroethylene.

Worksheet #1 in Section 4.5 presents a generalized procedure for destruction and removal efficiency calculations.

4.3 INCINERATOR EVALUATION

A logic diagram for evaluating both liquid injection and rotary kiln incinerator designs and operating criteria is shown in Figure 4-1. It consists of six separate evaluation procedures intended to answer the following questions:

• Are the basic incinerator components properly incorporated in the design?

• Have the physical, chemical, and thermodynamic properties of the waste been properly considered in the incinerator design and proposed operating conditions?

• Are the proposed temperature/excess air/residence time combinations internally consistent and achievable? Can adequate turbulence and mixing be achieved under these conditions?

• Is the auxiliary fuel firing capacity acceptable?

• Does the design incorporate suitable combustion process control and safety shutdown interlocks?

• Are appropriate materials of construction employed?

Subsections 4.3.1 through 4.3.6 present background information and procedures for answering questions.
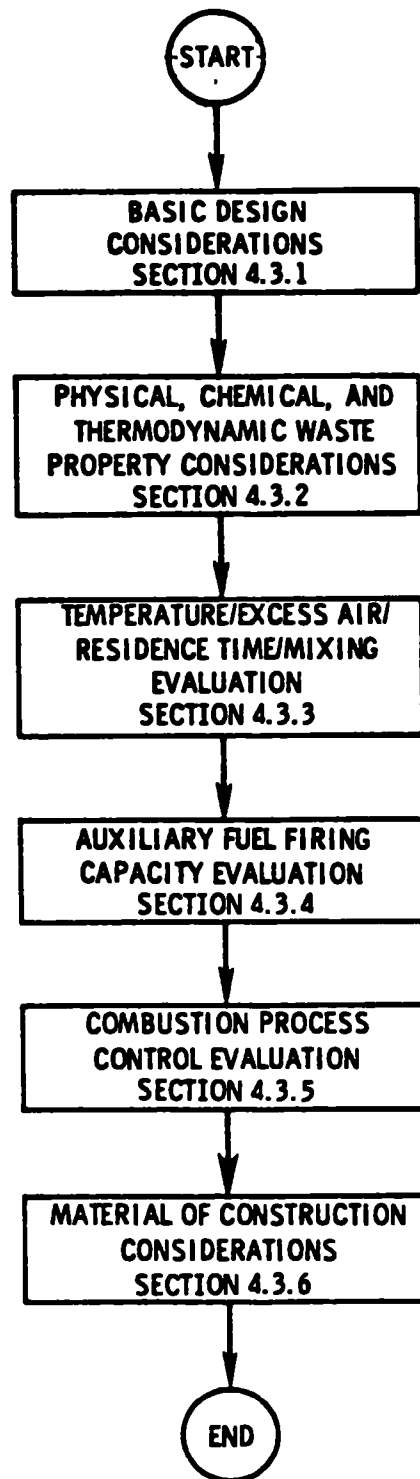
Figure 4-1. Incinerator design evaluation criteria.

4.3.1 Basic Design Considerations

4.3.1.1 Liquid Injection Incinerators--
Liquid injection incinerators are usually simple, refractory-lined cylinders (either horizontally or vertically aligned) equipped with one or more waste burners. Liquid wastes are injected through the burner(s), atomized to fine droplets, and burned in suspension. To heat the unit to operating temperature before waste is introduced, however, all liquid injection incinerator designs should also include an auxiliary fuel firing system. This may consist of separate burners for auxiliary fuel, dual-liquid burners, or single-liquid burners equipped with a premix system whereby fuel flow is gradually turned down and waste flow is increased after the desired operating temperature is attained. If auxiliary fuel firing is needed during routine operation the same types of systems are needed: fuel/waste premix, dual-liquid burners, or separate auxiliary fuel burners.

Each burner, regardless of type, is generally mounted in a refractory block or ignition tile (see Figure 4-2 for an illustration). This is necessary to confine the primary combustion air introduced through the burner, to ensure proper air/waste mixing, and to maintain ignition. The shape of the ignition tile cavity also affects the shape of the flame and the quantity of primary air which must be introduced at the burner. Some burners and tiles are arranged to aspirate hot combustion gases back into the tile, which aids in vaporizing the liquid and increasing flame temperature more rapidly.
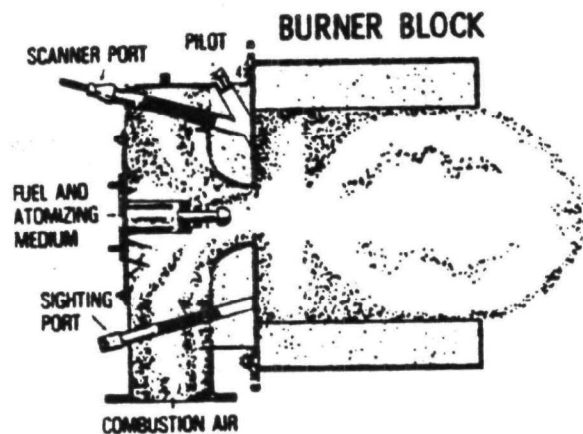
"Reproduced courtesy of Trane Thermal Company, Conshohocken, Pa."

Figure 4-2. High heat release burner for combustion of liquid waste [1].

The dimensions of the burner block, or ignition tile, vary depending on the burner design. Each manufacturer has his own geometrical specifications, which have been developed through past experience. Therefore, it is not possible to specify a single burner block geometry for design evaluation purposes. However, this aspect of the design can be checked to eliminate systems that do not provide for any flame retention.

The location of each burner in the incinerator and its firing angle, relative to the combustion chamber, should also be checked. In axial or side-fired nonswirling units, the burner is mounted either on the end firing down the length of the chamber or in a sidewall firing along a radius. Such designs, while simple and easy to construct, are relatively inefficient in their use of combustion volume. Improved utilization of combustion space and higher heat release rates can be achieved with the utilization of swirl or vortex burners or designs involving tangential entry. Regardless of the burner location and/or gas flow pattern, however, the burner is placed so that the flame does not impinge on refractory walls. Impingement results in flame quenching, and can lead to smoke formation or otherwise incomplete combustion. In multiple burner systems, each burner should be aligned so that its flame does not impact on other burners.

Engineering judgment is used in predicting whether or not these undesirable phenomena will occur with a specific incinerator design.

4.3.1.2 Rotary Kiln Incinerators--
To insure complete waste combustion rotary kiln incinerator designs normally include an afterburner. The primary function of the kiln is to convert solid wastes to gases, which occurs through a series of volatilization, destructive distillation, and partial combustion reactions. However, an afterburner is almost always required to complete the gas-phase combustion reactions. The afterburner is connected directly to the discharge end of the kiln, whereby the gases exiting the kiln turn from a horizontal flow path to a vertical flow path upwards to the afterburner chamber. The afterburner itself may be horizontally or vertically aligned.

Both the afterburner and kiln are usually equipped with an auxiliary fuel firing system to bring the units up to the desired operating temperatures. As explained in Section 4.3.1.1 for liquid injection incinerators, the auxiliary fuel system may consist of separate burners for auxiliary fuel, dual-liquid burners designed for combined waste/fuel firing, or single-liquid burners equipped with a premix system, whereby fuel flow is gradually turned down and liquid waste flow is increased after the desired operating temperature is attained.

If liquid wastes are to be burned in the kiln and/or afterburner, additional considerations are:

- flame retention characteristics of the burners,

- burner alignment to avoid flame impingement on refractory walls, and

- in multiple burner systems, burner alignment to avoid interference with the operation of other burners.

These topics are discussed in Section 4.3.1.1 under liquid injection incinerator evaluation.

One difference between liquid injection incinerators and rotary kilns burning liquid wastes in conjunction with solids is that in the kiln liquid wastes may

be fired either at the feed or discharge end of the unit. Cocurrent and countercurrent firing designs are both widely used.

4.3.2 Physical, Chemical, and Thermodynamic Waste Property Considerations

4.3.2.1 Liquid Injection Incinerators--

Before a liquid waste can be combusted, it must be converted to the gaseous state. This change from a liquid to a gas occurs inside the combustion chamber and requires heat transfer from the hot combustion gases to the injected liquid. To effect a rapid vaporization (i.e., increase heat transfer), it is necessary to increase the exposed liquid surface area. Most commonly the amount of surface exposed to heat is increased by finely atomizing the liquid to small droplets, usually to a 40 μM size or smaller. Good atomization is particularly important when high aqueous wastes or other low heating value wastes are being burned. It is usually achieved in the liquid burner directly at the point of air/fuel mixing.

The degree of atomization achieved in any burner depends on the kinematic viscosity of the liquid and the amount of solid impurities present. Liquids should generally have a kinematic viscosity of 10,000 SSU or less to be satisfactorily pumped and handled in pipes. For atomization, they should have a maximum kinematic viscosity of about 750 SSU. If the kinematic viscosity exceeds this value the atomization may not be fine enough. This may cause smoke or other unburned particles to leave the unit. However, this is only a rule of thumb. Some burners can handle more viscous fluids, while others cannot handle liquids approaching this kinematic viscosity.

Viscosity can be reduced by heating with tank coils or in-line heaters. However, 400-500°F (200-260°C) is normally the limit for heating to reduce viscosity, since pumping a hot tar or similar material becomes difficult above these temperatures. Should gases be evolved in any quantity before the desired viscosity is reached, they may cause unstable fuel feed and burning. If this occurs, the gases should be trapped and vented safely, either to the incinerator or elsewhere. Prior to heating a liquid waste stream, a check should also be made to insure that undesirable preliminary reactions such as polymerization, nitration, oxidation, etc., will not occur. If preheating is not feasible, based on these considerations, a lower viscosity and miscible liquid may be added to reduce the viscosity of the mixture; fuel oil for example.

Solid impurities in the waste can interfere with burner operation via pluggage, erosion, and ash buildup. Both the concentration and size of the solids, relative to the diameter of the nozzle, need to be considered. As discussed in Chapter 5, filtration may be employed to remove solids from the waste prior to injection through the burner.

Liquid waste atomization can be achieved by any of the following means:

- rotary cup atomization
- single-fluid pressure atomization
- two-fluid, low pressure air atomization
- two-fluid, high pressure air atomization
- two-fluid, high pressure steam atomization

In air or steam atomizing burners, atomization can be accomplished internally, by impinging the gas and liquid stream inside the nozzle before spraying; externally, by impinging jets of gas and liquid outside the nozzle; or by sonic means (see Figures 4-3 through 4-5). Sonic atomizers use compressed gas to create high frequency sound waves which are directed on the liquid stream. The liquid nozzle diameter is relatively large, and little waste pressurization is required. Some slurries and liquids with relatively large particles can be handled without plugging problems.
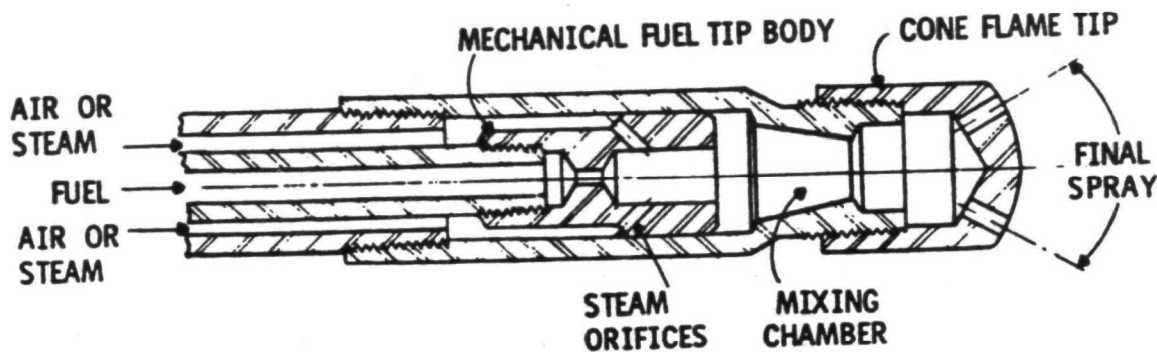
"Reprinted by permission of Chemical Engineering Progress."

Figure 4-3. Internal mix nozzle [2].
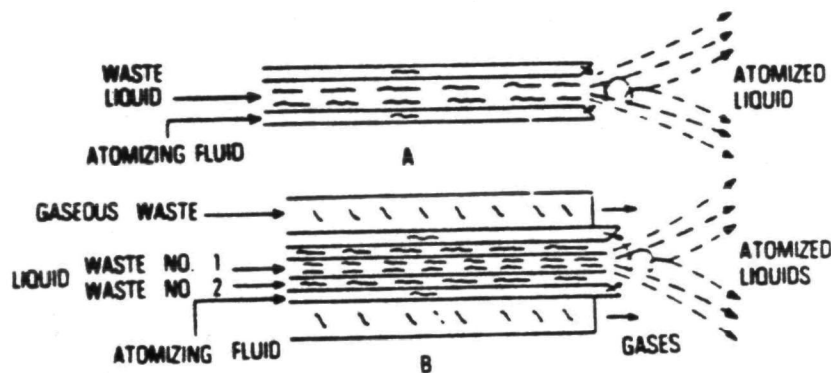
"Reproduced courtesy of Trane Thermal Company, Conshohocken, Pa."

Figure 4-4. External mix nozzles [1].

The rotary cup consists of an open cup mounted on a hollow shaft. The cup is spun rapidly and liquid is admitted through the hollow shaft. A thin film of the liquid to be atomized is centrifugally torn from the lip of the cup and surface tension reforms it into droplets. To achieve conical shaped flames an annular high velocity jet of air (primary air) must be directed axially around the cup. If too little primary air is admitted the fuel will impinge on the sides of the incinerator. If too much primary air is admitted the flame will not be stable and will be blown off the cup. For fixed firing rates, the proper adjustment can be found and the unit operated for long periods of time without cleaning. This requires little liquid pressurization and is ideal for

SPRAY DEFLECTOR   CAPNUT   DISTRIBUTOR

LIQUID

GAS

LIQUID

* SONIC WAVE ATOMIZER
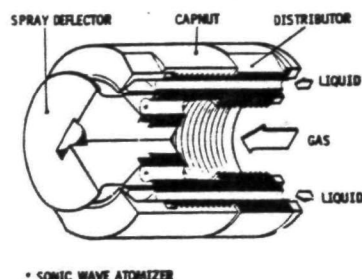
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Figure 4-5. Sonic atomizing nozzle [3].

atomizing liquids with relatively high solids content. Burner turndown is about 5:1 and capacities from 1 to 265 gal/hr, (1-280 cm^3/S) are available.

In single-fluid pressure atomizing nozzle burners, the liquid is given a swirl as it passes through an orifice with internal tangential guide slots. Moderate liquid pressures of 100-150 psi provide good atomization with low to moderate liquid viscosity. In the simplest form, the waste is fed directly to the nozzle but turndown is limited to 2.5 to 3:1 since the degree of atomization drops rapidly with decrease in pressure. In a modified form, involving a return flow of liquid, turndown up to 10:1 can be achieved.

When this type of atomization is used, secondary combustion air is generally introduced around the conical spray of droplets. Flames tend to be short, bushy, and of low velocity. Combustion tends to be slower as only secondary air is supplied and a larger combustion chamber is usually required.

Typical burner capacities are in the range of 10 to 105 gal/hr. Disadvantages of single-fluid pressure atomization are erosion of the burner orifice and a tendency toward pluggage with solids or liquid pyrolysis products, particularly in smaller sizes.

Two-fluid atomizing nozzles may be of the low pressure or high pressure variety, the latter being more common with high viscosity materials. In low pressure atomizers, air from blowers at pressures from 0.5 to 5 psig is used to aid atomization of the liquid. A viscous tar, heated to a viscosity of 15-18 centistokes, requires air at a pressure of somewhat more than 1.5 psig, while a low viscosity or aqueous waste can be atomized with 0.5 psig air. The waste liquid is supplied at a pressure of 4.5-17.5 psig. Burner turndown ranges from 3:1 up to 6:1. Atomization air required varies from 370 to 1,000 ft^3/gal of waste liquid. Less air is required as atomizing pressure is increased. The flame is relatively short as up to 40% of the stoichiometric air may be admixed with the liquid in atomization.

High pressure two-fluid burners require compressed air or steam at pressures from 30 to 150 psig. Air consumption is from 80 to 210 ft^3/gal of waste, and steam requirements may be 2.1 to 4.2 lb/gal with careful control of the operation. Turndown is relatively poor (3:1 or 4:1) and considerable energy is

employed for atomization. Since only a small fraction of stoichiometric air is used for atomization, flames tend to be relatively long. The major advantage of such burners is the ability to burn barely pumpable liquids without further viscosity reduction. Steam atomization also tends to reduce soot formation with wastes that would normally burn with a smoky flame.

Table 4-1 identifies typical kinematic viscosity and solids handling limitations for the various atomization techniques. These data are based on a survey of 14 burner manufacturers. In evaluating a specific incinerator design, however, the viscosity and solids content of the wastes should be compared with manufacturer specifications for the particular burner employed.

TABLE 4-1. KINEMATIC VISCOSITY AND SOLIDS HANDLING LIMITATIONS
OF VARIOUS ATOMIZATION TECHNIQUES

Atomization type	Maximum kinematic viscosity, SSU	Maximum solids mesh size	Maximum solids concentration
Rotary cup	175 to 300	35 to 100	20%
Single-fluid pressure	150		Essentially zero
Internal low pressure air ($\leq$30 psi)	100		Essentially zero
External low pressure air	200 to 1,500	200 (depends on nozzle ID)	30% (depends on nozzle ID)
External high pressure air	150 to 5,000	100 to 200 (depends on nozzle ID)	70%
External high pressure steam	150 to 5,000	100 to 200 (depends on nozzle ID)	70%

A procedure for evaluating whether or not a given burner atomization technique is suitable for the waste under consideration is presented in Table 4-2.

Chemical and thermodynamic properties of the waste that need to be considered in incinerator design evaluation are its elemental composition, its net heating value, and any special properties (e.g., explosive properties) that may interfere with incinerator operation or require special design considerations. The percentages of carbon, hydrogen, oxygen, nitrogen, sulfur, halogens, and phosphorus in the waste, as well as its moisture content, need to be known to calculate stoichiometric combustion air requirements and to predict combustion gas flow and composition[a]. In these calculations, the following reactions are assumed:

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[a] Air requirements, combustion gas flow, and gas composition form the basis for many subsequent evaluation procedures.

4-11

$$C + O_2 \rightarrow CO_2$$

$$H_2 + 1/2O_2 \rightarrow H_2O$$

$$H_2O \rightarrow H_2O$$

$$N_2 \rightarrow N_2$$

$$Cl_2 + H_2O \rightarrow 2HCl + 1/2O_2$$

$$F_2 + H_2O \rightarrow 2HF + 1/2O_2$$

$$Br_2 \rightarrow Br_2$$

$$I_2 \rightarrow I_2$$

$$S + O_2 \rightarrow SO_2$$

$$2P + 2.5O_2 \rightarrow P_2O_5$$
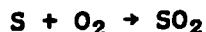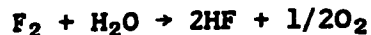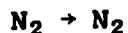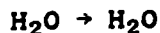
TABLE 4-2. EVALUATION PROCEDURE FOR PHYSICAL WASTE
PROPERTY/ATOMIZATION TECHNIQUE COMPATIBILITY

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1. Identify the atomization technique employed.

2. Identify the kinematic viscosity of the waste at the proposed injection temperature.

3. Check Table 4-1 and/or burner manufacturer specifications to determine if the waste viscosity and atomization technique are compatible.

4. Identify the solids content of the waste and the maximum size of the particles (after pretreatment, if any).

5. Check Table 4-1 and/or burner manufacturer specifications to determine if the solids content of the waste and the atomization technique are compatible.

Table 4-3 shows the stoichiometric or theoretical oxygen requirements and combustion product yields for each of these reactions. Once the weight fraction of each element in the waste has been determined, the stoichiometric oxygen requirements and combustion product yields can be calculated on a lb/lb waste basis. The stoichiometric air requirement is determined directly from the stoichiometric oxygen requirement via the weight fraction of oxygen in air.

Of course, the reactions listed above are not the only ones that occur in combustion processes. Carbon, carbon monoxide, free hydrogen, nitrogen oxides, free chlorine and fluorine, hydrogen bromide and iodide, sulfur trioxide, and

TABLE 4-3. STOICHIOMETRIC OXYGEN REQUIREMENTS AND COMBUSTION PRODUCTS YIELDS

Elemental waste component	Stoichiometric oxygen requirement	Combustion product yield
C	2.67 lb/lb C	3.67 lb CO_2/lb C
H_2	8.0 lb/lb H_2	9.0 lb H_2O/lb H_2
O_2	-1.0 lb/lb O_2	-
N_2	-	1.0 lb N_2/lb N_2
H_2O	-	1.0 lb H_2O/lb H_2O
Cl_2	-0.23 lb/lb Cl_2	1.03 lb HCl/lb Cl_2
		-0.25 lb H_2O/lb Cl_2
F_2	-0.42 lb/lb F_2	1.05 lb HF/lb F_2
		-0.47 lb H_2O/lb F_2
Br_2	-	1.0 lb Br_2/lb Br_2
I_2	-	1.0 lb I_2/lb I_2
S	1.0 lb/lb S	2.0 lb SO_2/lb S
P	1.29 lb/lb P	2.29 lb P_2O_5/lb P
Air N_2	-	3.31 lb N_2/lb $(O_2)_{stoich}$

Stoichiometric air requirement = 4.31 x $(O_2)_{stoich}$

hydrogen sulfide, among other compounds, are also formed to some extent when the corresponding elements are present in the waste or fuel being burned. However, these combustion product yields are usually small in comparison to the yields of the primary combustion products identified above, and need not be considered in gas flow scoping calculations. (They do, however, need to be considered to determine the potential products of incomplete combustion). For most organic wastes and fuels, nitrogen, carbon dioxide, and water vapor are the major combustion products. When excess air is factored into the combustion gas flow, oxygen also becomes a significant component of the gas. Excess air requirements are discussed in Section 4.3.3.

Exceptions to the aforementioned combustion stoichiometry can occur when highly chlorinated or fluorinated wastes are being burned and insufficient hydrogen is present for equilibrium conversion to the halide form. Since hydrogen halides are much more readily scrubbed from combustion gases than halogens themselves, sufficient hydrogen should be provided for this equilibrium conversion to take place. If the waste itself contains insufficient hydrogen, auxiliary fuel or steam injection is needed to supply the necessary hydrogen equivalents. The stoichiometric (absolute minimum) requirements are 1 lb H_2/ 35.5 lb Cl_2 and 1 lb H_2/19 lb F_2 in the waste.

Equilibrium between halogens and hydrogen halides in incinerator gases is given by:

$$X_2 + H_2O = 2HX + 1/2\ O_2$$
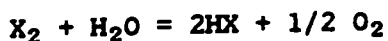
where X_2 represents any free halogen.

For chlorine, this expression becomes:

$$Cl_2 + H_2O = 2HCl + 1/2\ O_2$$

At equilibrium, the concentrations of Cl_2, H_2O, HCl, and O_2 in the combustion gas (at essentially atmospheric pressure) is given by:

$$K_\rho = \frac{(\rho_{HCl})^2\ (\rho_{O_2})^{1/2}}{(\rho_{Cl_2})\ (\rho_{H_2O})}$$

where K_ρ = equilibrium constant

ρ_i = partial pressure of ith component, atm

Figure 4-6 presents a plot of the equilibrium constant, K_ρ, vs. temperature for the conversion of Cl_2 to HCl. If the combustion temperature is known, K_ρ can be identified from Figure 4-6 and the following equation can be used to predict the extent of conversion of Cl_2 to HCl.

$$K_\rho = \frac{4x^2 P_{Cl_2 i}\ (P_{O_2 i} + 1/2x\ P_{Cl_2 i})^{1/2}}{P_{H_2 O i}\ (1 - X)^2}$$

where   x = fractional conversion of Cl_2

$P_{Cl_2 i}$, $P_{O_2 i}$, $P_{H_2 O i}$ = calculated partial pressures of Cl_2, O_2, and H_2O assuming that all organic chlorine is converted to Cl_2 before the reaction to form HCl occurs.

In addition to the aforementioned waste constituents, metallic elements present in the waste influence the assessment of air pollution control requirements and materials of construction (e.g., refractory type). However, the metals content of a waste will not significantly affect the stoichiometric air requirements or combustion gas flow rate.

The heating value of a waste corresponds to the quantity of heat released when the waste is burned, commonly expressed as Btu/lb. Since combustion reactions are exothermic, all organic wastes have some finite heating value. However, the magnitude of this heating value must be considered in establishing an energy balance for the combustion chamber and in assessing the need for auxiliary fuel firing. To maintain combustion, the amount of heat released by the burning waste must be sufficient to heat incoming waste up to its ignition temperature and to provide the necessary activation energy for the combustion reactions to occur. Activation energy, expressed as Btu/lb or the equivalent,
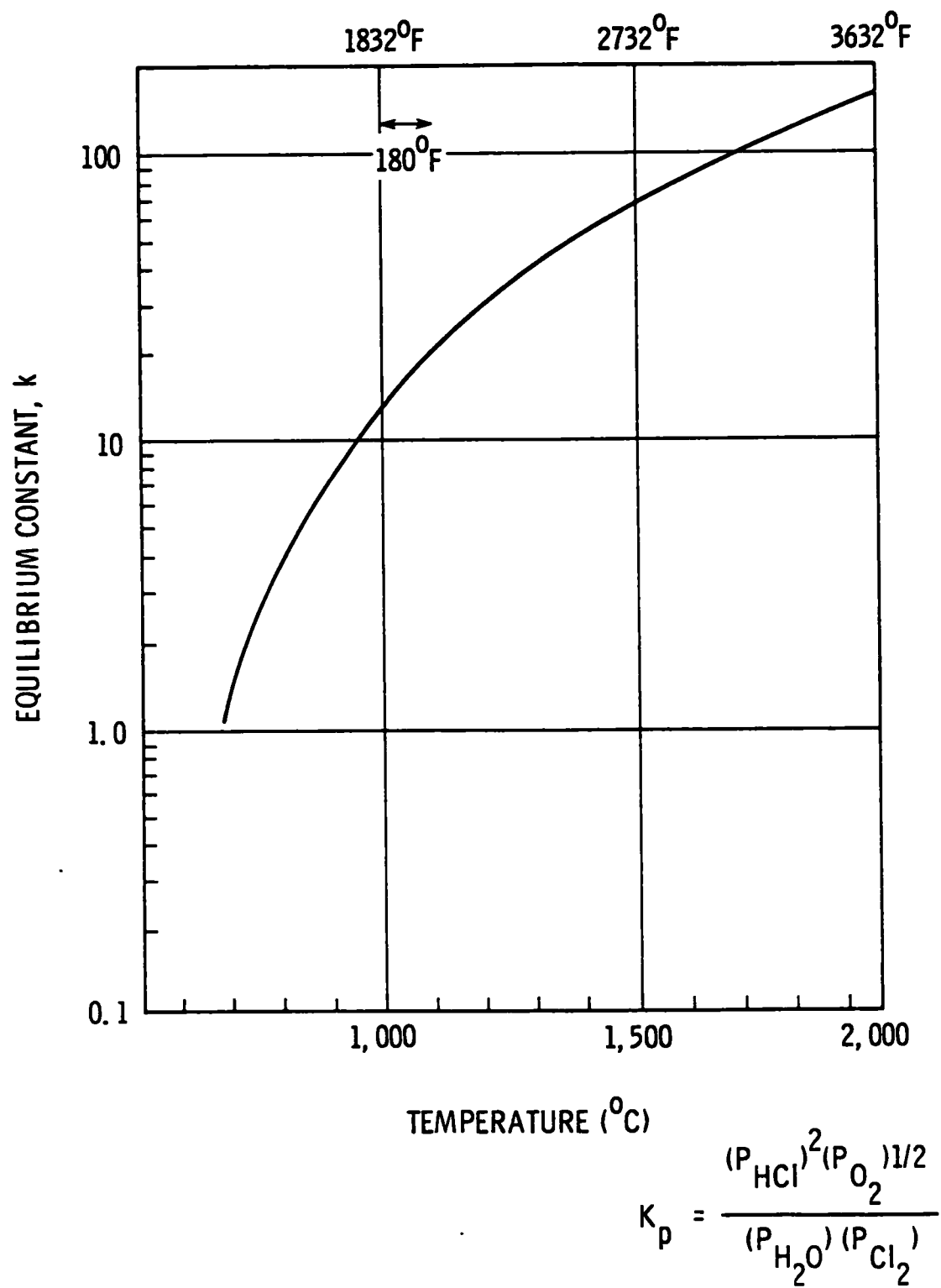
Figure 4-6. Equilibrium constant versus temperature.

$$K_p = \frac{(P_{HCl})^2 (P_{O_2})^{1/2}}{(P_{H_2O})(P_{Cl_2})}$$

is the quantity of heat needed to destabilize molecular bonds and create reactive intermediates so that the exothermic reaction with oxygen will proceed. Figure 4-7 shows the general relationship between activation energy and heating value.
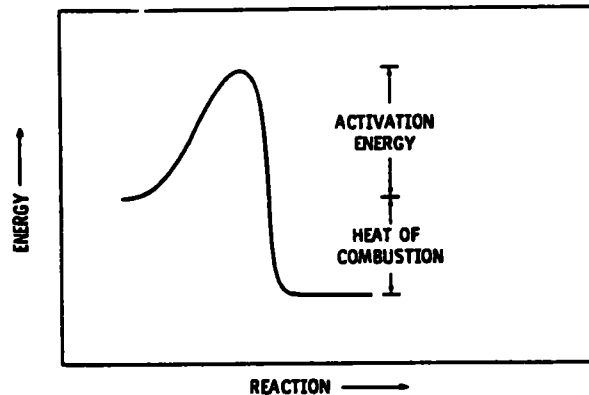
Figure 4-7. Relationship between activation energy and heat of combustion.

Note: The diagram is simplified in the sense that it shows a single activation energy for the reaction. Reactions with more than one intermediate have correspondingly more activation energy levels.

Waste heating values needed to sustain combustion without auxiliary fuel firing depend on the following criteria:

• physical form of the waste (i.e., gaseous vs. liquid vs solid),

• temperature required for refractory waste component destruction,

• excess air rate, and

• heat transfer characteristics of the incinerator.

In general, higher heating values are required for solids vs liquids vs gases, for higher operating temperatures, and for higher excess air rates, if combustion is to be sustained without auxiliary fuel consumption. Gases can sustain combustion at heating values as low as 3,000 Btu/lb, while 4,500 to 5,500 Btu/lb may be considered minimum heating value requirements for combustion of liquid wastes in high efficiency burners [1]. Higher heating values are needed for solid wastes, but the requirements depend on particle size, and thus, the area available for heat and mass transfer. In the hazardous waste incineration industry, it is common practice to blend wastes (and fuel oil, if necessary) to an overall heating value of 8,000 Btu/lb.

When an organic waste exhibits a low heating value, it is usually due to high concentrations of moisture or halogenated compounds. Since water is an ultimate oxidation product, it has no heating value. In fact, a portion of the heat generated by combustion of the organic waste fraction is consumed in vaporizing and heating the moisture up to incinerator temperature. Therefore, an increase in the moisture content of an organic waste proportionately decreases the overall heating value on a Btu/lb waste basis.

The heating value of a waste also decreases as the chlorine (or other halogen) content increases, although there is no simple mathematical relationship. Figure 4-8 shows an empirical relationship between heating value and chlorine content for pure substances. At chlorine contents of 70% or greater, auxiliary fuel is needed to maintain combustion. Auxiliary fuel may also be required for less highly chlorinated waste unless high efficiency burners are used.
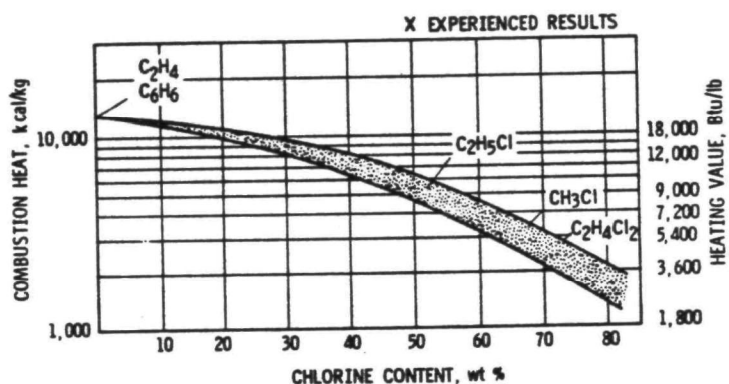
"Reproduced courtesey of Trane Thermal Company, Conshohockon, Pa."

Figure 4-8. Heat of combustion of chlo-
rinated hydrocarbons [4].

In hazardous waste incineration, it is common practice to blend wastes so that the chlorine content does not exceed 30%. This is done to maintain sufficient heating value for sustained combustion and to limit free chlorine concentration in the combustion gas.

When heating value data are reported for a given waste, it is desirable to know whether they are "higher heating values," "lower heating values," or "net heating values." The difference between the higher heating value and lower heating value of a material is that the higher value includes the heat of condensation of water formed in the combustion reaction. In the combustion of methane, for example, the higher heating value is based on the following stoichiometry:

$$CH_{4(g)} + 2O_{2(g)} \rightarrow CO_{2(g)} + 2H_2O_{(\ell)}$$
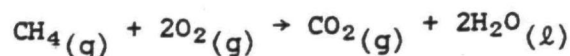
where the subscripts g and ℓ represent gaseous and liquid states, respectively. The lower heating value is based on:

$$CH_4{}_{(g)} + 2O_2{}_{(g)} \rightarrow CO_2{}_{(g)} + 2H_2O{}_{(g)}$$
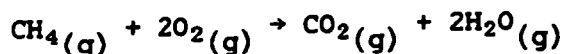
The net heating value of a waste is determined by subtracting from its lower heating value the energy necessary to vaporize any moisture present in the waste initially. Thus, high aqueous wastes may exhibit a negative net heating value. Since this quantity represents the true energy input to the combustion process, only net heating values should be used in developing energy balances for incinerators.

The heating value of a complex waste mixture is difficult to predict a priori. Therefore, these values should be measured experimentally. Since heating values measured using oxygen bomb calorimeters are higher heating values, conversion to the net heating value is required for energy balance calculations. Worksheet 4-3 in Section 4.5 shows how this conversion is performed. Approximate net heating values for common auxiliary fuels are:

Residual fuel oil (e.g., No. 6) - 17,500 Btu/lb
Distillate fuel oil (e.g., No. 2) - 18,300 Btu/lb
Natural gas - 19,700 Btu/lb (1,000 Btu/scf)

Special characteristics of a waste such as extreme toxicity, mutagenicity or carcinogenicity, corrosiveness, fuming, odor, pyrophoric properties, thermal instability, shock sensitivity, and chemical instability should also be considered in incinerator facility design. Thermal or shock instability is of particular concern from a combustion standpoint, since wastes with these properties pose an explosion hazard. Other special properties relate more directly to the selection of waste handling procedures and air pollution control requirements. If potentially explosive wastes are encountered, technical assistance is advised.

Table 4-4 presents a procedure for chemical and thermodynamics waste property evaluation.

4.3.2.2 Rotary Kiln Incinerators--

When liquid wastes are to be burned in the kiln or afterburner, the kinematic viscosity of the liquid and its solids concentration and solids particle size must be considered to determine whether or not good atomization can be achieved with the proposed burner design. This subject is addressed in subsection 4.3.2.1 under liquid injection incinerator evaluation. The procedure outlined in Table 4-2, along with the discussion preceding this table, can be used to check physical waste property/burner compatibility for rotary kiln incinerators burning liquid wastes.

Although liquid wastes are frequently incinerated in rotary kilns, kilns are primarily designed for combustion of solid wastes. They are exceedingly versatile in this regard, capable of handling slurries, sludges, bulk solids of varying size, and containerized wastes. The only wastes that create problems in rotary kilns are (1) aqueous organic sludges that become sticky on drying and form a ring around the kiln's inner periphery, and (2) solids (e.g., drums) that tend to roll down the kiln and are not retained as long as the bulk of solids. To reduce this problem, drums and other cylindrical

TABLE 4-4. CHEMICAL AND THERMODYNAMIC WASTE
PROPERTY EVALUATION PROCEDURE

1. Identify the elemental composition and moisture content of the waste and record this information on Worksheet 4-2 for future reference.

2. Does the waste contain chlorinated or fluorinated materials? (If YES, proceed to checkpoint #3. If NO, proceed to checkpoint #5.)

3. Is sufficient hydrogen present in the waste for equilibrium conversion of chlorine and fluorine to hydrogen chloride and hydrogen fluoride, respectively? See aforementioned evaluation criteria in Section 4.3.2.1. (If YES, proceed to checkpoint #5. If NO, proceed to checkpoint #4.)

4. Is auxiliary fuel firing or steam injection employed to provide the necessary hydrogen equivalents?

5. Identify the major components of the combustion gas, based on the elemental composition of the waste, that need to be considered in subsequent material and energy balance calculations. See Worksheet 4-2 for the recommended procedure. This procedure also determines the stoichiometric air requirement and combustion gas flow, which will be needed for subsequent evaluation procedures.

6. Determine the net heating value of the waste. Worksheet 4-3 shows how the net heating value can be calculated when higher heating values are known.

7. Does it appear likely that the waste will sustain combustion, based on its net heating value? (If YES, proceed to checkpoint #9. If NO, proceed to the following checkpoint.)

8. Is auxiliary fuel to be burned in conjunction with the waste?

9. Is the waste potentially explosive when exposed to high temperature or shock?

containers are usually not introduced to the kiln when it is empty. Other solids in the kiln help to impede the rolling action.

The major design checkpoint for rotary kiln/physical waste property compatibility is the type(s) of solid waste feed systems employed. These feed systems are discussed in Chapter 5.

Chemical and thermodynamic properties of the waste that need to be considered in rotary kiln design evaluation are its elemental composition, its net heating value, and any special properties (e.g., explosive properties, extreme toxicity) that may interfere with incinerator operation or require special design considerations. These are essentially the same properties that must be

considered in liquid injection incinerator evaluation. Therefore, the background discussion in Section 4.3.2.1 and the evaluation procedure presented in Table 4-4 can be used for rotary kilns as well as liquid injection incinerators with some modifications.

The first modification relates to the calculation procedures for stoichiometric air requirement, combustion gas flow and composition. These calculations are more complex for rotary kiln incinerators because (a) liquid and solid wastes may be fed simultaneously to the kiln, and (b) liquid wastes and auxiliary fuel may be fed to the kiln,afterburner, or both. Therefore, Worksheet 4-4 (See Section 4-5) should be used instead of Worksheet 4-2 for combustion gas flow calculations. Worksheet 4-3 can still be used to calculate net heating values.

The second modification relates to the consideration of special waste properties. As discussed in Section 4.3.2.1 for liquid injection incinerators, technical assistance may be required if wastes with explosive properties are encountered. For rotary kilns, technical assistance is also advised if extremely toxic, mutagenic, or carcinogenic wastes are to be burned. This recommendation is based on the fact that kilns are much more prone to release of fugitive emissions than are liquid injection incinerators.

Unlike liquid injection incinerators which have no moving parts, rotary kiln designs incorporate high temperature seals between the stationary end plates and rotating section. These seals are inherently difficult to maintain airtight, which creates the potential for release of unburned wastes. Rotary kilns burning hazardous wastes are almost always operated at negative pressure to circumvent this problem, however, difficulties can still arise when batches of waste are fed semi-continuously. When drums containing relatively volatile wastes are fed to the kiln, for example, extremely rapid gas expansion occurs. This results in a positive pressure surge at the feed end of the kiln (even though the discharge end may still be under negative pressure), which forces unburned waste out through the end plates seals. This phenomenon is known as "puffing", and can pose a major problem if extremely toxic or otherwise hazardous materials are being burned.

Fugitive emissions can also exit the kiln through the feed chute if improperly designed. Therefore, the design of the solid waste feed system is an extremely important consideration in evaluating rotary kiln incinerators. This topic is addressed in Chapter 5.

4.3.3 Temperature, Excess Air, Residence Time, and Mixing Evaluation

Temperature, residence time, oxygen concentration, and the degree of air/waste mixing achieved are the primary variables affecting combustion efficiency in any incinerator design. The theoretical significance of these interrelated variables is discussed in the following subsection under "Liquid Injection Incinerators." Subsection 4.3.3.2 addresses additional temperature, time, excess air, and mixing considerations for rotary kilns.

In general, two major factors are involved in evaluating these variables as they relate to incinerator design. The first factor is whether or not the temperature, residence time, and excess air level, along with the degree of

mixing achieved in the incinerator, are _adequate_ for waste destruction. The second factor is whether or not the proposed operating conditions are _achievable_, since temperature, excess air, residence time, and mixing are all interrelated.

At the current state of the art, the _adequacy_ of incinerator operating conditions can only be determined by past experience with the waste or by actual testing. Therefore, this factor is not addressed _per se_ in the following subsections. The major focus of the following evaluation procedures is on whether or not a proposed set(s) of operating conditions is _achievable_. Basically, this involves a series of internal consistency checks.

4.3.3.1 Liquid Injection Incincerators--

The most basic requirement of any combustion system is a sufficient supply of air to completely oxidize the feed material. The stoichiometric, or theoretical air requirement is calculated from the chemical composition of the feed material, as shown in Section 4.3.2. If perfect mixing could be achieved and liquid waste burnout occurred instantaneously, then only the stoichiometric requirement of air would be needed. Neither of these phenomena occur in real-world applications, however, so some excess air is always required to ensure adequate waste/air contact. Excess air is usually expressed as a percentage of the stoichiometric air requirement. For example, 50% excess air implies that the total air supplied to the incinerator is 50% greater than the stoichiometric requirement.

The amount of excess air used or needed in a given application depends on the degree of air/waste mixing achieved in the primary combustion zone, process-dependent secondary combustion requirements, and the desired degree of combustion gas cooling. Since excess air acts as a diluent in the combustion process, it reduces the temperature in the incinerator (e.g., maximum theoretical temperatures are achieved at zero percent excess air). This temperature reduction is desirable when readily combustible, high heating value wastes are being burned in order to limit refractory degradation. When high aqueous or other low heating value waste is being burned, however, excess air should be minimized to keep the system temperature as high as possible. Even with highly combustible waste, it is desirable to limit excess air to some extent so that combustion chamber volume and downstream air pollution control system capacities can be limited.

In liquid injection incinerators, two excess air rates must be considered: (1) the excess air present in the primary combustion air introduced through the burner, and (2) the total excess air, which includes secondary combustion air. Normally, 10% to 20% excess air (i.e., 1.1 to 1.2 times the stoichiometric requirement) is supplied to the burner to prevent smoke formation in the flame zone. When relatively homogeneous wastes are being burned in high efficiency burners, 5% excess air may be adequate. Too much excess air through the burner is also undesirable, since this can blow the flame away from its retention cone. Burner manufacturer specifications are the best source of information for analysis.

In general, the total excess air rate should exceed 20% to 25% to insure adequate waste/air contact in the secondary combustion zone. However, the

minimum requirement for a given incinerator depends on the degree of mixing achieved and waste specific factors.

Four basic questions should be considered in evaluating whether or not a proposed operating temperature is sufficient for waste destruction:

(1) Is the temperature high enough to heat all waste components (and combustion intermediates) above their respective ignition temperatures and to maintain combustion?

(2) Is the temperature high enough for complete reaction to occur at the proposed residence time?

(3) Is this temperature within normal limits for the generic design and/or attainable under the other proposed operating conditions?

(4) At what point in the combustion chamber is the proposed temperature to be measured?

Complete waste combustion requires a temperature, and heat release rate, in the incinerator high enough to raise the temperature of the incoming waste constituents above their respective ignition temperatures (i.e., to provide energy input in excess of their respective activation energies). In cases where combustion intermediates are more stable than the original waste constituents, higher temperatures are required for complete combustion of the intermediates than for parent compound destruction.

Since heat transfer, mass transfer, and oxidation all require a finite length of time, temperature requirements must also be evaluated in relation to the proposed residence time in the combustion chamber. Heat transfer, mass transfer, and kinetic reaction rates all increase with increasing temperature, lowering the residence time requirements. For extremely short residence times, however, temperatures higher than those needed for ignition may be required to complete the combustion process.

The current state of the art in combustion modeling does not allow a purely theoretical determination of temperature and residence time requirements for waste and combustion intermediate destruction. Therefore, the only reasonable alternative is an examination of temperature/residence time combinations used to destroy the same or similar waste in a similar or identical incinerator.

After addressing the temperature requirements for waste destruction, it is reasonable to determine whether or not the proposed temperature is within normal limits for the generic incinerator design and whether or not this temperature can be attained under the proposed firing conditions. Generally, liquid injection incinerator temperatures range from 1,400°F to 3,000°F depending on the generic design, type of waste being burned, and location within the combustion chamber. Usually 1,400°F is the minimum temperature needed to avoid smoke formation. A more typical hazardous waste incineration temperature is 1,800°F, although temperatures of 2,000°F to 2,200°F or higher are usually employed for halogenated aromatic wastes.

The question of whether or not the proposed temperature and excess air rate
are attainable can be resolved by approximate calculations based on a heat
balance around the combustion chamber. Figure 4-9 shows the heat inputs and
outputs for the combustion chamber.
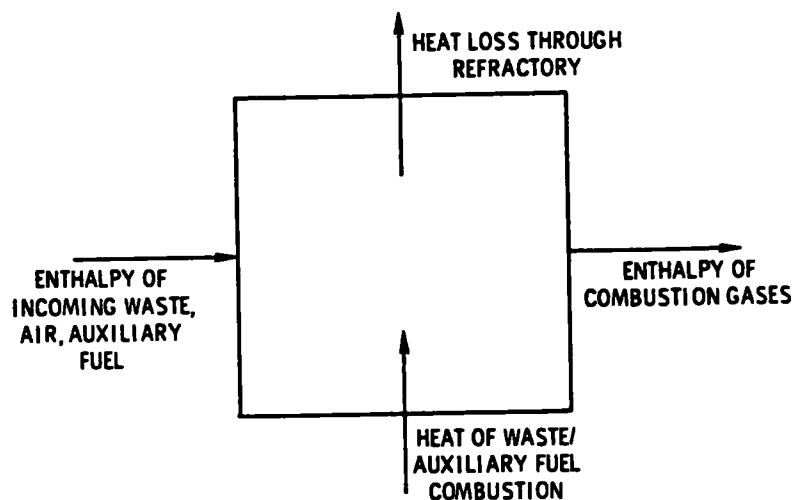
Figure 4-9. Energy balance for combustion chamber.

Since liquid waste incineration is a steady state (or quasi-steady state)
process, the enthalpy of the waste/auxiliary fuel/combustion air feed plus the
heat released by combustion must equal the enthalpy of the combustion gases
leaving the unit plus the heat loss through the refractory walls. This yields
the general relationship:

$$\left(\begin{array}{c}\text{Heat loss}\\ \text{through refractory}\end{array}\right) = \left(\begin{array}{c}\text{Enthalpy of}\\ \text{incoming feed}\end{array}\right) + \left(\begin{array}{c}\text{Heat released by}\\ \text{combustion}\end{array}\right) - \left(\begin{array}{c}\text{Enthalpy}\\ \text{of combus-}\\ \text{tion gases}\end{array}\right)$$

or
$$Q = \Delta H$$

where   Q = heat loss through refractory, Btu/lb waste
       ΔH = overall enthalpy change in the combustion chamber, Btu/lb waste

Since enthalpy is a thermodynamic state function, the overall enthalpy change
can be represented by any series of incremental enthalpy changes, so long as
the initial state and final state correspond to the incinerator inlet and
outlet conditions, respectively. The key is to select an enthalpy change
pathway that simplifies the calculations involved, such as that shown in
Figure 4-10.

Using this approach, the overall energy balance equation becomes:

$$Q = \Delta H = \Delta H_{1\_2} + \Delta H_{2\_3} + \Delta H_{3\_4}$$

where ΔH_{j-k} = incremental enthalpy changes, Btu/lb waste

In Figure 4-10, the first enthalpy change, ΔH_{1-2}, represents the difference in feed enthalpy between injection temperature and standard conditions of 77°F (25°C). This term is seldom significant unless the combustion air is preheated to high temperature.

①

WASTE AND AIR
AT INJECTION
TEMPERATURE

④

COMBUSTION PRODUCTS,
UNREACTED WASTE, AND
EXCESS AIR AT COMBUSTION
TEMPERATURE

②

WASTE AND AIR

AT 77°F (25°C)

③ COMBUSTION PRODUCTS,
UNREACTED WASTE, AND
EXCESS AIR AT

77°F (25°C)
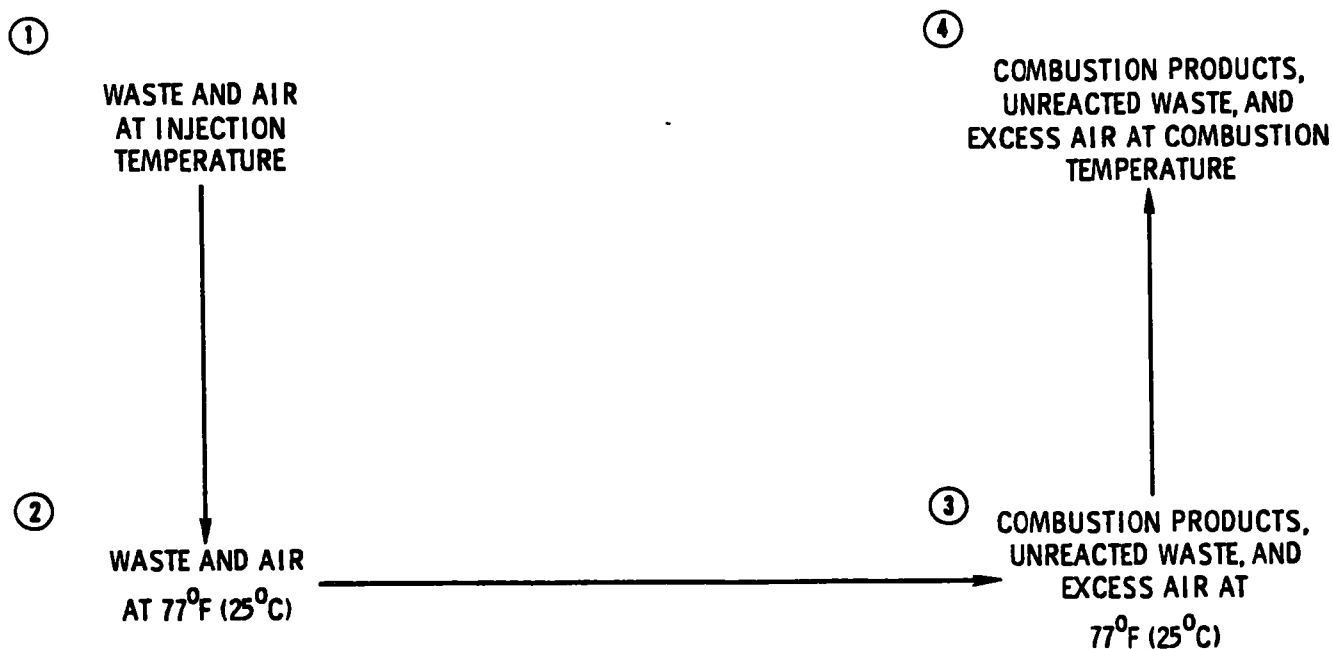
Figure 4-10. Enthalpy balance for combustion processes.

The term ΔH_{2-3} represents the heat released by combustion at isothermal conditions of 25°C. This corresponds to the way in which heats of combustion are measured and presented in the literature. The third term, ΔH_{3-4}, represents the difference in combustion product enthalpy between 25°C and the temperature at the combustion chamber outlet.

In mathematical terms, these incremental enthalpy changes are expressed as:

$$\Delta H_{1-2} = \sum_{\substack{i=1 \\ \text{waste} \\ \text{components}}}^{k} n_i \overline{C_{pi}} (77 - T_{in})$$

$$+ 4.31 \overline{C_p}_{\text{air}} (77 - T_{air})(O_2)_{\text{stoich}}(1 + EA)$$

$$\Delta H_{2-3} = \sum_{\substack{i=1 \\ \text{reactive} \\ \text{waste} \\ \text{components}}}^{k} n_i X_i (\Delta H_c)_{i_{77°F}}$$

and

$$\Delta H_{3-4} = \left\{ \sum_{\substack{i=1 \\ \text{reaction} \\ \text{products}}}^{k} n_i \overline{C_{pi}} X_i + \sum_{\substack{i=1 \\ \text{reactive} \\ \text{waste} \\ \text{components} \\ \text{remaining}}}^{k} n_i \overline{C_{pi}} (1 - X_i) \right.$$

$$+ 4.31 \overline{C_p} \, air (O_2)_{stoich} (EA) \left[1 + \sum_{\substack{i=1 \\ \text{reactive} \\ \text{components}}}^{k} n_i \left(1 - X_i\right) \right]$$

$$\left. + \sum_{\substack{i=1 \\ \text{inert} \\ \text{waste} \\ \text{components}}}^{k} n_i \overline{C_{pi}} \right\} (T_{out} - 77)$$

where $\quad n_i$ = lb ith component/lb waste

$\overline{C_{pi}}$ = mean heat capacity of ith component over the temperature range involved, Btu/lb °F

T_{in} = waste injection temperature, °F

T_{air} = air inlet temperature, °F

X_i = fractional conversion of ith component (X_i = 1.0 at 100% combustion of ith component)

$(\Delta H_c)_{i_{77°F}}$ = heat of combustion of ith component at 77°F (25°C), Btu/lb

T_{out} = temperature at the combustion chamber outlet, °F

$(O_2)_{stoich}$ = stoichiometric oxygen requirement, lb O_2/lb waste

EA = excess air, %/100

To determine whether or not the proposed temperature/excess air combination is achievable, it is necessary to specify the desired temperature and calculate the corresponding excess air rate for comparison with the proposed value. However, there are far too many unknowns in these equations to solve for EA.

These equations can be simplified considerably by assuming that the combustion reactions go to essentially 100% completion.[a] With this assumption, the overall energy balance reduces to:

$$Q = \overline{C_p}_{\text{ waste}}(77 - T_{in}) + 4.31 \, \overline{C_p}_{\text{ air}}(77 - T_{air})(O_2)_{stoich}(1 + EA)$$

$$+ (- \text{NHV})_{77°F} + (T_{out} - 77) \left[\sum_{\substack{i=1 \\ \text{combustion} \\ \text{products}}}^{k} n_i \, \overline{C_{pi}} + 4.31 \, \overline{C_p}_{\text{ air}}(O_2)_{stoich}EA \right]$$

where NHV = net heating value of the waste, Btu/lb

From the empirical waste composition (carbon content, hydrogen content, etc.), proposed excess air rate, and combustion stoichiometry discussed in Section 4.3.2, all the variables in this equation are fixed except the outlet temperature or excess air rate, mean heat capacities of the combustion gases, and the heat loss through the walls of the combustion chamber. To avoid rigorous heat transfer calculations, this heat loss can be assumed to be about 5% of the heat released in the combustion chamber, based on operating experience with hazardous waste incinerators. With this assumption, the energy balance reduces to:

$$\overline{C_p}_{\text{ waste}}(77 - T_{in}) + 4.31 \, \overline{C_p}_{\text{ air}}(77 - T_{air})(O_2)_{stoich}(1 + EA) + 0.95 \, (- \text{NHV})$$

$$+ \left[\sum_{\substack{i=1 \\ \text{combustion} \\ \text{products}}}^{k} n_i \, \overline{C_{pi}} + 4.31 \, \overline{C_p}_{\text{ air}}(O_2)_{stoich}EA \right](T_{out} - 77) = 0$$

from which the first two terms can be deleted if neither waste nor air pre-heating is employed. (The waste enthalpy term can almost always be deleted anyway.) This yields:

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[a] Acceptance of the proposed temperature/residence combination should ensure combustion efficiencies close enough to 100% for this value to be used in heat balance calculations.

$$0.95 \ (-NHV) + \left[\sum_{\substack{i=1 \\ \text{combustion} \\ \text{products}}}^{k} n_i \overline{C_{pi}} + 4.31 \ \overline{C}_p \ \text{air} (O_2)_{\text{stoich}} EA \right] (T_{\text{out}} - 77) = 0$$

The mean heat capacities of the combustion gases will vary to a small degree depending on the incinerator outlet temperature. For the purposes of approximate calculations, however, the following values can be assumed:

Gas component	$\overline{C}_p$, Btu/lb °F
Excess air	0.26
N_2	0.26
CO_2	0.26
H_2O	0.49
HCl	0.20
SO_2	0.18

This yields the expression[a]:

$$0.95 \ (-NHV) + \left[0.26 \ (n_{N_2} + n_{CO_2}) + 0.49 \ N_{H_2O} \right.$$

$$\left. + 1.12 \ (O_2)_{\text{stoich}} EA \right] (T_{\text{out}} - 77) = 0$$

for wastes containing only carbon, hydrogen, oxygen, and nitrogen. If other gas components, constitute more than a few percent of the total flow, additional heat capacity terms must be added.

If auxiliary fuel is to be burned in conjunction with the waste, a modification of the previous equation is needed. This is as follows:

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[a]The term n_{N_2} in this equation refers to the nitrogen present in the combustion gases under stoichiometric conditions. It does not include excess air nitrogen.

$$0.95\left[(-\text{ NHV})_{\text{waste}} + n_{\text{fuel}}(-\text{ NHV})_{\text{fuel}}\right] + \left[\sum_{\substack{i=1 \\ \text{waste} \\ \text{combustion} \\ \text{products}}}^{k} n_i \overline{C_{pi}}\right.$$

$$\left. + n_{\text{fuel}}\sum_{\substack{i=1 \\ \text{fuel} \\ \text{combustion} \\ \text{products}}}^{k} (n_{i\ \text{fuel}}\ \overline{C_{pi}}) + 4.31\ \overline{C_p}\ \text{air}^{(O_2)}\text{stoich}^{EA}\right](T_{\text{out}} - 77) = 0$$

where $n_{i\ \text{fuel}}$ = lb ith combustion gas component/lb fuel

$\overline{C_p}_{\text{ fuel}}$ = mean heat capacity of fuel over the applicable temperature range, Btu/lb °F

NHV_{fuel} = heating value of fuel, Btu/lb

n_{fuel} = lb fuel/lb waste

If only carbon, hydrogen, oxygen, and nitrogen are present, the equation can be simplified to[a]:

$$0.95\left[(-\text{NHV})_{\text{waste}} + n_{\text{fuel}}\ (-\text{NHV})_{\text{fuel}}\right]$$

$$+ \left[0.26\ (n_{N_2} + n_{CO_2}) + 0.49\ n_{H_2O} + 1.12\ (O_2)_{\text{stoich}}\ EA\right](T_{\text{out}} - 77) = 0$$

By fixing the outlet temperature at the proposed value, the equations shown above can be used to estimate the maximum achievable excess air rate for comparison with that proposed. Thus, the equations provide an internal consistency check for proposed temperature/excess air combinations. Worksheet 4-5 in Section 4-5 shows how the calculation can be performed in a step-by-step manner.

When identifying a minimum temperature acceptable for waste destruction, it is also important to identify the location in the combustion chamber at which

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[a]In this equation, n_{N_2}, n_{CO_2}, n_{H_2O}, $(O_2)_{\text{stoich}}$, and EA apply to the combined waste/auxiliary fuel mix, and n_{N_2} accounts refers to the nitrogen present in the combustion gases under stoichiometric conditions.

this temperature should be measured. Temperature varies tremendously from one point to another in the combustion chamber, being highest in the flame and lowest at the refractory wall or at a point of significant air infiltration (e.g., in the vicinity of secondary air ports). Ideally, temperature should be measured in the bulk gas flow at a point after which the gas has traversed the combustion chamber volume that provides the specified residence time for the unit. It should not be measured at a point of flame impingement or at a point directly in sight of radiation from the flame. Chapter 5 discusses temperature measurement in more detail.

A comprehensive evaluation procedure for temperature/excess air considerations is shown in Table 4-5 (on page 4-31).

In addition to temperature and excess air, residence time is a key factor affecting the extent of combustion. This variable, also referred to as retention time or dwell time, is the mean length of time that the waste is exposed to the high temperatures in the incinerator. It is important in designing and evaluating incinerators because a finite amount of time is required for each step in the heat transfer/mass transfer/reaction pathway to occur.

In liquid waste combustion, discrete (although short) time intervals are required for heat transfer from the gas to the surface of the atomized droplets, liquid evaporation, mixing with oxygen in the gas stream, and reaction, which itself involves a series of individual steps depending on the complexity of the waste's molecular structure. The total time required for these processes to occur depends on the temperature in the combustion zone, the degree of mixing achieved, and the size of the liquid droplets. Residence time requirements increase as combustion temperature is decreased, as mixing is reduced, and/or as the size of discrete waste particles is increased. Typical residence times in liquid injection incinerators range from 0.5 s to 2.0 s.

Gas residence times are defined by the following formula:

$$\theta = \int_0^V \frac{dV}{q}$$

where θ = mean residence time, s
     V = combustion chamber volume, ft^3
     q = gas flow rate, ft^3/s within the differential volume, dv

and gas flow rate is given by:

$$q = \left(\frac{0.79}{Y_{N_2}}\right)\left(\frac{T + 460}{528}\right)[4.31 \ (O_2)_{stoich \ 68°F}]^{(1 \ + \ EA)}$$

where Y_{N_2} = mole fraction N_2 in the gas within the differential volume

          T = gas temperature, °F, within the differential volume

$(O_2)_{stoich}$ = stoichiometric oxygen requirement, scf/s

EA = excess oxygen fraction, %/100, within the differential volume

As indicated in this equation, residence time is not an independent variable. For an incinerator of fixed volume and relatively constant feed, residence time is influenced by the temperature and excess air rate employed.

Gas flow rate at any point along the length of the combustion chamber is a function of the temperature at that point, the amount of excess air added up to that point, and the extent to which the combustion reactions are completed at that point. Therefore, solution of the above equation requires a knowledge of the temperature profile, excess air profile, and waste conversion profile along the combustion chamber. These factors must be expressed as functions of combustion chamber length (i.e., volume) in order for the integration to be performed.

Since this detailed information can rarely, if ever, be determined with a reasonable degree of accuracy, an alternate approach is normally adopted. In this approach, the flow rate, q, is specified at the desired operating temperature (measured at the incinerator outlet) and total excess air rate. The equation is then simplified to:

$$\theta = \frac{V}{q_{out}}$$

The chamber volume used in this calculation is an estimated value, corresponding to the volume through which the combustion gases flow after they have been heated to the desired operating temperature. Thus, the chamber volume used in residence time calculations should be at least somewhat less than the total volume of the chamber. However, an upper bound residence time can be estimated by:

$$\theta_{max} = \frac{V_T}{q_{out}}$$

where V_T = total volume of the chamber

Any residence times calculated by this equation should only be used for general comparison purposes.

In the preceding discussion, all equations apply to the nominal, or mean, residence time in the combustion chamber. A thoroughly rigorous approach would require tracer studies to determine residence time distributions in the incinerator. However, nominal residence times are sufficient for evaluation purposes, so long as the incinerator design is such that significant channeling (analogous to dead space in the combustion chamber) does not occur. Channeling is usually prevented by creating abrupt changes in flow direction or by establishing a definite flow pattern in the combustion chamber (e.g., cyclonic flow).

4-30

TABLE 4-5. TEMPERATURE/EXCESS AIR EVALUATION PROCEDURE.

1. Identify the proposed operating temperature.

2. Is this temperature sufficient to convert all waste components to their ultimate oxidation products, assuming that adequate residence time, oxygen, and mixing are provided? See the preceding discussion (Section 4.3.3.1) for general guidelines. Outside sources of information can be consulted for waste-specific data.

3. Identify the excess primary combustion air rate proposed in the permit application.

4. Does this excess air rate meet or exceed the general requirements identified in the preceding discussion and/or burner manufacturer specifications?

5. Identify the total excess air rate proposed.

6. Is this excess air rate acceptable? General guidelines are presented in Section 4.3.3.1.

7. Independently calculate the total excess air rate needed to maintain the proposed operating temperature (see Worksheet 4-5).

8. Is this calculated excess air rate greater than or comparable to the proposed total excess air rate? (If YES, proceed to checkpoint #11. If NO, proceed to the following checkpoint).

9. Is this excess air rate acceptable, even though it is less than the proposed excess air rate? See the preceding discussion for general guidelines. (If YES, proceed to checkpoint #11. If NO, proceed to the following checkpoint.)

10. Are there any mechanical restraints in the system that would prevent increasing the auxiliary fuel-to-waste firing ratio (which would be needed to maintain both an acceptable temperature and excess air rate)? If necessary, repeat the calculations shown in Worksheet 4-5 for the maximum achievable fuel-to-waste ratio.

11. Identify the location at which temperature is to be measured in the incinerator.

12. Is this location (a) suitable based on the considerations in the preceding discussion or (b) comparable to the location at which temperature was measured during an appropriate prior test?

Table 4-6 presents a gas residence time evaluation procedure which can be used in conjunction with the evaluation procedure for temperature and excess air shown in Table 4-5, since all three variables are interrelated.

TABLE 4-6. GAS RESIDENCE TIME EVALUATION PROCEDURE

1. Identify the proposed gas residence time.

2. Does this residence time appear adequate, considering the proposed operating temperature and excess air rate, and assuming that good mixing is achieved? See the preceding discussion for general guidelines and the appendices for specific information.

3. Does the proposed residence time appear to be achievable? See Worksheet 4-6.

Temperature, oxygen, and residence time requirements for waste destruction all depend to some extent on the degree of mixing achieved in the combustion chamber. This parameter is difficult to express in absolute terms, however. Many of the problems involved in interpreting burn data relate to the difficulty involved in quantifying the degree of mixing achieved in the incinerator, as opposed to the degree of mixing achieved in another incinerator of different design.

In liquid waste incinerators, the degree of mixing is determined by the specific burner design (i.e., how the primary air and waste/fuel are mixed), combustion product gas and secondary air flow patterns in the combustion chamber, and turbulence. Turbulence is related to the Reynolds number for the combustion gases, expressed as:

$$Re = \frac{Dv\rho}{\mu}$$

where D = combustion chamber diameter, ft
       v = gas velocity, ft/s
       ρ = gas density, lb/ft^3
       μ = gas viscosity, lb/ft s

Turbulent flow conditions exist at Reynold's numbers of approximately 2,300 and greater. Below this Reynold's number laminar or transition flow prevails and mixing occurs only by diffusion.

In conventional liquid injection incinerators or afterburners, it is possible to simplify the Reynold's number to consideration of superficial gas velocity only. Adequate turbulence is usually achieved at superficial gas velocities of 10 to 15 ft/s. Superficial gas velocities are determined by

$$v = \frac{q}{A}$$

where q = gas flow rate at operating temperature, ft^3/s
       A = cross-sectional area of the incinerator chamber, ft^2

When primary combustion air is introduced tangentially to the burner (e.g., vortex burners), secondary air is introduced tangentially, or burner alignment is such that cyclonic flow prevails in the incinerator, actual gas velocities exceed the superficial velocity. Thus, adequate turbulence may be achieved at superficial velocities less than 10 ft/s in cyclonic flow systems. However, the tradeoff is difficult to quantify. Turbulence can also be increased by installing baffles in the secondary combustion zone of the incinerator, which abruptly change the direction of gas flow. However, this also increases pressure drop across the system and is not a common practice in liquid injection incinerator design. Steam jets can also be used to promote turbulence.

Table 4-7 presents a procedure for evaluating the mixing characteristics of liquid injection incinerators. Since mixing is related to the gas flow rate through the incinerator, this evaluation procedure can be used in conjunction with that for temperature and excess air, which affect gas flow independent of the waste feed rate.

TABLE 4-7. MIXING EVALUATION PROCEDURE

1. Calculate the superficial gas velocity in the incinerator chamber at operating temperature (see Worksheet 4-7).

2. Does this velocity meet or exceed the general guidelines provided above (i.e., 10-15 ft/s)?

3. If not, is cyclonic flow or some mechanical means of enhancing turbulence designed into the system? If YES, somewhat lower superficial velocities than those listed above may still provide suitable mixing.

4.3.3.2 Rotary Kiln Incinerators--
In rotary kiln/afterburner incineration systems, three excess air rates must be considered: (1) excess air present in the primary combustion air introduced through liquid waste burners in the kiln or afterburner section, (2) total excess air fed to the kiln, and (3) the excess air percentage maintained in the afterburner.

Normally, 10% to 20% excess air (i.e., 1.1 to 1.2 times the stoichiometric requirement) must be supplied to liquid waste burners to prevent smoke formation in the flame zone. When relatively homogeneous wastes are being burned in high efficiency burners, 5% excess air may be adequate. Too much excess air through the burner is also undesirable, since this can blow the flame away

from its retention cone. Burner manufacturer specifications are the best source of information for case-by-case analysis.

As stated in Section 4.3.3.1, 20% to 25% total excess air is a practical minimum for liquid injection incinerators to achieve adequate air/waste contact. Higher excess air rates are needed in rotary kilns, however, because the efficacy of air/solids contact is less than that for air and atomized liquid droplets. Typical excess air rates range from 140% to 210% or greater, depending on the desired operating temperature and the heating value of the waste. When high aqueous wastes are being burned, lower excess air rates may be needed to maintain adequate temperature. However, less than 100% excess air in the kiln may not provide adequate air/solids contact.

Since it is usually desirable to maintain the afterburner at a higher temperature than the kiln, and because only liquid wastes or auxiliary fuel is fired in the afterburner, the excess air rate in the afterburner is usually less than that in the kiln. In a typical system operating at 1,500°F in the kiln and 1,800°F in the afterburner, approximately 160% to 170% excess air would be maintained in the afterburner compared to ~210% in the kiln. Considering 100% excess air in the kiln as a practical minimum, approximately 80% excess air or more should be maintained in the afterburner. This includes air contained in the kiln exit gases as well as air introduced in the afterburner itself, and is based on the total stoichiometric oxygen requirement for all wastes and fuels burned in the system.

In evaluating temperature requirements for a rotary kiln/afterburner system, seven basic questions should be considered:

(1) Is the temperature in the kiln high enough to volatilize, partially oxidize, or otherwise convert all organic components of the waste to a gaseous state?

(2) Is this temperature high enough for the aforementioned processes to occur within the proposed solids retention time?

(3) Is the afterburner temperature high enough to heat all volatilized wastes (and combustion intermediates) above their respective ignition temperatures and maintain combustion?

(4) Is the temperature high enough for complete reaction to occur within the proposed afterburner residence time?

(5) Is the kiln operating temperature within normal limits and/or attainable under the other proposed operating conditions?

(6) Is the afterburner temperature within normal limits and/or attainable under the other proposed operating conditions?

(7) At what points in the system are the temperatures to be measured?

The current state-of-the-art in combustion modeling does not allow a purely theoretical determination of time and temperature requirements for solid waste

burnout or combustion in the gas phase. Therefore, the only reasonable alternative is an examination of temperature/time combinations used to destroy the same or similar waste in a similar or identical rotary kiln/afterburner system. This information is needed to address questions 1 through 4 above. The latter three questions are addressed in the following paragraphs.

Temperatures in rotary kiln incinerators usually range from about 1,400°F to 3,000°F, depending on the types of waste being burned and the location in the kiln. Common operating temperatures, measured outside of the flame zone, are 1,500°F to 1,600°F. The question of whether or not these or other proposed temperatures are attainable at the proposed excess air rate can be resolved by approximate calculations based on a heat balance around the kiln (see Section 4.3.3.1 for a discussion of how heat balances are formulated).

The difficulty that arises in this calculation is that the extent of combustion, or actual heat release compared to the maximum attainable heat release, is unknown. However, the maximum achievable excess air rate in the kiln at the specified operating temperature can still be estimated by assuming complete combustion. This corresponds to a worst case analysis. The maximum calculated excess air rate must exceed the proposed excess air rate, or the specified operating temperature will not be attainable.

The applicable heat balance equation for the kiln, assuming complete combustion is shown on the following page.

This equation is also based on the assumptions that (a) heat loss through the kiln walls is about 5% of the heat released on combustion, and (b) waste preheating, if employed, will result in negligible heat input compared to the heat released on combustion (which is almost always the case). This equation can be solved directly for EA, the maximum attainable excess air rate in the kiln, once the desired operating temperature is specified. Mean heat capacities for common combustion gas components, applicable over temperature ranges normally encontered, are shown in Section 4.3.3.1.

Worksheet 4-8 in Section 4-5 presents a step-by-step calculation procedure.

$$
4.31\ \overline{C}_{p\ air}\ (77 - T_{air})(O_2)_{stoich(k)}(1 + EA_k)
$$

$$
- 0.95 \left(\frac{n_1 NHV_1 + n_2 NHV_2 + n_{fK} HV_{fK}}{1 + n_{fK}} \right)
$$

$$
+ \left[\sum_{\substack{i=1 \\ \text{combustion} \\ \text{products} \\ \text{from kiln}}}^{k} n_i\ \overline{C_{pi}} + 4.31\ \overline{C}_{p\ air}(O_2)_{stoich} EA_k \right] (T_{out} - 77) = 0
$$

where $\overline{C_{pi}}$ = mean heat capacity of ith component over the temperature range involved, Btu/lb °F

T_{air} = air preheat temperature, °F

$(O_2)_{stoich}$ = total stoichiometric oxygen requirement for wastes and auxiliary fuel fed to the kiln, lb O_2/lb feed

EA_k = percent excess air/100(in kiln)

n_1 = lb liquid waste/lb waste

n_2 = lb solid waste/lb waste

n_{fK} = lb fuel/lb waste

NHV_1 = net heating value of liquid waste, Btu/lb

NHV_2 = net heating value of solid waste, Btu/lb

HV_{fK} = net heating value of fuel, Btu/lb

n_i = lb ith combustion product/lb feed

T_{out} = desired temperature at the kiln outlet, °F

When no combustion air preheating is employed, this equation simplifies to:

$$-0.95 \left(\frac{n_1 NHV_1 + n_2 NHV_2 + n_{fK} HV_{fK}}{1 + n_{fK}} \right)$$

$$+ \left[\sum_{\substack{i=1 \\ \text{combustion} \\ \text{products} \\ \text{from kiln}}}^{k} n_i \overline{C_{pi}} + 4.31 \overline{C_p} \text{ air} (O_2)_{stoich} EA_k \right] (T_{out} - 77) = 0$$

Using the heat capacities presented in Section 4.3.3.1, and assuming that CO_2, H_2O, N_2, and O_2 are the only significant components of the combustion gas, the equation further simplifies to[a]:

$$-0.95 \left(\frac{n_1 NHV_1 + n_2 NHV_2 + n_{fK} HV_{fK}}{1 + n_{fK}} \right) + \left[0.26 \ n_{CO_2} + n_{N_2} + 0.49 \ n_{H_2O} \right.$$

$$\left. + 1.12 \ (O_2)_{stoich} \right] EA_K \ (T_{out} - 77) = 0$$

---

[a] The term n_{N_2} in this equation relates to the nitrogen present in the combustion gas under stoichiometric conditions. It does not include excess air nitrogen.

Excess air in the afterburner can be estimated in similar fashion, after the desired operating temperature is specified. In this calculation, heat inputs to and from the entire system (kiln and afterburner) are considered. The resulting heat balance equation is shown below.

This equation is also based on assumptions of 5% heat loss from the system and negligible energy input due to waste/auxiliary fuel or air preheating. Worksheet 4-9 presents a step-by-step calculation procedure.

$$
-0.95 \left(\frac{\dfrac{n_1 NHV_1 + n_2 NHV_2 + n_{fK} HV_{fK}}{1 + n_{fK}} + n_{AK} \dfrac{NHV_3 + n_{fA} HV_{fA}}{1 + n_{fA}}}{1 + n_{AK}} \right)
$$

$$
+ \left[\frac{\displaystyle\sum_{\substack{i=1 \\ \text{combustion} \\ \text{products} \\ \text{from kiln}}}^{k} n_{iK}\, \overline{C_{pi}} + n_{AK} \displaystyle\sum_{\substack{i=1 \\ \text{combustion} \\ \text{products} \\ \text{afterburner} \\ \text{feed}}}^{k} n_{iA}\, \overline{C_{pi}}}{1 + n_{AK}} \right] (T_{out} - 77)
$$

$$
+ 4.31\, \overline{C_p}_{air} \left[(O_2)_{stoich(K)} + (O_2)_{stoich(A)} \right] EA\ (T_{out} - 77) = 0
$$

where $(O_2)_{stoich(A)}$ = stoichiometric oxygen requirement for waste and auxiliary fuel fed to the afterburner, lb O_2/lb feed

EA = percent excess air/100(in afterburner)

n_{AK} = lb afterburner feed/lb kiln feed

NHV_3 = net heating value of liquid waste fed to the afterburner, Btu/lb

n_{fA} = lb fuel/lb waste in afterburner

HV_{fA} = heating value of auxiliary fuel burned in the afterburner, Btu/lb

n_{iK} = lb ith combustion product from kiln/lb kiln feed

n_{iA} = lb ith combustion product from afterburner feed/lb afterburner feed

T_{out} = desired afterburner outlet temperature, °F

Once the major components of the combustion gas have been identified (CO_2, H_2O, N_2, and O_2 in most cases), the latter two terms in this equation can be simplified by substituting in the heat capacities reported in Section 4.3.3.1. A similar substitution is shown on the preceding page for the rotary kiln heat balance equation.

4-37

When quantifying the desired temperatures in the kiln and afterburner, it is also important to fix the locations at which these temperatures should be measured. Temperature varies tremendously from one point to another in each unit, being highest in the flame and lowest at the refractory wall or at a point of significant air infiltration (e.g., in the vicinity of secondary air ports, end plate seals, and feed chute). Ideally, temperatures should be measured in the bulk gas flow at a point after which the gas has traversed the volume of each chamber that provides its specified residence time. Temperatures should not be measured at a point of flame impingement or at a point directly in sight of radiation from the flame. Temperature measurement is discussed in more detail in Chapter 5.

An evaluation procedure for temperature/excess air considerations is shown in Table 4-8.

In rotary kiln incineration systems, both the solids retention time in the kiln and the gas residence time in the afterburner must be considered. Afterburner residence time considerations are essentially the same as those for liquid injection incinerators, a topic which is addressed in Section 4.3.3.1. Therefore, the following discussion focuses primarily on solids retention time estimates. For a discussion of gas residence time estimates and corresponding evaluation procedures, see Section 4.3.3.1.

Solids retention times in rotary kilns are a function of the length-to-diameter ratio of the kiln, the slope of the kiln, and its rotational velocity. The functional relationship between these variables is [5]:

$$\theta = 0.19 \ (L/D)/SN$$

where θ = retention time, min
       L = kiln length, ft
       D = kiln diameter, ft
       S = kiln slope, ft/ft
       N = rotational velocity, rpm

This equation can be used for a rough approximation of the retention time.

Typical ranges for the parameters are L/D = 2-10, 0.03-0.09 ft/ft slope, and 1-5 ft/min rotational speed measured at the kiln periphery (which can be converted to rpm by dividing by the kiln circumference measured in ft). Some examples of retention time requirements are 0.5 s for fine propellants, 5 min for wooden boxes, 15 min for refuse, and 60 min for railroad ties [5]. However, the retention time requirements for burnout of any particular solid waste should be determined experimentally or extrapolated from operating experience with similar wastes.

Table 4-9 presents an evaluation procedure for kiln retention time.

In rotary kiln incineration systems, both the degree of air/solids contact in the kiln and gas mixing in the afterburner must be considered. Afterburner mixing considerations are essentially the same as for liquid injection incinerators, a topic which is addressed in Section 4.3.3.1. See Table 4-7 for the afterburner mixing evaluation procedure.

TABLE 4-8. TEMPERATURE/EXCESS AIR EVALUATION PROCEDURE FOR
ROTARY KILN/AFTERBURNER INCINERATORS

1. Identify the proposed kiln and afterburner operating temperatures.

2. Is the kiln temperature sufficient for complete solid waste burnout, assuming that adequate retention time, excess air, and mixing are provided? This determination must be based on operating experience and/or other burn data.

3. Is the afterburner temperature sufficient to complete the combustion reactions, assuming that adequate residence time, excess air, and mixing are provided? See the preceding discussion (Section 4.3.3.2) for general guidelines.

4. Identify the excess primary air rates for each liquid waste burner in the kiln or afterburner.

5. Does this excess air rate meet or exceed the general requirements identified in the preceding discussion and/or burner manufacturer specifications?

6. Identify the total excess air rate for the kiln.

7. Is this excess air rate acceptable? See the preceding discussion guidelines.

8. Independently calculate the maximum total excess air rate needed to maintain the proposed operating temperature in the kiln (see Worksheet 4-8).

9. Is this calculated excess air rate greater than the proposed total excess air rate? (If YES, proceed to checkpoint #12. If NO, proceed to the following checkpoint.)

10. Is this excess air rate acceptable, even though it is less than or comparable to the proposed excess air rate? See the preceding discussion for general guidelines. (If YES, proceed to checkpoint #12. If NO, proceed to the following checkpoint.)

11. Are there any mechanical restraints in the system that would prevent increasing the auxiliary fuel-to-waste firing ratio in the kiln (which would be needed to maintain both an acceptable temperature and excess air rate). In other words, is the maximum achievable fuel-to-waste firing ratio insufficient to maintain an acceptable excess air rate? Repeat the calculations shown in Worksheet 4-8 at this fuel-to-waste ratio, if necessary.

12. Identify the total excess air rate for the system (i.e., in afterburner).

(continued)

4-39

TABLE 4-8 (continued)

13. Is this excess air rate acceptable? See the preceding discussion for general guidelines.

14. Independently calculate the total excess air rate needed to maintain the proposed operating temperature in the afterburner (see Worksheet 4-9). Is the calculated excess air rate greater than or comparable to the proposed total excess air rate? (If YES, proceed to checkpoint #17. If NO, proceed to the following checkpoint.)

15. Is this excess air rate acceptable, even though it is less than the proposed excess air rate? See the preceding discussion for general guidelines. (If YES, proceed to checkpoint #17. If NO, proceed to the following checkpoint.)

16. Are there any mechanical restraints in the system that would prevent increasing the auxiliary fuel-to-waste firing ratio in the afterburner (which would be needed to maintain both an acceptable temperature and excess air rate)? If necessary repeat the calculations shown in Worksheet 4-9 at the maximum achievable fuel-to-waste ratio.

17. Identify the locations at which temperature is to be measured in the kiln and afterburner.

18. Are these locations (a) suitable based on the general guidelines given in the preceding discussion, or (b) comparable to the location at which temperature was measured during a prior similar burn?

TABLE 4-9. KILN RETENTION TIME EVALUATION PROCEDURE

1. Identify the estimated solids retention time in the kiln.

2. Is this retention time acceptable, based on past experience and/or prior burn data?

3. Independently estimate solids retention time in the kiln (see Worksheet 4-10).

4. Does the proposed retention time appear to be achievable?

Air/solids mixing in the kiln is primarily a function of the kiln's rotational velocity, assuming a relatively constant gas flow rate. As rotational velocity is increased, the solids are carried up higher along the kiln wall and

showered down through the air/combustion gas mixture. Typical rotational velocities are in the range of 1-5 ft/min, measured at the kiln periphery.

Since solids retention time is also affected by rotational velocity, there is a tradeoff between retention time and air/solids mixing. Mixing is improved to a point by increased rotational velocity, but the solids retention time is reduced. Mixing is also improved by increasing the excess air rate, but this reduces the kiln operating temperature. Thus, there is a distinct interplay between all four operating variables.

4.3.4 Auxiliary Fuel Capacity Evaluation

4.3.4.1 Liquid Injection Incinerators--

As discussed in Section 4.3.1, liquid injection incinerators should be equipped with an auxiliary fuel firing system to heat the unit to operating temperature before waste is introduced. Although not essential from an engineering standpoint, it is desirable for the auxiliary fuel system to have sufficient capacity to attain this temperature at the design air flow rate for waste combustion. This capacity requirement can be approximated by the following heat balance equation[a]:

$$0.95 \ m_f \ NHV_f = m_f \sum_{i=1}^{k} n_{if} \ \overline{C_{pi}} \ (T_{out} - 77)$$

$$+ \ 4.31 \ m_w \ (O_2)_{stoich(w)} \ (1 + EA) \ \overline{C_p} \ air \ (T_{out} - 77)$$

$$- \ 4.31 \ m_f \ (O_2)_{stoich(f)} \ \overline{C_p} \ air \ (T_{out} - 77)$$

where

m_f = required auxiliary capacity, lb/hr

NHV_f = net heating value of auxiliary fuel, Btu/lb

N_{if} = lb combustion ith product lb fuel

$\overline{C_{pi}}$ = heat capacity of ith component, Btu/lb °F

T_{out} = proposed operating temperature, measured at the incinerator outlet, °F

$4.31(O_2)_{stoich(w)}$ = stoichiometric air requirement for waste combustion, lb air/lb waste

m_w = proposed waste feed rate (average), lb/hr

---

[a]See Section 4.3.3.1 for a discussion of how heat balances are formulated.

$$EA = \text{proposed excess air rate, \%/100}$$

$$4.31(O_2)_{\text{stoich}(f)} = \text{stoichiometric air requirement for fuel combustion,} \\ \text{lb air/lb fuel}$$

This equation is based on these assumptions: (a) air is not preheated, (b) there is a 5% heat loss through the refractory walls, and (c) the air flow rate for normal waste burning operation exceeds the air requirements for fuel combustion during startup.

Since CO_2, H_2O, and N_2 are the only major components of fuel combustion gases at stoichiometric firing conditions, this equation can be further simplified using the heat capacities presented in Section 4.3.3.1 The simplified form is:

$$0.95 \, m_f NHV_f = m_f \left[0.26 \, (n_{CO_2} + n_{N_2} + 0.49 \, n_{H_2O}) \right] (T_{out} - 77)$$

$$+ 1.12 \, m_w \, (O_2)_{\text{stoich}(w)} \, (1 + EA) \, (T_{out} - 77)$$

$$- 1.12 \, m_f \, (O_2)_{\text{stoich}(f)} \, (T_{out} - 77)$$

where n_{CO_2}, n_{N_2}, n_{H_2O}, are based on the stoichiometric air/fuel ratio.

Worksheet 4-11 presents a step-by-step procedure to solve this equation for n_{lf}, the required auxiliary fuel capacity. This value can then be compared to the auxiliary fuel rating of the incinerator.

If this rating is reported in Btu/hr rather than lb/hr, the capacity requirement calculated in Worksheet 4-11 can be converted to equivalent units by:

$$Q_f = m_f \, NHV_f$$

where Q_f = required auxiliary fuel capacity, Btu/hr

4.3.4.2 Rotary Kiln Incinerators--

In rotary kiln incinerators, both the kiln and afterburner need to be heated to operating temperature before waste is introduced. Since the afterburner temperature is usually higher than the kiln temperature and more critical in terms of emissions, it should be sufficient to limit the auxiliary fuel capacity evaluation to the afterburner section. The evaluation procedure described for liquid injection incinerators can be modified for this purpose in the following manner:

- The proposed average waste feed rate (m_w) and stoichiometric air requirement for waste combustion should be based on the combined kiln and afterburner waste feed.

- Temperature (T_{out}) should be specified at the afterburner outlet.

- The excess air rate (EA) used in the calculation should be the proposed excess air level for the afterburner section.

With these modifications, Worksheet 4-11 can be used to estimate the auxiliary fuel startup requirements for rotary kiln incinerators as well as liquid injection units.

4.3.5 Combustion Process Control and Safety Shutdown System Evaluation

All incinerators should be equipped with combustion process control systems to maintain the desired conditions of temperature and excess air. Incinerators burning hazardous wastes should also be equipped with automatic shutdown systems in order to prevent the release of hazardous materials to the environment in the event of flameout, other combustion process upsets, or air pollution control device failure. The following subsections discuss combustion process control and automatic shutdown procedures related to upsets in liquid injection and rotary kiln incinerators. Process control procedures for air pollution control devices are discussed in Section 4.4.5.

4.3.5.1 Liquid Injection Incinerators--
In most liquid injection incinerator designs, the desired temperature at the chamber outlet is preset by the operator, and secondary air is fed to the system at a constant rate. Fluctuations in temperature are controlled by increasing or reducing the waste or auxiliary fuel feed rate to the burner within the design turndown ratio. This turndown ratio is fixed, in part, by the limited range of liquid waste injection velocities required to prevent flame liftoff or flashback. If waste is injected through the burner nozzle at too high a velocity, the flame will separate from the burner and be extinguished. If the injection velocity is too low, the waste will burn in the nozzle and damage it. The range of injection velocities needed to prevent these occurrences is determined by the flame propagation rate for the wastes and the flame retention characteristics of the burner.

Since the burner turndown ratio is also limited by the atomization technique employed (see Section 4.3.1) and the need to maintain air/fuel stoichiometry in the burner on turndown, the burner must be equipped with a primary air feed control system. There are a number of ways to control burner stoichiometry, depending on whether aspirator burners or forced-draft burners are used and on manufacturer preference.[a] For evaluation purposes, a package burner/primary air control system provided by the same manufacturer can be considered sufficient.

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[a]In aspirator burners, primary air is supplied by an induced-draft fan downstream from the incinerator. In forced-draft burners, primary air is supplied by a separate blower, although an induced-draft fan may still be employed to pull the combustion gases through the air pollution control system.

Problems with the automatic temperature control system described above occur on loss of ignition, or flameout. When flameout occurs, the temperature in the incinerator drops and more waste is automatically fed to the burner. Without a heat source for ignition, this waste passes through the incinerator partially or completely unreacted. Thus, temperature continues to drop, more waste is automatically injected, and the problem of incomplete combustion is magnified.

To prevent this phenomenon from occurring, burners are usually equipped with flame scanners. These devices sense ultraviolet radiation from the flame. When used in conjunction with an automatic waste feed cutoff, flame scanners immediately terminate the feed to the burner on loss of ignition.

Flame scanners are usually designed to sense ultraviolet radiation from gas or fuel oil flames. These flames tend to be more stable than the flames from burning wastes which are usually much more heterogeneous than fuels. For example, organic wastes containing a significant amount of moisture burn with a sputtering flame, particularly when a slug of water passes through the burner. Although combustion may continue despite such occurrences, flame scanners often sense loss of ignition. This leads to unnecessary waste feed cutoff.

To prevent unnecessary shutdown, flame scanners can be used in conjunction with temperature sensors at the outlet of the incinerator. With this system, feed is only cut off by a combination of flameout, as sensed by the flame scanner, and low temperature at the combustion chamber. This considerably reduces operator problems when relatively heterogeneous wastes are being burned. If the low temperature cutoff is preset to the minimum temperature needed for waste destruction, release of hazardous substances to the environment is also prevented.

The other automatic shutdown parameter related to the combustion process is high temperature at the incinerator outlet. This can signal loss of secondary combustion air or other control system malfunctions. The high temperature cutoff point should be well above the tolerance level associated with normal operating temperature fluctuations to prevent shutdown in the event of routine variations, and should be low enough to prevent damage to downstream air pollution control equipment.

Table 4-10 lists three checkpoints for liquid injection incinerator combustion process control evaluation.

4.3.5.2 <u>Rotary Kiln Incinerators</u>--
In rotary kiln incinerators, temperature is controlled within a specified range by automatically varying the liquid waste or auxiliary fuel firing rate within the design turndown ratio and/or manually or automatically controlling the solid waste feed. Regardless of which technique is employed, provisions should be included for the following:

- Termination of liquid waste feed on loss of ignition in the burner. If more than one liquid waste burner is employed, feed only needs to be terminated in the burner where flameout occurs. See Section 4.3.5.1 for a discussion of flame supervision systems.

- Termination of solid waste feed to the kiln when low temperatures are sensed at the kiln outlet. If the feed to the kiln is automatic or semiautomatic, then the low temperature cutoff system should also be automatic. If manual feeding is employed, an alarm system is needed to warn the operator. The low temperature cutoff point should be such that solid waste burnout can be maintained, but at lower than the normal operating temperature to avoid shutdown due to routine temperature fluctuations. Engineering judgment must be used to determine an acceptable minimum temperature.

- Termination of solid waste feed on loss of negative pressure at the kiln outlet.

TABLE 4-10. COMBUSTION PROCESS CONTROL EVALUATION PROCEDURE

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1. Is each burner equipped with an automatic flame supervision system, as discussed in the preceding subsection, (Section 4.3.5.1)?

2. Is the system equipped with an automatic high temperature/low temperature control system, employing variable flow of either waste or auxiliary fuel?

3. Is each burner equipped with an air supply control system so that air: fuel stoichiometry is maintained on turndown?

Afterburner burner temperature can be controlled by varying the liquid or auxiliary fuel feed or by varying the secondary air flow rate. Regardless of which technique is employed, provisions should be included for the following:

- Termination of liquid waste or auxiliary fuel feed on loss of ignition (see Section 4.3.5.1 for a discussion of flame supervision). This cutoff is necessary to prevent the release of unburned waste contaminants (if liquid waste is being burned) and to prevent potential explosion on release of unburned fuel. However, it also eliminates the function of the afterburner. Therefore, solid waste feed to the kiln should also be terminated on loss of ignition in the afterburner. To minimize the occurrence of flameout in the afterburner, only "clean," homogeneous liquid wastes (or fuel) should be burned.

- Termination of solid waste feed to the kiln if low temperatures are sensed at the afterburner outlet. The afterburner feed should be maintained, however, to minimize potential release of unburned contaminants. As previously stated, the low temperature cutoff point should be such that combustion is maintained, but at lower than normal operating temperatures to avoid shutdown due to routine fluctuations.

- Termination of solid waste feed to the kiln if high temperatures are sensed at the afterburner outlet. This is necessary to prevent damage to

the refractory lining and to downstream air pollution control devices. The high temperature cutoff point should be well above normal operating temperatures, but low enough to avoid damage to the system. In the event of this cutoff, some liquid waste or fuel feed to the afterburner should be maintained to complete combustion of off-gases from solid wastes remaining in the kiln.

In addition to these criteria, all liquid waste burners in the kiln and afterburner should be equipped with manufacturer specified primary air control systems so that air/fuel stoichiometry is maintained on turndown.

Table 4-11 presents a five-point checklist for rotary kiln incinerator combustion process control evaluation.

TABLE 4-11. COMBUSTION PROCESS CONTROL EVALUATION PROCEDURE

1. Is each burner in the kiln and afterburner equipped with an automatic flame supervision system for waste feed shutdown?

2. Is the afterburner equipped with an automatic high temperature/low temperature control system employing variable flow of waste, auxiliary fuel, or secondary combustion air?

3. Is the kiln equipped with an automatic temperature control system employing variable feed of either waste or auxiliary fuel?

4. Is the kiln equipped with a pressure monitoring system which alerts the operator or automatically terminates waste feed if negative pressure is lost?

5. Is each burner equipped with an air supply control system so that air:fuel stoichiometry is maintained on turndown?

4.3.6 Construction Material Evaluation

Since hazardous waste incinerators usually operate at temperatures of 1,800°F or higher (sometimes hundreds of degrees higher for halogenated wastes), refractory linings are virtually always employed to prevent damage to the structural steel shell and to reduce heat loss. Aluminosilicate refractories backed up by insulating brick are most commonly used, although refractories made predominantly of silica or specialty refractories may be used in certain applications. Table 4-12 lists various types of aluminosilicate and silica refractories[a] along with their approximate chemical compositions, fusion

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[a]See references listed in Table 4-12 for information on specialty refractions.

temperatures, and resistances to degradation by different chemical species that may be encountered in incinerator combustion gases.

Table 4-12, along with the operating temperature range and the chemical composition of the waste, can be used to evaluate the suitability of a refractory for a given application.

In addition to refractory composition, the physical form of the material should also be considered in evaluating liquid injection vs. rotary kiln incinerator designs. Suspended refractory brick is normally used in stationary liquid injection units and afterburners. In kilns, however, castable refractories are normally used to better withstand the physical abrasion and vibration imparted by rotation and contact with solid wastes. Castable refractories are made of the same clays as those used in aluminosilicate firebrick, but bonding agents are added to impart strength until the temperature in the incinerator during initial startup is raised sufficiently high to "cure" the material and develop ceramic bonds. Castable refractories are easily installed in much the same manner as cement; thus, they are also used for quick repairs and spot patching.

4.4 AIR POLLUTION CONTROL AND GAS HANDLING SYSTEM DESIGN EVALUATION

Figure 4-11 presents a logic diagram for air pollution control and gas handling system design evaluation. It consists of six separate evaluation procedures intended to answer the following questions:

(1) Are the generic air pollution control device designs appropriate for removal of the pollutants present in the combustion gases?

(2) Are the air pollution control device designs and operating criteria consistent with current industry practice and capable of achieving the necessary pollutant removal efficiencies?

(3) Have combustion gas quenching and mist elimination been properly considered in the system design?

(4) Does the prime mover have sufficient capacity to handle the combustion gas flow and overcome pressure drops across the air pollution control system?

(5) Are appropriate process control and safety shutdown interlocks incorporated?

(6) Are appropriate materials of construction employed?

These topics are addressed in Sections 4.4.1 through 4.4.6

4.4.1 Emission/Air Pollution Control Device Matching Criteria

When incinerating hazardous wastes, air pollutants may arise from two sources: incomplete combustion of organic waste constituents and conversion of certain inorganic constituents present in the waste and/or combustion air to ultimate

TABLE 4-12. GENERAL CHARACTERISTICS OF SILICA AND ALUMINO-
SILICATE REFRACTORY BRICK [6, 7, 8, 9, 10]

Type	Typical composition	Fusion temperature, °F[a]	Resistant to	Degraded by
Silica	95% SiO_2	3,100	HCl, NH_3, acid slags	Basic slags, Al, Na, Mg, F_2, Cl_2, H_2, (>2,550°F)
High-duty fireclay	54% SiO_2, 40% Al_2O_3	3,125	Most acids, slag conditions	High-lime slags, other bases at high temperature
Super-duty fireclay	52% SiO_2, 42% Al_2O_3	3,170	HCl, NH_3, SO_2, most acids	Basic slags, Na, Mg, F_2, Cl_2, H_2, (>2,550°F)
Acid-resistant (type H)	59% SiO_2	3,040	Excellent for most acids; bases in moderate concentration	HF, H_3PO_4
High-Alumina	50-85% Al_2O_3	3,200-3,400	HCl, NH_3, SO_2	Basic slags, Na, Mg, F_2, Cl_2, H_2 (>2,550°F)
Extra-High-Alumina	90-99% Al_2O_3	3,000-3,650	HCl, HF, NH_3, SO_2, S_2, HNO_3, H_2SO_4, Cl_2	Na, F_2 (>1,800°F)
Mullite	71% Al_2O_3	3,290	HCl, SO_2, NH_3	Na, F_2, Cl_2, H_2 (>2,550°F)

[a]A safety factor of at least several hundred degrees between refractory fusion
temperature and incinerator operating temperature is advisable.
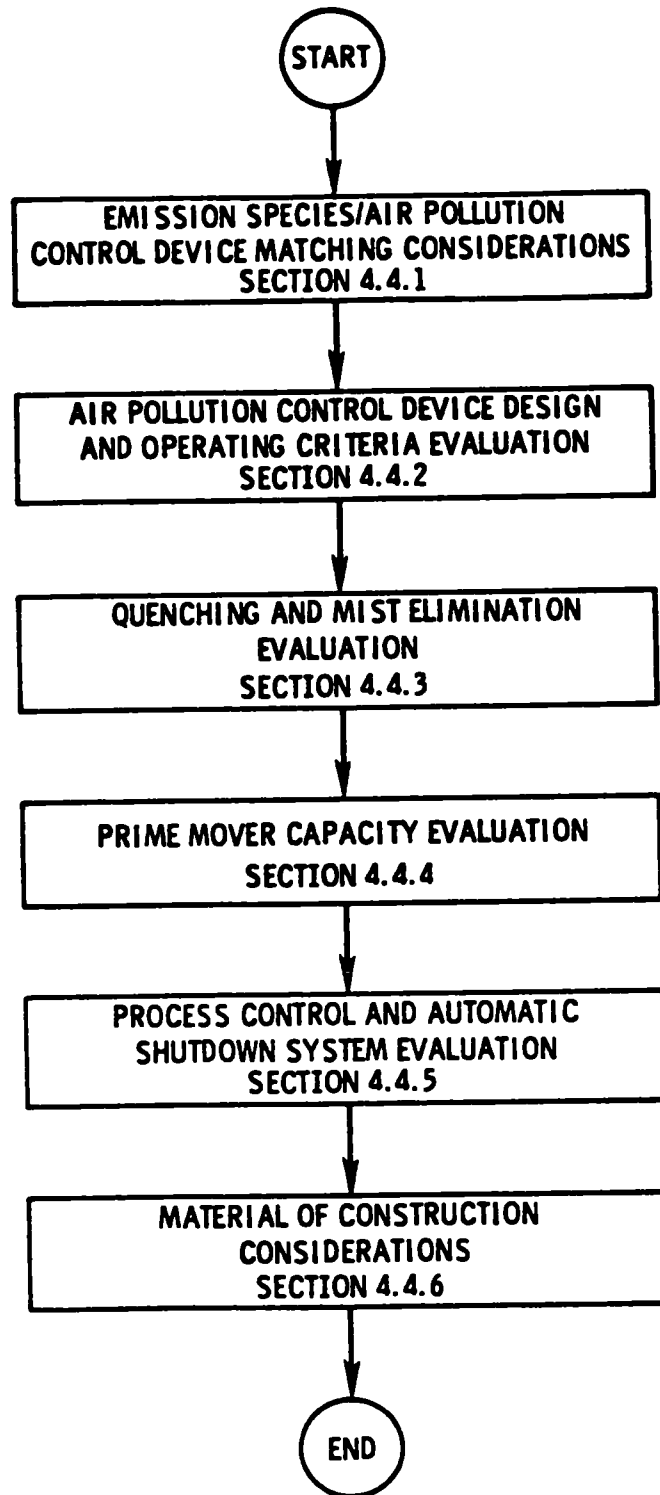
Figure 4-11. Logic diagram for air pollution control and gas handling system design.

oxidation products. The products of incomplete combustion include carbon monoxide, carbon, hydrocarbons, aldehydes, amines, organic acids, polycyclic organic matter (POM), and any other waste constituents or their partially degraded products that escape thermal destruction in the incinerator. In well designed and operated incinerators, however, these incomplete combustion products are only emitted in insignificant amounts. The primary end products of combustion are, in most cases, carbon dioxide (CO_2) and water vapor (H_2O).

When wastes containing elements other than carbon, hydrogen, and oxygen are burned, however, ultimate combustion products other than CO_2 and water vapor are formed. These include:

- Hydrogen chloride (HCl) and small amounts of chlorine (Cl_2) from the incineration of chlorinated hydrocarbons,

- Hydrogen fluoride (HF) from the incineration of organic fluorides,

- Bromine (Br_2) and lesser quantities of hydrogen bromide (HBr) when organic bromides are burned,

- Iodine (I_2) from organic iodide compound incineration,

- Sulfur oxides, mostly as sulfur dioxide (SO_2), but also including 1% to 5% sulfur trioxide (SO_3), formed from sulfur present in the waste material and auxiliary fuel,

- Phosphorus pentoxide (P_2O_5), formed from the incineration of organophosphorus compounds,

- Nitrogen oxides (NO_x) from thermal fixation of nitrogen in the combustion air or from organic nitrogen compounds present in the waste, and

- Particulates, including metal salts from the waste, metal oxides formed by combustion, and fragments of incompletely burned material (primarily carbon).

Gaseous pollutant concentrations in the combustion gases leaving an incinerator can be estimated by the methods described in Section 4.3.2[a]. Step-by-step procedures for calculating these concentrations are presented in Worksheets 4-2 and 4-4. Particulate emissions from liquid injection incinerators can also be estimated from the ash content of the waste, the combustion gas flow rate corrected to standard conditions of temperature and pressure (see Worksheet 4-2), and the oxygen content of the combustion gas. Oxygen concentration is important because particulate loadings are often expressed as gr/scf (mg/m^3) corrected to zero percent excess air. A procedure to estimate particulate concentrations in combustion gases from liquid injection incinerators is presented in Worksheet 4-12. Particulate emissions from rotary kilns are more difficult to estimate because sizable fractions of incombustible material are removed as bottom ash, and the fly ash:bottom ash

[a]These procedures are not applicable for products of incomplete combustion.

ratio is usually unknown prior to actual testing. In general, particulate emissions from rotary kilns burning solid wastes are greater than particulate emissions from liquid injection incinerators. This is due to the fact that solid wastes frequently have a higher ash content than liquid wastes.

As indicated in Section 4.1, venturi scrubbers, packed bed scrubbers, and plate tower scrubbers are used for air pollution control at the majority of hazardous waste incineration facilities. In selecting from among these generic scrubber designs, the factors most frequently considered are the need for particulate emission control, particulate loading in the combustion gas (assuming that control is required to meet emission standards), the types of gaseous pollutants to be removed, and the desired removal efficiencies. Particulate loading governs the choice between venturi and packed bed or plate tower scrubbers for a given application, and the characteristics of the gaseous emission species govern the choice of scrubber medium (e.g., water vs. caustic solution, lime solution, etc.) as well as generic scrubber design.

These factors are discussed in the following subsections.

4.4.1.1 Particulate Removal--

Particulate removal is required when the ash content of the waste is such that emissions will exceed applicable state, local, or Federal standards. Particulate removal is nearly always required at rotary kiln incineration facilities, and may or may not be required for liquid injection incinerators depending on the ash content of the waste. (See Worksheet 4-12 for a method to estimate particulate emissions from liquid incinerators). Venturi, packed bed, and plate tower scrubbers can all be used to control particulate emissions from hazardous waste incinerators, depending on the particulate loading in the gas. Packed bed or plate tower scrubbers are commonly used at liquid injection incinerator facilities where particulate control is considered secondary to gaseous emission control. These devices are superior to venturi scrubbers for removal of gaseous pollutants and they operate at lower pressure drops; thus they are more economical to operate. Both the plate tower and the packed bed scrubber have some capacity for particle collection, and they are considered applicable for streams containing low particulate loadings with particles generally >5 μm in diameter [11]. Cut diameters as low as 1 μm can be attained with plate scrubbers or packed bed scrubbers employing 1-inch berl saddles or Raschig rings [12]. However, packed bed and plate tower scrubbers are not primarily designed for particulate control. Both devices, particularly packed bed scrubbers, are susceptible to pluggage by solids. Therefore, they are seldom, if ever, used as the primary particulate collection devices at rotary kiln incineration facilities or liquid injecton incineration facilities where high ash content wastes are burned. Venturi scrubbers are the most popular devices for these applications.

High energy venturi scrubbers are capable of 99% removal of particulate in the 1- to 2-μm size range and above, 90-99% removal of particulate in the 0.5 - to 1-μm size range, and 50% removal of particulate in the 0.3- to 0.5-μm size range [13]. By comparison, particulates emitted from liquid and solid waste incinerators have mean diameters in the 0.5- to 3-μm and 5- to 100-μm ranges, respectively. Therefore, venturi scrubbers are capable of efficient particulate removal for most hazardous waste incineration applications.

Table 4-13 presents a checklist procedure that can be used to compare particulate removal requirements with proposed control strategies.

TABLE 4-13. PROCEDURE TO COMPARE PARTICULATE REMOVAL
REQUIREMENTS WITH PROPOSED CONTROL STRATEGIES

1. If a rotary kiln incinerator facility is being evaluated, is a venturi scrubber provided for particulate control?

2. If a liquid injection incinerator facility is being evaluated, does the estimated particulate emission rate exceed applicable standards? See Worksheet 4-12 for a procedure to estimate particulate emissions.

3. If particulate emissions do exceed standards, is a venturi scrubber provided for particulate removal (upstream from other gaseous emission control devices)?

4. If not, are packed bed or plate tower scrubbers to be used for simultaneous particulate and gaseous pollutant removal?

5. If so, can the selected control device function properly in its dual role? (Technical assistance may be needed to make this determination).

4.4.1.2 Gaseous Pollutant Removal--

Gaseous pollutants generated by hazardous waste incineration include HCl, Cl_2, SO_x, Br_2, HBr, HF, P_2O_5 and NO_x, of which NO_x and HCl are most commonly encountered.[a,b,c] These compounds are usually removed from the combustion gases by packed bed or plate tower scrubbers, although venturi scrubbers are used in some applications for simultaneous particulate and gaseous pollutant removal. For highly soluble gases such as HCl and HF, water can be used in packed bed or plate tower scrubbers to control emissions. When water is used as the scrubbing liquor, an acidic blowdown stream is produced that must be neutralized prior to discharge. HCl concentration in the scrubbing liquor is normally limited to 1-2% by adjusting the makeup water and blowdown rates. The

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[a] NO_x emissions are not economically amenable to control by scrubbing or other post-generation removal techniques. NO_x emissions can be minimized by controlled temperature combustion, but this is seldom possible in hazardous waste incineration due to the requirements for efficient, high temperature waste destruction.

[b] I_2 and HI emissions may be an occasional problem as well.

[c] Cl_2 is present in conjuncton with HCl, but equilibrium favors HCl formation at the high temperatures employed in chlorinated waste incinerators. Cl_2 and the other free halogens are not readily removed by scrubbing.

4-52

scrubber must also be lined with an acid-resistant material, as discussed in Section 4.4.6.

Caustic solution (typically 18-20 wt % caustic soda in water) is also commonly used in packed bed and plate tower scrubbers to control HCl and HF emissions. Because these compounds react with caustic, the driving force for mass transfer is increased and more efficient removal is achieved at the same liquid-to-gas ratio and packing depth (or number of trays). Neutralization is also achieved "in situ" if sufficient caustic is supplied for complete conversion of HCl to NaCl. Unlike water scrubbing, caustic scrubbing can also achieve high removal efficiencies for SO_2, P_2O_5, and HBr, which are less soluble in water than HCl or HF. When gases such as SO_2 are being scrubbed, the caustic addition rate is adjusted to maintain an alkaline scrubbing media. Alternatively, the caustic addition rate can be adjusted to sub-stoichiometric levels. This reduces the scrubber water makeup and blowdown rates needed to maintain a specified acid concentration in the scrubber liquor.

Lime slurry, typically 10-32 wt % $Ca(OH)_2$ in water, can also be used to control emissions of HCl, HF, SO_2, and P_2O_5. However, lime slurries are not often used as the scrubbing liquid in packed bed designs because of plugging problems. Also, the use of lime slurries can lead to plugging of the spray nozzles and cause scale formation on the surfaces of the scrubber equipment, particularly scrubber internals and mist eliminator surfaces. The magnitude of the scaling problem will depend on the levels of HCl, HF, P_2O_5, and SO_x in the incinerator exhaust gases. Lime solutions are used in plate tower scrubbers, however, because lime is less expensive than caustic. At several hazardous waste incineration facilities, venturi scrubbers with lime slurry injection are used to control emissions of HCl, HF, and P_2O_5.

When organic bromine and iodine wastes are incinerated, the exhaust gases from the incinerator will contain bromine and iodine both as hydrogen halides and as free halogens. Hydrogen bromide can be readily removed by scrubbing with caustic soda. The technology for controlling emissions of bromine, hydrogen iodide, and iodine, however, is not well developed. Some of the methods that could be considered to control bromine emissions include: (1) absorption in ammonia solution with the formation of ammonia bromide; (2) absorption in caustic soda or soda ash solution in which bromine reacts to form sodium bromate, sodium bromide, and either water or carbon dioxide; and (3) absorption in lime slurry in which bromine reacts to form calcium bromide and calcium bromate. It is also conceivable that bromine can be reduced by the sulfur dioxide present in the flue gas, giving rise to the formation of a spray of fine droplets of hydrobromic and sulfuric acids, which could subsequently be removed by absorption in caustic solutions or lime slurries.

When combustion gases contain a high particulate loading as well as one or more of the gaseous pollutants discussed above, venturi scrubbers are often used in conjunction with packed bed or plate tower scrubbers. Venturi scrubbers remove the particulate from the stream to prevent fouling of the packed bed or plate tower absorber, and may also remove a significant fraction of gases highly soluble in water. However, venturi scrubbers alone are not considered suitable for removal of low solubility gases; when water is used as the scrubbing medium, estimated efficiencies are less than 50-75% [11].

Venturi scrubbers using water are not suitable for highly efficient (>99%) removal of HCl or HF either.

Table 4-14 presents a checklist procedure that can be used to compare gaseous pollutant removal requirements with proposed control strategies. The following rules of thumb are generally applicable:

- Water, caustic, or lime in packed bed or plate tower scrubbers for removal of HCl and/or HF,

- Caustic or lime in packed bed or plate tower scrubbers for removal of other acid gases discussed above, and

- Specialized scrubbing techniques for HBr, Br_2, HI, and I_2. Technical assistance is advised in evaluating these systems.

TABLE 4-14. PROCEDURE TO COMPARE GASEOUS POLLUTANT REMOVAL
REQUIREMENTS WITH PROPOSED CONTROL STRATEGIES

1. From Worksheet 4-2 or 4-4, identify the gaseous pollutants present in the combustion gases in excess of desired emission levels.

2. Is removal of Br_2, HBr, I_2, or HI required? If YES, technical assistance may be required.

3. Is removal of SO_x or P_2O_5 required? If YES, proceed to checkpoint #4.
   If NO, proceed to checkpoint #5.

4. Is caustic or lime slurry scrubbing to be used for SO_x/P_2O_5 removal, as described in the preceding pages? (Water scrubbing alone is usually not sufficient to remove these compounds).

5. Is removal of HCl or HF required?

6. Is alkali or aqueous scrubbing in a packed bed or plate tower scrubber, or alkali scrubbing in a venturi scrubber, to be used for HCl/HF removal?

7. If not, are other methods for HCl/HF removal provided?

8. If so, are these methods acceptable? (Technical assistance may be needed to make this determination).

4.4.2 Air Pollution Control Device Design and Operating Criteria Evaluation

4.4.2.1 Venturi Scrubbers--
Venturi scrubbers utilize the kinetic energy of a moving gas stream to atomize the scrubbing liquid into droplets. Liquid is injected into the high velocity

gas stream either at the inlet to the converging section or at the venturi
throat. In the process, the liquid is atomized by the formation and subse-
quent shattering of attenuated, twisted filaments and thin, cuplike films.
These initial filaments and films have extremely large surface areas available
for mass transfer [14].

Venturi scrubbers are usually designed for particulate collection, but they
can be used for simultaneous gas absorption as well. However, the design of
venturi scrubbers for removal of gaseous contaminants is dependent on the
availability of applicable experimental data. There is no satisfactory gener-
alized design correlation for these types of scrubbers, especially when
absorption with chemical reaction is involved. Reliable design must be based
on full-scale data or at least laboratory- or pilot-scale data.

Correlations are available to design venturi scrubbers for particulate removal.
The important design parameters are particulate loading and desired removal
efficiency, particle size distribution, pressure drop, liquid-to-gas ratio,
and gas velocity.

Particulate loading, size distribution, and removal efficiency--If the partic-
ulate size distribution and desired removal efficiency are known, several
correlations can be used to predict the required cut diameter for design
purposes. Calvert et al. [15] have developed parametric plots of overall
penetration versus the ratio of cut diameter to mass median diameter with
geometric standard deviation as the third parameter. These plots can be used
to determine the required cut diameter if the desired removal efficiency and
particle size distribution are known. Cut diameter can then be related to
pressure drop, liquid-to-gas ratio, and gas velocity for design purposes as
described in the following subsection.

Hesketh [16] has also developed an empirical relationship between penetration
of all particles 5 µm or less in diameter and the pressure drop across
venturis based on data from the collection of a variety of industrial dusts.
Assuming that particles larger than 5 µm are collected with 100% efficiency,
this relationship may be utilized with size distribution data to estimate
overall penetration:

$$Pt = 0.065W(\Delta P)^{-1.43}$$

where Pt = fractional penetration
       W = the weight fraction of inlet particles 5 µm or less in diameter
       ΔP = pressure drop, in. WG

The major drawback in applying these correlations to venturi scrubber design
evaluation is that the particle size distribution will rarely be known until
testing is performed after startup. The size distribution of particles emit-
ted from an incinerator depends upon the relative number of particles genera-
ted by several factors responsible for the formation of particulate emissions:
(1) mechanical entrainment of combustible and noncombustible particles in the
furnace gases, (2) pyrolysis of hydrocarbons and subsequent condensation, and
(3) volatilization of metallic salts and oxides present in the wastes and
auxiliary fuels. Further, particle growth due to agglomeration and

condensation of moisture between the incinerator and the control device will affect the particle size distribution. There is no method for the a priori prediction of particle size distributions resulting from waste incineration. While incineration of liquid wastes may result in mean particle diameters in the 0.5- to 3-µm range, mean particle diameters resulting from incineration of solid waste could range from 5 to 100 µm, depending upon the size distribution of feed solids, their combustion characteristics, and the incinerator design. If particle size distribution data is available, methods described in references 15 or 16 can be used to determine the required cut diameter.

Pressure drop, liquid-to-gas ratio, and gas velocity--As described above, particle cut diameter is a frequently used parameter for expressing and determining the particle collection performance of wet scrubbers. One reason for this is because plots of collection efficiency versus particle diameter tend to be rather steep in the region where inertial impaction is the predominant collection mechanism. Because the cut is fairly sharp for venturi scrubbers, a rough approximation of scrubber performance may be made by assuming that particles larger than the cut diameter are collected with 100% efficiency while those smaller will not be collected. A plot of cut diameter versus pressure drop for gas-atomized scrubbers is presented in Figure 4-12 [12]. The plot is based on industrial and experimental data as well as mathematical models, and can be used in conjunction with the methods developed by Calvert et al. [15] to estimate penetration as a function of pressure drop.

Available data indicate that venturis at hazardous waste incineration facilities operate with pressure drops in the 30- to 50-in. WG range. Based on Figure 4-12, this indicates that venturi scrubbers at these facilities are designed for 0.3- to 0.4-µm cut diameters.

Pressure drop in venturi scrubbers is theoretically related to gas velocity and liquid-to-gas ratio, as shown in the following relation developed by Calvert [15]. This relationship assumes that all energy is used to accelerate the liquid droplets to the throat velocity of the gas.

$$\Delta P = 2.12 \times 10^{-5}(U_G)^2 \frac{Q_L}{Q_G}$$

where ΔP = pressure drop, in. WG

U_G = gas velocity, ft/s

Q_L/Q_G = liquid-to-gas ratio, gal/1,000 ft^3

An alternative empirical approach by Hesketh [16] indicates that the pressure drop for venturis is proportional to $U_G{}^2$ and $(Q_L/Q_G)^{0.78}$, as well as to the gas density ρ_G (measured downstream from the venturi throat) and to $A^{0.133}$, where A is the cross-sectional area of the venturi throat:

$$\Delta P = \frac{(U_G)^2 \rho_G A^{0.133} \left(\dfrac{Q_L}{Q_G} \right)^{0.78}}{1270}$$

4-56
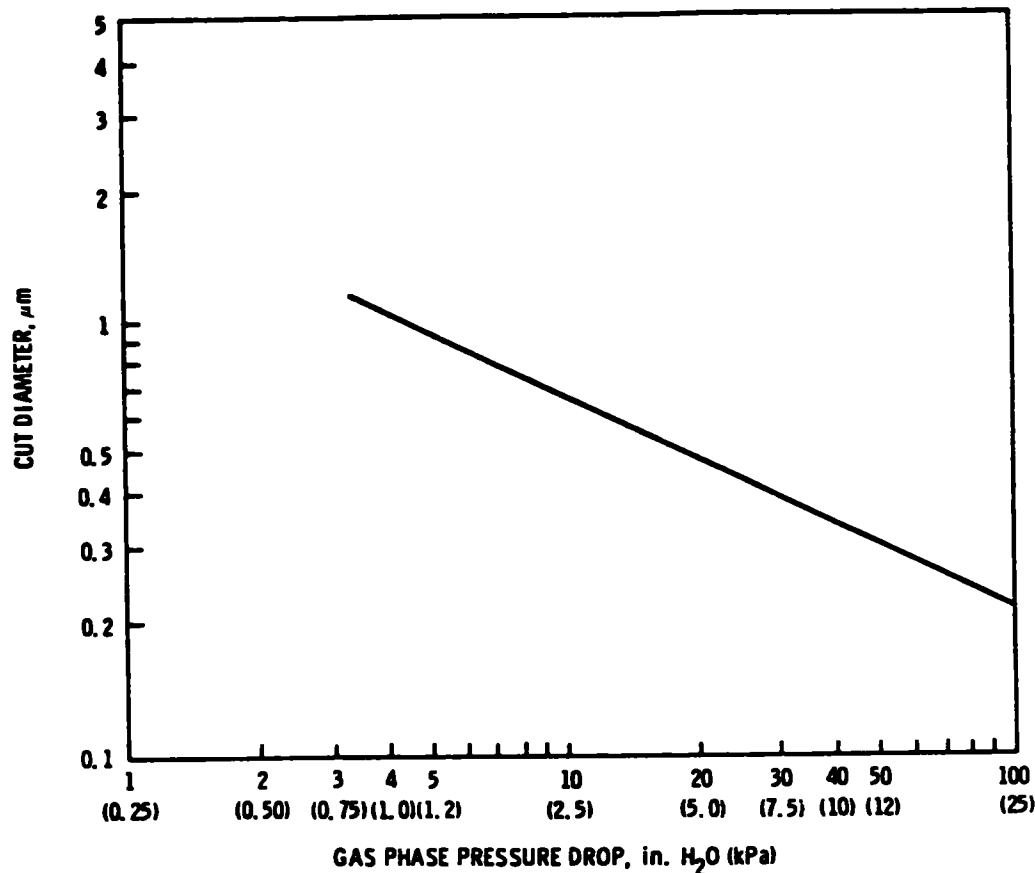
Figure 4-12.   Pressure drop versus cut diameter for gas-atomized scrubber
systems (Experimental data from large venturis, other gas-
atomizers, scrubbers, and mathematical model.) [12].

Pressure drop will be relatively unsensitive to changes in A because of the
small exponent, but density will be inversely proportional to the gas tempera-
ture.   These relationships can be used as internal consistency checks for the
proposed conditions of gas velocity, liquid-to-gas ratio, and pressure drop.

Liquid-to-gas ratios for venturi scrubbers are usually in the range of 5 to 20
gal/1,000 ft^3 of gas.   At existing hazardous waste incineration facilities,
liquid-to-gas ratios ranging from 7 to 45 gal/1,000 ft^3 of gas have been
reported.   In many cases, a minimum ratio of 7.5 gal/1,000 ft^3 is needed to
ensure that adequate liquid is supplied to provide good gas sweeping.   Gas
velocity data are not available at this time for venturi scrubbers operating
at hazardous waste incineration facilities.   Typical venturi throat velocities
for other applications, however, are in the 100- to 400-ft/s range.   The low
end of this range, 100-150 ft/s, is typical of power plant applications, while
the upper end of the range has been applied to lime kilns and blast furnaces.

Table 4-15 presents a procedure that can be used to evaluate proposed design
and operating criteria for venturi scrubbers.

TABLE 4-15. VENTURI SCRUBBER DESIGN EVALUATION PROCEDURE

1. Is the design pressure drop comparable to current industry practice
    (i.e., 30-50 in. WG)?

2. Are the proposed gas velocity and liquid-to-gas ratio comparable to
    current industry practice?

3. Are the design pressure drop, gas velocity, and liquid-to-gas ratio
    internally consistent? (see Worksheet 4-13.)

4.4.2.2 Packed Bed Scrubbers--
As described in Chapter 2, packed bed scrubbers are vessels filled with ran-
domly oriented packing material such as saddles and rings. The scrubbing
liquid is fed to the top of the vessel, with the gas flowing in either cocur-
rent, countercurrent, or crossflow modes. As the liquid flows through the
bed, it wets the packing material and thus provides interfacial surface area
for mass transfer with the gas phase. Water and caustic solution are both
commonly used as the liquid absorbent.

In the absorption of gaseous contaminants, the rate of mass transfer is direc-
tly proportional to the concentration gradient driving force, and restricted
by both gas and liquid film resistances. The primary design variables for gas
absorption are the depth of packing, liquid-to-gas ratio, superficial gas
velocity, and contact time. Pressure drop across the bed is also an important
design consideration, but does not directly affect absorption efficiency.
Packed bed scrubbers can be used for limited particulate collection as well as
gas absorption, but, as explained in Section 4.4.1, they are not primarily
designed for this purpose.

Packing depth--The depth of packing required is best calculated from the
following expression [6]:

$$Z = N_{OG} \times H_{OG}$$

where Z is the packing depth, N_{OG} is the number of overall transfer units, and
H_{OG} is the height of a transfer unit.

The number of transfer units depends on the removal efficiency requirement.
In gaseous emission control for hazardous waste incineration, the gaseous
contaminants to be removed usually constitute less than 10% of the total gas
stream because of the presence of nitrogen, oxygen, carbon dioxide, and water
vapor as the major gaseous components. Under these circumstances, the number
of transfer units can be calculated from the expression [6]:

$$N_{OG} = \int_{Y_2}^{Y_1} \frac{dY}{Y - Y_e}$$

where Y is the actual gas concentration of the contaminant, Y_2 is the concentration at the scrubber outlet, Y_1 is the concentration at the inlet, and Y_e is the gas concentration of the contaminant in equilibrium with the scrubbing liquid. In industrial applications, the gaseous contaminant is often very soluble in the scrubbing liquid, as is the case of hydrogen chloride in water, or reacts very rapidly with the scrubbing liquid, as is the case of hydrogen chloride with caustic solution. For both of these cases, the equilibrium gas concentration is negligible and the number of transfer units can be calculated as:

$$N_{OG} = \ln\left(\frac{Y_1}{Y_2}\right)$$

where Y_1 and Y_2 are the inlet and outlet concentrations of the gaseous contaminant.

The height of a transfer unit is a characteristic of the particular system, and is influenced by the type and size of packing, gas and liquid flow rates, and gas and liquid physical and chemical properties. It is often taken as a constant over fixed ranges of operation and is given by the expression [6]:

$$H_{OG} = \frac{G}{K_g aP}$$

where G is the total gas flow rate per unit cross section of bed, K_g is the overall gas mass transfer coefficient, a is the interfacial surface area per unit volume of packing, and P is the total pressure. Values of $K_g a$ for many of the more commonly used gas absorption processes have been published in the literature [17,18]. Typical values of $K_g a$ are given in Table 4-16. For gaseous contaminants that are highly soluble or chemically reactive with the scrubbing liquid, the height of a transfer unit H_{OG} is typically in the 1 to 1.7-ft range.

The transfer unit concept can be used to calculate packing depth requirements if overall gas mass transfer coefficients are available. For quicker estimates, however, other methods can be used. In Table 4-17, the estimated depths of packing beds required are given for various removal efficiencies of gaseous contaminants that are highly soluble or chemically reactive with the scrubbing liquid. These estimated packing depth requirements are based on the general rule that 1 in. size packings yield an H_{OG} (height of a transfer unit) equal to 1 ft, 1-1/2 in. size packings yield an H_{OG} equal to 1.3 ft, and 2 in. size packings yield an H_{OG} equal to 1.5 ft [11].

TABLE 4-16. TYPICAL VALUES OF $K_g a$ [18]

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Gas	Scrubbing solution	$\dfrac{\text{lb mole}}{\text{in. } H_2O \cdot ft^3 \cdot s}$
Cl_2	NaOH	1.4×10^{-5}
HCl	H_2O	1.1×10^{-5}
SO_2	NaOH	4.8×10^{-6}
CO_2	NaOH	1.6×10^{-6}
SO_2	H_2O	2.2×10^{-7}
Cl_2	H_2O	9.5×10^{-8}

TABLE 4-17. PACKING DEPTH REQUIRED TO ACHIEVE
SPECIFIED REMOVAL EFFICIENCY[a] [11]

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Removal efficiency, percent	Packing size				
	1 in.	1-1/2 in.	2 in.	3 in.	3.5 in.
	Depth, ft				
90	2.5	3.2	3.74	5.74	6.99
95	3.0	3.74	4.49	6.76	8.50
98	4.00	4.99	6.00	8.99	11.3
99	4.59	5.74	6.99	10.2	13.0
99.5	5.24	6.50	8.01	12.0	14.8
99.9	6.99	8.76	10.5	15.7	19.8
99.99	9.25	11.5	14.0	21.0	26.0

[a]Applicable only to gaseous contaminants that are highly soluble
or chemically reactive with the scrubbing liquid. Also, there are
variations in packing depths vs. the type of packing used (approx-
imately ±25% to 30%) which have not been taken into account.

The depth of packed beds for gaseous emission control typically ranges from
4.0 to 9.3 ft. The depth of packing can also be changed if removal efficiency
is lower than anticipated or if the carrier gas flow rate or waste streams
incinerated change. However, an evaluation of the packing depth requirement
is still desirable to assure that a packed tower design has sufficient
capacity.

<u>Liquid-to-gas ratio</u>--The liquid-to-gas ratio is a design and operating parameter of prime importance. It is needed in the determination of the scrubber diameter, and it has an effect on the height of a transfer unit. A high liquid-to-gas ratio will lead to the requirement of a larger diameter, but at the same time will also reduce the height of a transfer unit.

For each set of design conditions, there is a minimum liquid-to-gas ratio that is required to achieve the desired removal efficiency. This minimum ratio can be computed from equilibrium relationships. For gas contaminants that are highly soluble or chemically reactive with the scrubbing liquid, the equilibrium vapor pressure approaches zero. Theoretically, there is no minimum liquid-to-gas ratio for the removal of these gas contaminants, based on vapor-liquid equilibrium considerations. In practice, of course, sufficient scrubbing liquid must be provided to assure that it is not saturated with the gas contaminants removed, and to keep the packing surfaces thoroughly wet. When scrubbing HCl, for example, acid concentration in the scrubber liquor is normally limited to 1-2%.

The chemical requirement for acid gas neutralization in a scrubber is directly proportional to the halogen content, sulfur content, and phosphorus content of the hazardous waste streams incinerated. If caustic soda is used, at 60%[a] in excess of the stoichiometric amount, the requirement is given as:

Caustic soda requirement = 0.0176 x wt % Cl in waste + 0.0328
(lb/lb waste)   x wt % F in waste + 0.0604 x wt % P
                                  in waste + 0.0389 x wt % S in waste

If the caustic content of the scrubbing solution is known, the minimum liquid flow rate for neutralization can then be calculated in terms of gallons of solution per pound of waste incinerated. The combustion gas yield per pound of waste (previously calculated in Section 4.3.2) can then be used in conjunction with this value to determine the minimum liquid-to-gas ratio in units of gallons per standard cubic foot of combustion gas.

Such methods can be used to determine the chemical requirements and minimum liquid-to-gas ratio for scrubber water <u>neutralization</u>. However, complete neutralization is not required for efficient acid gas scrubbing, as evidenced by the fact that water is often used as the scrubbing liquor. When water is used, acid gas solubilities as functions of temperature must be known to accurately determine equilibrium relationships and minimum liquid-to-gas ratios. A more complex situation is encountered in caustic scrubbing since absorption in water and reaction occur simultaneously.

A simpler approach to evaluating minimum liquid-to-gas ratio requirements is to examine current industry practices and/or to rely on actual test data. Normal liquid-to-gas ratios in packed beds vary from 6 to 75 gal/1000 acf, with most units operating at between 22 and 52 gal/1000 acf. In general, lower liquid-to-gas ratios are needed for once-through scrubbing systems than

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[a]60% excess is typical for single pass scrubbing. When scrubber liquid is recycled, 5-30% excess can be acceptable for neutralization.

for recycle systems to achieve the same removal efficiency because the driving force for mass transfer is greater for once-through scrubbing. Likewise, increasing the caustic addition rate will lower the minimum required liquid-to-gas ratio, all other factors being equal.

The upper limit for liquid-to-gas ratio in packed towers is set by the flooding condition. Generalized correlations of flooding velocities are available and can be used to estimate the maximum liquid-to-gas ratio [6]. In practice, however, flooding can be readily detected by sharply increased pressure drop across the packed bed, and it can be eliminated by adjustment of the liquid flow rate during operation. A quick check for proper column diameter sizing can be accomplished by calculating the superficial gas velocity through the tower. For packed beds with countercurrent flow, superficial gas velocities are normally in the range of 7 to 10 ft/s, corresponding to approximately 60% of the flooding velocity. The 40% safety factor allows for fluctuating gas flows from the incinerator caused by changing waste composition and feed rate.

Contact time--In gas absorption devices, higher efficiencies are attained by allowing the gas and liquid phases to be in contact for a longer period of time. Removal efficiencies for gaseous contaminants in packed beds are directly related to the depth of packing, which in turn determines the contact time.

The contact time required for gas absorption is a function of the rate of mass transfer. The mass transfer rate, in general, is dependent upon four separate resistances: gas phase resistance, liquid phase resistance, chemical reaction resistance, and a solids dissolution resistance for scrubbing liquids containing solid reactants. For absorption of gaseous contaminants that are highly soluble or chemically reactive with the scrubbing liquid, such as the absorption of HCl by caustic solution, the contact time required for 99% removal is extremely short (on the order of 0.4 to 0.6 s).

Pressure drop--For gas flow through packed beds, the pressure drop may be calculated using the approximate correlation developed by Leva [6]:

$$\Delta P/Z = C_2 \, 10^{C_3 U_L} \, \rho_G U_G^2$$

where $\Delta P/Z$ is the pressure drop in in. WG/ft of packing, U_L is the liquid superficial velocity in ft/s, ρ_G is the gas density in lb/ft^3, U_G is the superficial gas velocity in ft/s, and C_2 and C_3 are constants. Pressure drops for the common commercial packings can also be obtained from plots of pressure drop versus gas and liquid flow rates. These plots are available from the packing manufacturers and should be used for more accurate estimation of pressure drop in the design evaluation process. For packed beds used for gaseous emission control in hazardous waste incineration facilities, the pressure drop usually ranges from 2.0 to 7.2 in. WG. Since the total pressure drop across the packed bed is directly proportional to the depth of packing, it indirectly affects the removal efficiency of gaseous contaminants. Higher pressure drops also result in more efficient particulate collection.

Table 4-18 presents a procedure that can be used to evaluate packed bed scrubber design, based on the foregoing considerations of packing depth, liquid-to-gas ratio, superficial gas velocities, contact time, and pressure drop.

TABLE 4-18. PACKED BED SCRUBBER EVALUATION PROCEDURE

1. Is the proposed packing depth sufficient to attain the desired gas absorption efficiency? See Table 4-17[a].

2. Is the proposed liquid-to-gas ratio within normal limits, as described in the preceding discussion?

3. Is the superficial gas velocity through the scrubber reasonable, based on the preceding discussion? (Worksheet 4-7 shows how superficial gas velocities may be calculated for incinerators. The same procedure may be used for scrubber velocity calculation.)

4. Are the contact times and pressure drops through the scrubber reasonable, based on the preceding discussion? (Contact time can be estimated using the methods shown in Worksheet 4-6 for incinerator gas residence time, replacing the incinerator volume term with the total volume occupied by the packed section of the scrubber:

$$V_p = Z \left(\frac{\pi D^2}{4} \right)$$

where Z = bed depth and D = column diameter.)

[a]Table 4-17 is only applicable for highly soluble gases such as HCl and HF. If other gaseous pollutants are to be removed, technical assistance may be requested.

4.4.2.3 Plate Tower Scrubbers--
Plate towers are vertical cylindrical columns with a number of plates or trays inside. The scrubbing liquid is introduced at the top plate and flows successively across each plate as it moves downward to the liquid outlet at the tower bottom. Gas comes in at the bottom of the tower and passes through openings in each plate before leaving through the top. Gas absorption is promoted by the breaking up of the gas phase into small bubbles which pass through the volume of liquid on each plate. Water, caustic solution, and lime solution can all be used as the scrubbing liquid.

The primary design variables for gas absorption in plate tower scrubbers are the number of plates or trays, the liquid-to-gas ratio, and the contact time. Pressure drop is also an important design criteria although it does not directly affect absorption efficiency. Like packed bed scrubbers, plate tower

scrubbers can be used for limited particulate collection as well as gas absorption, but they are not primarily designed for this purpose.

Number of plates--In the design of plate towers for absorption of gaseous contaminants that are highly soluble or chemically reactive with the scrubbing liquid, the number of actual plates, N_p, may be calculated from the equation [6]:

$$N_p = - \frac{\ln(y_1/y_2)}{\ln(1-E_{MV})}$$

where y_1 and y_2 are the inlet and outlet concentrations of the gaseous contaminant and E_{MV} is the Murphree vapor phase efficiency. In developing the above equation, the assumption is made that E_{MV} is the same for each plate in the tower. The Murphree vapor phase efficiencies for the various plate designs may be obtained from published data for selected gas-liquid systems [6,17]. These would normally be in the 25% to 80% range. A rigorous estimation of the Murphree vapor phase efficiency is extremely complex. For the case of absorption towers operating with low viscosity liquids and without excessive weepage (liquid dripping) or entrainment, the figures in Table 4-19 can be used.

TABLE 4-19. MURPHREE VAPOR PHASE EFFICIENCY
FOR PLATE TOWERS [19]

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Perforation diameter, in.	Murphree vapor phase efficiency, percent
1/16	80
1/16 to 1/8	75
1/8 to 3/16	70
1/4 to 3/8	65

Liquid-to-gas ratio--For plate towers, the selection of the optimum liquid-to-gas ratio depends largely on operating experience. Experience has indicated that for single-pass crossflow bubble cap trays, the liquid flow should not exceed $0.72d$ ft^3/s, where d is the diameter of the tower in feet. Since the gas flow rate in the tower can be estimated from the Souders-Brown equation, the maximum liquid-to-gas ratio is given as follows:

$$\left(\frac{Liquid}{Gas}\right)_{max} = \frac{630}{Kd}\left(\frac{\rho_G}{\rho_L - \rho_G}\right)^{0.5}, gal/1,000 \ ft^3$$

where K is an empirical constant in the Souders-Brown equation, and ρ_G and ρ_L are the gas and liquid densities, respectively. Values of K are available from Chemical Engineers' Handbook [6] or any other standard chemical engineering reference on mass transfer, distillation, or unit operations. For towers with a tray spacing of 24 in., K is typically 0.17.

Contact time--As in packed bed scrubbers, gas/liquid contact time is an important factor affecting removal efficiency. In tray towers, greater depths of liquid on the plates lead to greater plate efficiency through longer contact time with the gas. Typical gas residence times in tray towers are comparable to those for packed bed scrubbers; for example, 0.4 s to 0.6 s for 99+% absorption of HCl in caustic solution. For absorption of SO_2 by lime solution, longer contact times (in the range of 3-9 s) are needed to overcome the additional mass transfer resistance due to solids dissolution.

Pressure drop--For plate towers, the pressure drop across a perforated plate is the sum of the gas resistance in passing through the perforations plus the head required to overcome the equivalent liquid depth on the plate:

$$\Delta P = \Delta P_h + h_L$$

P_h, the pressure drop due to gas resistance in in. WG, can be calculated from the equation [20]:

$$\Delta P_h = 2.0 \left(\frac{\rho_G}{\rho_L} \right) \left(\frac{U_o}{C_{VO}} \right)^2$$

where ρ_G and ρ_L are the gas and liquid densities, respectively; U_o is the linear velocity of the gas through perforations in ft/s; and C_{VO} is the orifice coefficient. Values of C_{VO} are 0.7-0.8 for sieve trays and 0.6-0.7 for bubble cap trays. The pressure drop due to liquid head in in. WG, h_L, can be calculated from a knowledge of weir dimensions:

$$h_L = 1.5 \times 10^{-7} \rho_L (h_w + h_{ow})$$

where ρ_L is the liquid density in lb/ft^3, h_w is height of weir on the tray in mm, and h_{ow} is height of weir crest in mm.

Total pressure drop can be roughly estimated by:

$$\Delta P_T = \Delta P_p \times N_p$$

where ΔP_T = total pressure drop

   ΔP_p = pressure drop per plate

   N_p = number of plates

Table 4-20 presents a procedure that can be used for plate tower scrubber design evaluation, based on consideraton of the number of plates required, liquid-to-gas ratio, contact time, and pressure drop. The equations presented above can be used to estimate pressure drop if this information is not available from the vendor. However, vendor data are preferable.

TABLE 4-20. PLATE TOWER SCRUBBER EVALUATION PROCEDURE

1. Are the proposed number of plates comparable to or greater than the required number of plates, as estimated by the procedures shown in Worksheet 4-14[a].

2. Are the proposed liquid flow and liquid-to-gas ratio reasonable and less than the maximum acceptable values calculated by the methods shown in Worksheet 4-15?

3. Are the contact time and pressure drop within reason?

[a]This procedure is only valid for gases highly soluble in the scrubber liquor.

4.4.3 Quenching and Mist Elimination Considerations

In addition to scrubbers used for particulate and gaseous emission control, air pollution control systems for hazardous waste incinerators frequently include quench towers and mist eliminators. Located upstream from the scrubbers, quench towers are designed to reduce the temperature of the combustion gases leaving the incinerator. This temperature reduction reduces the volumetric gas flow rate, and thus the scrubber capacity requirement. Quenching also reduces evaporative water losses in the scrubber, and allows the use of low temperature materials of construction such as fiber-reinforced plastic (FRP) rather than more expensive, high temperature alloys or refractory.

Since venturi scrubbers provide evaporative gas cooling by the very nature of their design, quenching may be considered optional when these devices are used for primary particulate and/or gaseous emission control. Packed bed and plate tower scrubbers, however, are not designed for evaporated cooling. When these devices are used without upstream venturi scrubbing, quenching is nearly always required. Without quenching, evaporative water loss from caustic or lime solution can lead to particulate emissions of sodium or calcium salts.

At existing hazardous waste incineration facilities, combustion gases are normally quenched to temperatures of 120-300°F, and below 200°F for FRP scrubber construction. Typical water consumption rates for quenching are in the range of 0.75 to 3.75 gal/1000 ft^3 (0.1 to 0.5 L/m^3) of gas.

Mist eliminators are widely used to reduce emissions of liquid droplets from scrubbers. Mist eliminators are normally installed downstream from, or as an

integral part of, the scrubbing system. In general, only one mist eliminator is needed. Where two or more scrubbers are used in series, intermediate mist elimination may be provided, but it is not considered necessary to prevent the release of liquid droplets to the environment.

The types of mist eliminators most commonly used in hazardous waste incineration facilities are cyclone collectors, simple inertial separators such as baffles, wire mesh mist eliminators, and fiber bed mist eliminators. Cyclones are used for collecting very heavy liquid loadings of droplets over 10 μm, such as those emitted from venturi scrubbers. The design of cyclone mist eliminators follows the principles of cyclone design for particles. For this type of mist eliminator, therefore, the collection efficiencies for liquid droplets and solid particles are about the same. Collection efficiencies of nearly 100% are possible for droplets in the 10- to 50-μm range, which is consistent with the liquid droplet sizes emitted from venturi scrubbers.

In the simple inertial separators, the primary collection mechanism is inertial impaction, and to a lesser extent interception. Devices such as louvers, zigzag baffles, tube banks, and chevrons are simple inertial separators. The cut diameter for liquid droplet collection in these devices is typically 10 μm. Pressure drops are in the 0.02- to 0.12-in. WG (50-to 300-Pa range) depending on the gas velocity and closeness in spacing of the collection surfaces.

Wire mesh eliminators are formed from meshes of wire knitted into a cylindrical open weave which is then crimped to give a stable wire configuration. As rising mist droplets contact the wire surface, they flow down the wire to a wire junction, coalesce, run off, and flow freely to the bottom of the bed. The depth of the wire pad varies from 2 to 12 in. (50 to 300 mm) with 4-6 in. pads being the most common. Pressure drops usually range from 0.02 to 4.0 in. WG, depending on the gas velocity, the wire density, and the depth of the pad. In normal operation, the pressure drop is not likely to be more than 1 in. WG. The cut diameter for liquid droplet collection is a strong function of the gas velocity, and can range from 1 to 10 μm. Sizing of the wire mesh mist eliminator is based on the allowable gas velocity, calculated using the Souders-Brown equation:

$$u = 0.107 \sqrt{\frac{\rho_L - \rho_G}{\rho_G}}$$

Where u is the gas velocity in m/s, ρ_L is the density of the scrubbing liquid, and ρ_G is the gas density.

For collection of fine acid mists, fiber bed mist eliminators are most appropriate. In this type of device, large mist particles are collected on the fibers by inertial impaction and direct interception, whereas smaller particles are collected by Brownian diffusion. Since fiber bed mist eliminators are designed so that Brownian diffusion is the predominant mechanism for mist collection, extremely small particles of less than 1 μm are recovered with high efficiency. Typical gas velocities through fiber bed mist eliminators

range from 5 to 10.0 ft/s (1.5 to 30 m/s), with corresponding pressure drops of 5 to 15 in. WG. Collection efficiencies are 100% for droplets larger than 3 μm, and 90% to 99.5% for droplets less than 3 μm.

In wire mesh and fiber bed mist eliminators, plugging by solid deposition is a potential problem. This problem can be partially overcome by intermittent washing with sprays, by selection of a less densely packed design, and by the use of sieve plate towers or cyclone separators upstream as an additional mist and particle collection device. At hazardous waste incineration facilities, the most common configuration used for gas cleanup is a high energy venturi scrubber followed by two sieve trays for additional gas absorption, and then another sieve tray and an inertial separator or a wire mesh eliminator to reduce emissions of liquid droplets. Operating experience has indicated that this is a most effective combination.

In general, three "rules of thumb" can be followed in evaluating provisions for quenching and mist elimination at hazardous waste incineration facilities.

- Quenching should be provided upstream from packed bed or plate tower scrubbers unless these devices are preceded by a venturi scrubber.

- Quenching is optional when venturi scrubbers are used, although high temperature materials of construction may be required if quenching is not employed.

- A mist eliminator should be provided downstream or as an integral part of the last scrubber in the air pollution control system.

4.4.4 Prime Mover Capacity Evaluation

Prime movers in rotary kiln incineration systems are always induced draft fans, located downstream from the air pollution control devices, while either induced draft or forced draft systems may be used with liquid injection incinerators. For the overall system to function properly, the prime mover must be capable of moving the combustion gases through each air pollution control device while overcoming the corresponding pressure drops. As the total pressure drop through the system increases, the volumetric flow capacity of the fan decreases. The functional relationship between these two variables, pressure and flow capacity at a specific temperature, should be specified by the manufacturer.

Therefore, it is necessary to (a) determine the combustion gas flow rate at the fan inlet temperature, (b) estimate the total pressure drop across the system, and (c) compare the fan capacity at the calculated pressure drop with the predetermined combustion gas flow rate in order to evaluate whether or not the fan has sufficient gas handling capacity. If this capacity is insufficient the burning rate must be decreased, the fan capacity must be increased, or the ductwork must be modified to reduce pressure drop. The following discussion focuses on Step (b) above, estimation of the total system pressure drop. Combustion gas flow rate calculations are discussed in Section 4.3.2.

The major pressure drops to be considered are the pressure drops across the various air pollution control devices. These pressure drops can be determined from manufacturer specifications once the gas flow rates at the inlets to these devices are known. Flow rates can be calculated quite simply as follows:

$$q = q_{std}\left(\frac{T + 460}{528}\right)$$

where q = combustion gas flow rate, acfm
          q_{std} = combustion gas flow rate, at standard conditions of 68°F and 1 atm, scfm (from Worksheet 4-2 or 4-4)
          T = inlet temperature, °F

Other pressure drops that need to be considered are frictional losses due to flow through the ductwork connecting each air pollution control device. For any given duct, the total pressure drop may consist of three component pressure drops: (1) frictional losses due to flow through straight lengths of ductwork, (2) frictional losses due to flow through bends in the ductwork, and (3) losses due to sudden constriction of flow at the inlet to the duct.

Pressure drop through a straight length of duct can be estimated using Figure 4-13, reproduced from Reference 6. This figure can be used in the following manner:

(1) Identify the temperature and average molecular weight of the gas.

(2) Draw a line through these two points on the temperature and molecular weight scales, and extrapolate this line to a point on the viscosity scale.

(3) Identify the inside diameter of the duct and the mass flow of combustion gases.

(4) Draw a line through these two points on the diameter and weight flow scales, and extrapolate this line to the arbitrary reference scale.

(5) Connect the point on the arbitrary reference scale with the predetermined point on the viscosity scale.

(6) Identify the pressure drop per foot of duct on the ΔP scale at the intersection of the line between the reference and viscosity scales.

(7) Calculate the total pressure drop across the length of straight duct as follows:

$$\Delta P = \left[\frac{\Delta P}{L}(P_G)\right]^a \left(L_S\right)$$

---

[a]From Figure 4-13.

where ΔP = total pressure drop, in. H_2O

L_S = length of straight duct, ft

P_G = absolute gas pressure, atm

For a reasonable approximation, assume

$$P_G \cong 1 \text{ atm}$$

FLOW IN PIPES AND CHANNELS
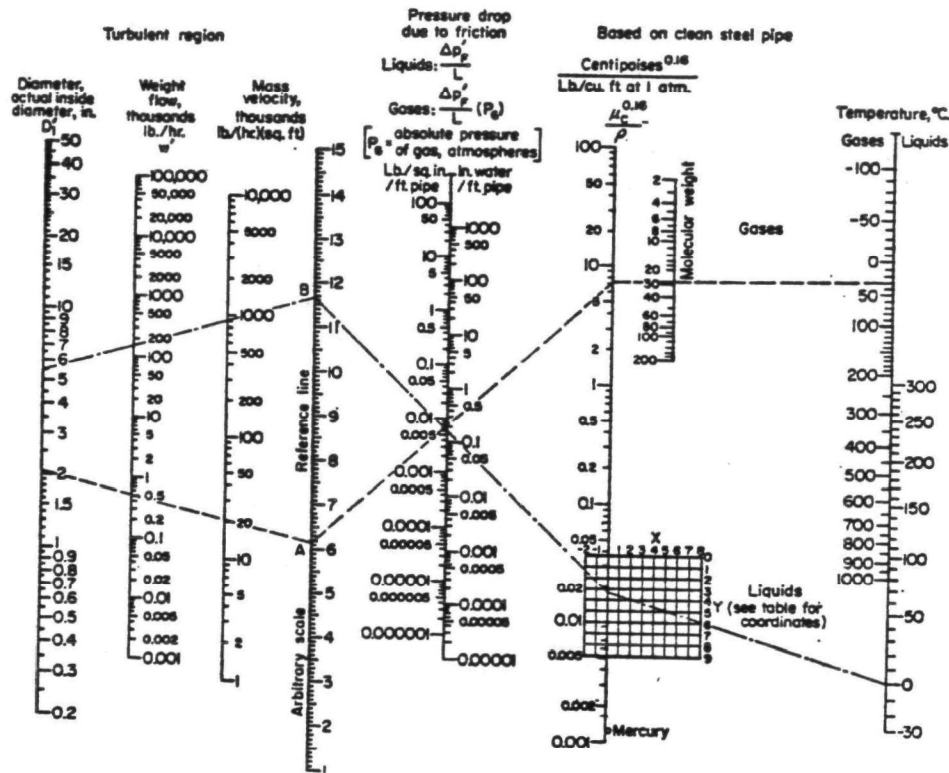
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Figure 4-13. Pipe flow chart [6].

If the duct is square or rectangular the following quantities should be used as equivalent diameters:

Square duct: D_{eq} = length of a side

Rectangular duct: $D_{eq} = \dfrac{2\ ab}{a + b}$

where a, b = width and depth of the duct

Pressure drops across bends in a duct can be estimated using Figure 4-14. Here, L_e/D, the equivalent straight-length-to-diameter ratio, is expressed as a function of the ratio of the radius of curvature of the elbow, R, to the diameter of the duct. Figure 4-15 shows the relationship between R and D.
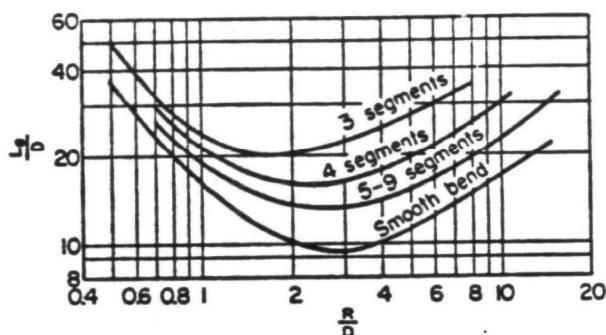
Figure 4-14. Total frictional pressure drops in 90° bends [6].
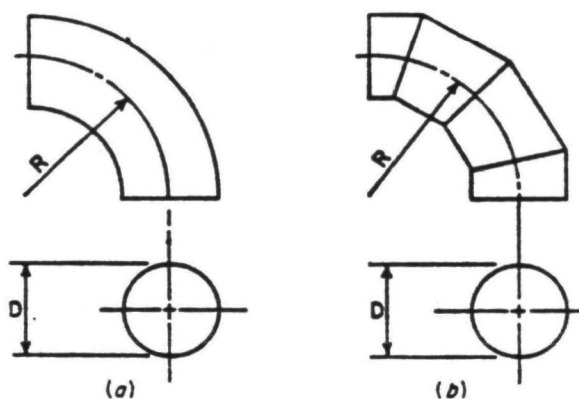
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Figure 4-15. 90° bends (a) smooth bend, (b) segmental bend [6].

The procedure for estimating pressure drops from Figure 4-14 is as follows:

(1) Determine R/D and read the corresponding L_e/D value from Figure 4-14.

(2) Identify the pressure drop across the length of straight duct upstream and downstream from the bend and the corresponding length of straight duct.

(3) Convert the L_e/D value to a pressure drop estimate:

$$\Delta P' = \Delta P \left(\frac{L_e}{D} \right) \left(\frac{12\ D}{L_s} \right)$$

4-71

where $\Delta P'$ = pressure drop across the bend, in. H_2O
       ΔP = pressure drop across the straight segment of duct, in. H_2O

       D = diameter of the duct, in.
       L_S = length of straight duct, ft

If 45° or 180° angle bends are encountered, the corrected pressure drops are:

$$\Delta P'_{45°} = 0.65 \ \Delta P'_{90°}$$

and

$$\Delta P'_{180°} = 1.4 \ \Delta P'_{90°}$$

Additional pressure drops occur at the inlet to a duct because of the sudden contraction of the gases. These pressure drops can be estimated by the following equation:

$$\Delta P'' = 6 \ K_c \left(\frac{v^2}{g_c}\right) \left(\frac{\rho_{gas}}{\rho_{H_2O}}\right)$$

where $\Delta P''$ = pressure drop, in. H_2O

         V = gas velocity, ft/s

         g_c = gravitational constant, 32.2 lb-m ft/lb-f s^2

         ρ_{gas} = gas density, lb/ft^3

         ρ_{H_2O} = density of liquid water, 62.4 lb/ft^3

         K_c = sudden contraction-loss coefficient for turbulent flow

Table 4-21 presents K_c values for various ratios of duct cross-sectional area, A_d, to the cross-sectional area of the unit upstream from the duct, A_p.

TABLE 4-21. SUDDEN CONTRACTION-LOSS COEFFICIENT
            FOR TURBULENT FLOW [6]

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A_d/A_p	0	0.2	0.4	0.6	0.8	1.0
K_c	0.5	0.45	0.36	0.21	0.07	0

When the pressure drops through each air pollution control device and segment of ductwork are calculated and summed, this should provide a rough estimate of the total pressure drop through the system.

Table 4-22 presents a procedure for evaluating the prime gas mover capacity. A step-by-step method for performing the necessary calculations is shown in Worksheet 4-16.

TABLE 4-22. PRIME MOVER CAPACITY EVALUATION PROCEDURE

1. Identify the approximate combustion gas flow rate in scfm (see Worksheet 4-2 or 4-4).

2. Identify the temperatures at (a) the incinerator outlet, (b) the inlet to each air pollution control device, and (c) the fan inlet. Record this information on Worksheet 4-16.

3. Identify the pressure drops across each air pollution control device, as specified by the manufacturer, and record this information on Worksheet 4-16.

4. Estimate the pressure drops across each segment of ductwork between the incinerator and the fan, and add these pressure drops to those determined in checkpoint #3 to estimate the total pressure drop across the system.

5. Identify the manufacturer specifications for fan capacity at the calculated pressure drop and fan inlet temperature.

6. Does this capacity meet or exceed the approximate combustion gas flow rate?

4.4.5 Process Control and Automatic Shutdown System Evaluation

In the design of the incinerator and scrubber systems, a number of safety features should be provided to allow for equipment failures and operational errors. Process control systems and safety interlocks for incinerators are discussed in Section 4.3.5. The following safety interlocks relating to the scrubber operation are recommended:

(1) Shutdown of the waste and auxiliary fuel feed systems on loss of scrubber water flow.

(2) Shutdown of the waste and auxiliary fuel feed systems if the incinerator effluent gas temperature exceeds the maximum design temperature for the quench section.

(3) Shutdown of the waste and auxiliary fuel feed systems if the quenched gas temperature exceeds the maximum design temperature for the scrubber.

(4) Shutdown of the waste and auxiliary fuel feed systems, followed by shutdown of the scrubber systems, on failure of forced or induced draft fan.

(5) Shutdown of the waste and auxiliary fuel feed systems followed by shut-
     down of the scrubber systems, if the pH of the scrubbing liquid does not
     meet specified values.

(6) Shutdown of the waste and auxiliary fuel feed systems, followed by shut-
     down of the scrubber systems, if the pressure drop across the scrubber
     becomes excessive, indicating unsteady-state operation or clogging
     problems.

When possible, it is desirable to have a time delay between shutting off the
waste to be incinerated and shutting off the auxiliary fuel. This will help
to ensure an adequate burnout of the waste and minimize emissions of
incomplete products of waste combustion and unreacted waste.

In situations when the incinerator effluent gas temperature or the quenched
gas temperature exceeds the maximum design temperature for the next piece of
equipment, it is desirable to have provisions for emergency stack bypass
designed into the system. An indication of excess temperature should lead to
shutdown of the incinerator through the safety interlock system. It is recog-
nized, however, that any of the interlock devices can and will malfunction
some of the time. To protect the scrubber system from damage by excess tem-
perature, switches for stack bypass can be provided. These switches should
only be operated as an emergency measure, and under strict supervision. To a
limited extent, the additional thermal lift caused by the excess temperature
will raise the effective stack height and alleviate the impact on plant
personnel.

At power plants, chemical plants, and refineries, stack bypass switches are
often provided to enable maintenace to be done on scrubber systems while
process operation continues. Stack bypass for maintenance purposes is not
recommended for hazardous waste incineration facilities.

4.4.6 Material of Construction Considerations

Effluent gases from incineration of hazardous wastes contain a number of
corrosive contaminants, including HCl, SO_2, SO_3, HF, and possibly Cl_2, HBr,
Br_2, P_2O_5, and organic acids. The presence of HCl, the principal gaseous
contaminant, is of particular concern because it accelerates pitting and
crevice corrosion of most materials. The careful selection of the materials
of construction for the quench tower and scrubber system is therefore
extremely important.

In the quench section where temperatures of approximately 1800°F are commonly
encountered, Hastelloy C and Inconel 625 have found wide acceptance. Other
possibilities are the use of carbon graphite or acid resistant refractories as
lining material for carbon steel or stainless steel construction, but the
quench spray nozzles should still be made of Hastelloy C or Inconel 625.

For the scrubber, Hastelloy C or Inconel 625 can again be used as materials of
construction. At more moderate temperatures, however, FRP is recommended
because it is economical, easily fabricated, and lightweight. It also has

good resistance in both acid and alkaline environments, up to a service temperature of around 200°F. Polyvinyl chloride (PVC) can also be considered as a material for wet scrubber construction, but its use is limited to temperatures of less than 160°F.

If structural strength becomes a prime consideration because of the size and weight of the scrubber, carbon steel or stainless steel can be used with a suitable lining material to provide the required corrosion protection. Field corrosion studies have shown that carbon steel and stainless steel both experienced severe corrosion problems and are not recommended as materials of construction for scrubber systems treating acid gases unless linings are used. Rubber, carbon graphite, FRP, Teflon, Kynar (polyvinylidene fluoride), acid resistant bricks, and refractories are examples of suitable lining materials. Teflon, however, cannot be bonded to a metal surface and requires multiple flanges to stay in place. Kynar is similar to Teflon in most of its properties, but it is available in sheet form bonded to a glass backing. In packed beds, the packing material should be made of ceramic, carbon, or plastics to withstand attack by corrosive acids.

A special concern is the potential presence of HF in the incinerator exhaust gases. It is well known that glass and any ceramic material containing silica are attacked by HF or H_2SiF_6. Many grades of rubber linings also contain silica as a filler, which could be leached out by HF or H_2SiF_6. Common materials of construction of HF scrubbers include FRP (with special shielding material to prevent attack of the glass fibers), rubber-lined steel, Kynar, and graphite-lined steel. Among the metals, monel has shown good resistance over wide concentration and temperature ranges. At one hazardous waste incineration facility, a Monel-lined stainless steel packed tower with polypropylene Intalox saddles is used to control HF emissions from the incinerator. In addition, both Hastelloy C and Inconel 625 have been used as lining material in hydrofluoric acid service and have demonstrated outstanding corrosion resistance to HF.

Although the corrosion and temperature aspects of materials selection are of primary importance, erosion must also be considered in scrubbers designed for particulate control. Venturi scrubbers are particularly susceptible to erosion due to the high gas velocities and particulate loadings encountered during normal duty. Throat and elbow areas are generally subject to the most wear. FRP does not stand up well in these regions and harder, corrosion resistant, materials are required for long service life.

All the foregoing factors should be considered in evaluating materials selection for the quench tower and scrubber system. If materials of construction other than those discussed above are proposed, the adequacy of these materials for the temperature/gas environment under consideration should be evaluated.

4.5 WORKSHEETS

The worksheets in this section can be used to perform the design evaluation calculations described in Sections 4.3 through 4.4.

WORKSHEET 4-1. PROCEDURE TO CALCULATE DESTRUCTION
AND REMOVAL EFFICIENCY

1. From trial burn data, identify the following parameters:

Total waste feed rate, $(W_{in})_{TOTAL}$ = _____ lb/hr

Mass fraction of each principal
organic hazardous constituent in
the waste, n_1 = _____ lb/lb waste
                                          n_2 = _____ lb/lb waste
                                          n_3 = _____ lb/lb waste
                                          n_4 = _____ lb/lb waste
                                          n_5 = _____ lb/lb waste

Gas flow rate in the stack, q = _____ scfm

Concentration of each prin-
cipal organic hazardous
constituent in the stack gas, c_1 = _____ µg/scf
                                c_2 = _____ µg/scf
                                c_3 = _____ µg/scf
                                c_4 = _____ µg/scf
                                c_5 = _____ µg/scf

2. Calculate the mass feed rate of each hazardous constituent to the incin-
erator, using the following equation:

$$(W_{in})_i = n_i \, (W_{in})_{TOTAL}$$

$(W_{in})_1$ = _____ lb/hr
$(W_{in})_2$ = _____ lb/hr
$(W_{in})_3$ = _____ lb/hr
$(W_{in})_4$ = _____ lb/hr
$(W_{in})_5$ = _____ lb/hr

3. Calculate the mass flow rate of each hazardous constituent in the stack
using the following equation:

$$(W_{out})_i = \frac{q \, c_i}{7.57 \times 10^6}$$

$(W_{out})_1$ = _____ lb/hr
$(W_{out})_2$ = _____ lb/hr
$(W_{out})_3$ = _____ lb/hr
$(W_{out})_4$ = _____ lb/hr
$(W_{out})_5$ = _____ lb/hr

4. Calculate the destruction and removal efficiency for each hazardous
constituent using the following equation:

$$DRE_1 = \frac{(W_{in})_i - (W_{out})_i}{(W_{in})_i} \quad (100)$$

$DRE_1 = $ _____ %

$DRE_2 = $ _____ %

$DRE_3 = $ _____ %

$DRE_4 = $ _____ %

$DRE_5 = $ _____ %

WORKSHEET 4-2. PROCEDURE TO CALCULATE STOICHIOMETRIC AIR REQUIREMENTS, COMBUSTION GAS FLOW, AND COMPOSITION

1. Identify the elemental composition and moisture content of the waste or waste mixture.

$$
\begin{array}{rll}
\text{Carbon, } C_w: & \underline{\hspace{2cm}} & \text{lb/lb waste} \\
\text{Fuel hydrogen, } H_w: & \underline{\hspace{2cm}} & \text{lb/lb waste} \\
\text{Moisture, } H_2O_w: & \underline{\hspace{2cm}} & \text{lb/lb waste} \\
\text{Oxygen, } O_w: & \underline{\hspace{2cm}} & \text{lb/lb waste} \\
\text{Nitrogen, } N_w: & \underline{\hspace{2cm}} & \text{lb/lb waste} \\
\text{Chlorine, } Cl_w: & \underline{\hspace{2cm}} & \text{lb/lb waste} \\
\text{Fluorine, } F_w: & \underline{\hspace{2cm}} & \text{lb/lb waste} \\
\text{Bromine, } Br_w: & \underline{\hspace{2cm}} & \text{lb/lb waste} \\
\text{Iodine, } I_w: & \underline{\hspace{2cm}} & \text{lb/lb waste} \\
\text{Sulfur, } S_w: & \underline{\hspace{2cm}} & \text{lb/lb waste} \\
\text{Phosphorus, } P_w: & \underline{\hspace{2cm}} & \text{lb/lb waste}
\end{array}
$$

2. If auxiliary fuel is to be burned in conjunction with the waste, identify the fuel type and approximate, proposed fuel-to-waste ratio from the permit application. (If auxiliary fuel is to be used only for startup, proceed to Step #5.)

Fuel type: _____

Fuel:waste ratio, n_f = _____ lb fuel/lb waste

3. Determine the approximate elemental composition of the fuel from the following table.

	lb Component/lb fuel [21]		
Component	Residual fuel oil (e.g., No. 6)	Distillate fuel oil (e.g., No. 2)	Natural gas
C_f	0.866	0.872	0.693
H_f	0.102	0.123	0.227
N_f	-	-	0.08
S_f	0.03	0.005	-

4. Calculate the composition of the combined waste/auxiliary fuel feed.

C: $\dfrac{C_w + n_f C_f}{1 + n_f}$ = _____ lb/lb feed

H: $\dfrac{H_w + n_f H_f}{1 + n_f}$ = _____ lb/lb feed

H_2O: $\dfrac{H_2O_w}{1 + n_f}$ = _____ lb/lb feed

4-78

$$\text{N:} \quad \frac{N_w + n_f N_f}{1 + n_f} = \underline{\hspace{2cm}} \quad \text{lb/lb feed}$$

$$\text{O:} \quad \frac{O_w}{1 + n_f} = \underline{\hspace{2cm}} \quad \text{lb/lb feed}$$

$$\text{Cl:} \quad \frac{Cl_w}{1 + n_f} = \underline{\hspace{2cm}} \quad \text{lb/lb feed}$$

$$\text{F:} \quad \frac{F_w}{1 + n_f} = \underline{\hspace{2cm}} \quad \text{lb/lb feed}$$

$$\text{Br:} \quad \frac{Br_w}{1 + n_f} = \underline{\hspace{2cm}} \quad \text{lb/lb feed}$$

$$\text{I:} \quad \frac{I_w}{1 + n_f} = \underline{\hspace{2cm}} \quad \text{lb/lb feed}$$

$$\text{S:} \quad \frac{S_w + n_f S_f}{1 + n_f} = \underline{\hspace{2cm}} \quad \text{lb/lb feed}$$

$$\text{P:} \quad \frac{P_w}{1 + n_f} = \underline{\hspace{2cm}} \quad \text{lb/lb feed}$$

5. Calculate the stoichiometric oxygen requirement based on the combustion reactions described in Section 4.3.2.1.

$$C \times 2.67 \, \frac{\text{lb } O_2}{\text{lb C}} = \underline{\hspace{2cm}} \quad \text{lb } O_2/\text{lb feed}$$

$$\left(H - \frac{Cl}{35.5} - \frac{F}{19}\right) \times 8.0 \, \frac{\text{lb } O_2}{\text{lb H}} = \underline{\hspace{2cm}} \quad \text{lb } O_2/\text{lb feed}$$

$$S \times 1.0 \, \frac{\text{lb } O_2}{\text{lb S}} = \underline{\hspace{2cm}} \quad \text{lb } O_2/\text{lb feed}$$

$$P \times 1.29 \, \frac{\text{lb } O_2}{\text{lb P}} = \underline{\hspace{2cm}} \quad \text{lb } O_2/\text{lb feed}$$

$$-O(\text{in feed}) = -\underline{\hspace{2cm}} \quad \text{lb } O_2/\text{lb feed}$$

$$(O_2)_{\text{stoich}} = \sum = \underline{\hspace{2cm}} \quad \text{lb } O_2/ \text{ lb feed}$$

6. Calculate the combustion gas mass flows, based on the stoichiometric oxygen requirement.

CO_2: $\quad$ C x 3.67 $\frac{lb\ CO_2}{lb\ C}$ $\qquad\qquad\qquad\qquad$ = ___ lb CO_2/lb feed

H_2O: $\quad \left[\left(H - \dfrac{Cl}{35.5} - \dfrac{F}{19}\right) \text{ x } 9.0\ \dfrac{lb\ H_2O}{lb\ H}\right] + H_2O(\text{in feed})$ = ___ lb H_2O/lb feed

N_2: $\quad \left[(O_2)_{stoich} \text{ x } 3.31\ \dfrac{lb\ N_2}{lb\ O_2}\ (\text{in air})\right] + N(\text{in feed})$ = ___ lb N_2/lb feed

HCl: $\quad$ Cl x 1.03 $\frac{lb\ HCl}{lb\ Cl}$ $\qquad\qquad\qquad\qquad$ = ___ lb HCl/lb feed

HF: $\quad$ F x 1.05 $\frac{lb\ HF}{lb\ F}$ $\qquad\qquad\qquad\qquad$ = ___ lb HF/lb feed

Br_2: $\quad$ Br $\qquad\qquad\qquad\qquad\qquad\qquad\qquad$ = ___ lb Br_2/lb feed

I_2: $\quad$ I $\qquad\qquad\qquad\qquad\qquad\qquad\qquad$ = ___ lb I_2/lb feed

SO_2: $\quad$ S x 2.0 $\frac{lb\ SO_2}{lb\ S}$ $\qquad\qquad\qquad\qquad$ = ___ lb SO_2/lb feed

P_2O_5: $\quad$ P x 2.29 $\frac{lb\ P_2O_5}{lb\ P}$ $\qquad\qquad\qquad\qquad$ = ___ lb P_2O_5/lb feed

_____

Combustion products = CP = $\sum$ = _____ lb/lb feed

7. Identify the total excess air rate.

$\qquad$ EA = _____ %/100

8. Calculate the additional nitrogen and oxygen present in the combustion gases due to excess air feed.

$\qquad (O_2)_{EA} = EA \text{ x } (O_2)_{stoich} = $ _____ lb O_2/lb waste

$\qquad (N_2)_{EA} = 3.31\ \dfrac{lb\ N_2}{lb\ O_2}\ (\text{in air}) \text{ x } (O_2)_{EA} = $ _____ lb N_2/lb waste

9. Calculate the total combustion gas flow.

$\qquad$ Combustion gases = CG = CP + $(O_2)_{EA}$ + $(N_2)_{EA}$ = _____ lb/lb waste

10. Calculate the mass fraction of each combustion gas component.

$\qquad CO_2$: $\quad \dfrac{CO_2}{CG}$ = _____ lb/lb gas

$\qquad H_2O$: $\quad \dfrac{H_2O}{CG}$ = _____ lb/lb gas

N_2: $\dfrac{N_2(\text{from \#6}) + (N_2)_{EA}}{CG}$ = _____ lb/lb gas

O_2: $\dfrac{(O_2)_{EA}}{CG}$ = _____ lb/lb gas

HCl: $\dfrac{HCl}{CG}$ = _____ lb/lb gas

HF: $\dfrac{HF}{CG}$ = _____ lb/lb gas

Br_2: $\dfrac{Br_2}{CG}$ = _____ lb/lb gas

I_2: $\dfrac{I_2}{CG}$ = _____ lb/lb gas

SO_2: $\dfrac{SO_2}{CG}$ = _____ lb/lb gas

P_2O_5: $\dfrac{P_2O_5}{CG}$ = _____ lb/lb gas

11. Identify those components that constitute less than 1-2% of the combustion gas. These components can be eliminated from further consideration in heat and material balance calculations. In most cases, CO_2, H_2O, N_2, and O_2 will be the only combustion gas components that need to be considered.

12. Calculate the volumetric flow of the major combustion products at standard conditions of 68°F and 1 atm.

CO_2: $\dfrac{CO_2}{CG}$ x CG ÷ 0.114 $\dfrac{lb}{scf}$ = _____ scf/lb feed

H_2O: $\dfrac{H_2O}{CG}$ x CG ÷ 0.0467 $\dfrac{lb}{scf}$ = _____ scf/lb feed

N_2: $\dfrac{N_2}{CG}$ x CG ÷ 0.0727 $\dfrac{lb}{scf}$ = _____ scf/lb feed

O_2: $\dfrac{O_2}{CG}$ x CG ÷ 0.083 $\dfrac{lb}{scf}$ = _____ scf/lb feed

Other: $\dfrac{Other}{CG}$ x CG ÷ (0.00259 M)$\dfrac{lb}{scf}$ = _____ scf/lb feed

where M = molecular weight

_____

Total flow, q = ___ = _____ $\dfrac{scf}{lb\ feed}$

q x m_{feed} (lb/hr) ÷ 60 = _____ scfm

WORKSHEET 4-3.   PROCEDURE TO CALCULATE THE NET HEATING VALUE OF THE WASTE

Basis: Heating value is reported as a higher heating value (HHV) determined
         at standard 77°F (25°C).

Identify the following:

HHV = _____   Btu/lb waste
  H = _____   lbH/lb waste
 Cl = _____   lbCl/lb waste
  F = _____   lbF/lb waste
H_2O = _____   lb/moisture/lb waste

Calculate the net heating value (NHV):

$$NHV = HHV - 1,050 \left[H_2O + 9\left(H - \frac{Cl}{35.5} - \frac{F}{19}\right)\right] = \underline{\hspace{3cm}} \text{ Btu/lb waste}$$

WORKSHEET 4-4.   PROCEDURE TO CALCULATE STOICHIOMETRIC AIR REQUIREMENTS,
               APPROXIMATE COMBUSTION GAS FLOWS, AND APPROXIMATE GAS
               COMPOSITIONS

1.   Identify the elemental composition and moisture content of the wastes fed
     to the kiln.

	1. Solids (kiln)	2. Liquids (kiln)	
Carbon, C_w:	_____	_____	lb/lb waste
Fuel hydrogen, H_w:	_____	_____	lb/lb waste
Moisture, H_2O_w:	_____	_____	lb/lb waste
Oxygen, O_w:	_____	_____	lb/lb waste
Nitrogen, N_w:	_____	_____	lb/lb waste
Chlorine, Cl_w:	_____	_____	lb/lb waste
Fluorine, F_w:	_____	_____	lb/lb waste
Bromine, Br_w:	_____	_____	lb/lb waste
Iodine, I_w:	_____	_____	lb/lb waste
Sulfur, S_w:	_____	_____	lb/lb waste
Phosphorus, P_w:	_____	_____	lb/lb waste

2.   Identify the approximate liquid and solid waste feed rates to the kiln,
     and calculate the liquid/solid feed fractions.

Liquid feed rate, m_1 = _____ lb/hr

Solid feed rate, m_2 = _____ lb/hr

Total feed, $m_{12} = m_1 + m_2$ = _____ lb/hr

Liquid fraction, $n_1 = m_1/m_{12}$ = _____ lb liquid/lb waste

Solid fraction, $n_2 = 1-n_1$ = _____ lb solid/lb waste

3.   If auxiliary fuel is to be burned in conjunction with the wastes, identify
     the fuel type and approximate, proposed fuel-to-waste ratio.

Fuel type: _____
Fuel:waste ratio in kiln: n_{fK} = _____ lb fuel/lb waste

4.   Determine the approximate elemental composition of the fuel from the
     following table.

	lb component/lb fuel [21]		
Component	Residual fuel oil (e.g. No. 6)	Distillate fuel oil (e.g. No. 2)	Natural gas
C_f	0.866	0.872	0.693
H_f	0.102	0.123	0.227
N_f	-	-	0.08
S_f	0.03	0.005	-

5. Calculate the composition of the combined waste/auxiliary fuel feed to the kiln.

$$C_k: \quad \frac{n_1 C_1 + n_2 C_2 + n_f C_f}{1 + n_f} \quad = \underline{\hspace{2cm}} \text{ lb/lb feed}$$

$$H_k: \quad \frac{n_1 H_1 + n_2 H_2 + n_f H_f}{1 + n_f} \quad = \underline{\hspace{2cm}} \text{ lb/lb feed}$$

$$H_2O_k: \quad \frac{n_1 H_2O_1 + n_2 H_2O_2}{1 + n_f} \quad = \underline{\hspace{2cm}} \text{ lb/lb feed}$$

$$N_k: \quad \frac{n_1 N_1 + n_2 N_2 + n_f N_f}{1 + n_f} \quad = \underline{\hspace{2cm}} \text{ lb/lb feed}$$

$$O_k: \quad \frac{n_1 O_1 + n_2 O_2}{1 + n_f} \quad = \underline{\hspace{2cm}} \text{ lb/lb feed}$$

$$Cl_k: \quad \frac{n_1 Cl_1 + n_2 Cl_2}{1 + n_f} \quad = \underline{\hspace{2cm}} \text{ lb/lb feed}$$

$$F_k: \quad \frac{n_1 F_1 + n_2 F_2}{1 + n_f} \quad = \underline{\hspace{2cm}} \text{ lb/lb feed}$$

$$Br_k: \quad \frac{n_1 Br_1 + n_2 Br_2}{1 + n_f} \quad = \underline{\hspace{2cm}} \text{ lb/lb feed}$$

$$I_k: \quad \frac{n_1 I_1 + n_2 I_2}{1 + n_f} \quad = \underline{\hspace{2cm}} \text{ lb/lb feed}$$

$$S_k: \quad \frac{n_1 S_1 + n_2 S_2 + n_f S_f}{1 + n_f} \quad = \underline{\hspace{2cm}} \text{ lb/lb feed}$$

$$P_k: \quad \frac{n_1 P_1 + n_2 P_2}{1 + n_f} \quad = \underline{\hspace{2cm}} \text{ lb/lb feed}$$

6. Calculate the stoichiometric oxygen requirement for the kiln, based on the combustion reactions described in Section 4.3.2.1.

$$C_k \times 2.67 \frac{\text{lb } O_2}{\text{lb } C} \quad = \underline{\hspace{2cm}} \text{ lb } O_2/\text{lb feed}$$

$$\left(H_k - \frac{Cl_k}{35.5} - \frac{F_k}{19} \right) \times 8.0 \frac{\text{lb } O_2}{\text{lb } H} = \underline{\hspace{2cm}} \text{ lb } O_2/\text{lb feed}$$

$$S_k \times 1.0 \frac{\text{lb } O_2}{\text{lb } S} \quad = \underline{\hspace{2cm}} \text{ lb } O_2/\text{lb feed}$$

4-84

$$P_k \text{ x } 1.29 \frac{\text{lb } O_2}{\text{lb P}} \qquad\qquad = \underline{\hspace{3cm}} \text{ lb } O_2/\text{lb feed}$$

$$-O_k \text{ (in feed)} \qquad\qquad = - \underline{\hspace{3cm}} \text{ lb}/O_2/\text{lb feed}$$

$$\overline{(O_2)_{\text{stoich}(k)}} = \sum = \underline{\hspace{3cm}} \text{ lb } O_2/\text{lb feed}$$

7. Calculate the combustion gas mass flows, based on the stoichiometric oxygen requirement (assume complete combustion is achieved for purposes of gas flow estimation).

$$CO_{2k}: \quad C_k \text{ x } 3.67 \frac{\text{lb } CO_2}{\text{lb C}} \qquad\qquad\qquad = \underline{\hspace{2cm}} \text{ lb } CO_2/\text{lb feed}$$

$$H_2O_k: \quad \left[\left(H_k - \frac{Cl_k}{35.5} - \frac{F_k}{19}\right) \text{ x } 9.0 \frac{\text{lb } H_2O}{\text{lb H}}\right]$$

$$+ H_2O_k \text{ (in feed)} = \underline{\hspace{2cm}} \text{ lb } H_2O/\text{lb feed}$$

$$N_{2k}: \quad \left[(O_2)_{\text{stoich}(k)} \text{ x } 3.31 \frac{\text{lb } N_2}{\text{lb } O_2} \text{ (in air)}\right]$$

$$+ N_k \text{ (in feed)} \qquad = \underline{\hspace{2cm}} \text{ lb } N_2/\text{lb feed}$$

$$HCl_k: \quad Cl_k \text{ x } 1.03 \frac{\text{lb } HCl}{\text{lb Cl}} \qquad\qquad = \underline{\hspace{2cm}} \text{ lb } HCl/\text{lb feed}$$

$$HF_k: \quad F_k \text{ x } 1.05 \frac{\text{lb } HF}{\text{lb F}} \qquad\qquad = \underline{\hspace{2cm}} \text{ lb } HF/\text{lb feed}$$

$$Br_{2k}: \quad Br_k \qquad\qquad\qquad = \underline{\hspace{2cm}} \text{ lb } Br_2/\text{lb feed}$$

$$I_{2k}: \quad I_k \qquad\qquad\qquad = \underline{\hspace{2cm}} \text{ lb } I_2/\text{lb feed}$$

$$SO_{2k}: \quad S_k \text{ x } 2.0 \frac{\text{lb } SO_2}{\text{lb S}} \qquad\qquad = \underline{\hspace{2cm}} \text{ lb } SO_2/\text{lb feed}$$

$$P_2O_{5k}: \quad P_k \text{ x } 2.29 \frac{\text{lb } P_2O_5}{\text{lb P}} \qquad\qquad = \underline{\hspace{2cm}} \text{ lb } P_2O_5/\text{lb feed}$$

$$\overline{\text{Kiln combustion products} = CP_k = \sum = \underline{\hspace{2cm}} \text{ lb}/\text{lb feed}}$$

4-85

8. Identify the elemental composition and moisture content of the liquid wastes to be burned in the afterburner (if any).

$$C_3: \underline{\hspace{2cm}} \text{ lb/lb waste}$$
$$H_3: \underline{\hspace{2cm}} \text{ lb/lb waste}$$
$$H_2O_3: \underline{\hspace{2cm}} \text{ lb/lb waste}$$
$$O_3: \underline{\hspace{2cm}} \text{ lb/lb waste}$$
$$N_3: \underline{\hspace{2cm}} \text{ lb/lb waste}$$
$$Cl_3: \underline{\hspace{2cm}} \text{ lb/lb waste}$$
$$F_3: \underline{\hspace{2cm}} \text{ lb/lb waste}$$
$$Br_3: \underline{\hspace{2cm}} \text{ lb/lb waste}$$
$$I_3: \underline{\hspace{2cm}} \text{ lb/lb waste}$$
$$S_3: \underline{\hspace{2cm}} \text{ lb/lb waste}$$
$$P_3: \underline{\hspace{2cm}} \text{ lb/lb waste}$$

9. Identify the fuel type and approximate, proposed fuel-to-waste ratio for the afterburner.

Fuel type: \underline{\hspace{3cm}}

Fuel: waste ratio, $n_{fA} = $ \underline{\hspace{4cm}} lb fuel/lb waste

10. Determine the approximate elemental composition of the fuel from the table shown in Step 4.

$$C_{fA} = \underline{\hspace{2cm}} \text{ lb/lb fuel}$$
$$H_{fA} = \underline{\hspace{2cm}} \text{ lb/lb fuel}$$
$$N_{fA} = \underline{\hspace{2cm}} \text{ lb/lb fuel}$$
$$S_{fA} = \underline{\hspace{2cm}} \text{ lb/lb fuel}$$

11. Calculate the composition of the combined waste/auxiliary fuel feed to the afterburner.

$$C_A: \quad \frac{C_3 + n_{fA} C_{fA}}{1 + n_{fA}} = \underline{\hspace{2cm}} \text{ lb/lb feed}$$

$$H_A: \quad \frac{H_3 + n_{fA} H_{fA}}{1 + n_{fA}} = \underline{\hspace{2cm}} \text{ lb/lb feed}$$

$$H_2O_A: \quad \frac{H_2O_3}{1 + n_{fA}} = \underline{\hspace{2cm}} \text{ lb/lb feed}$$

$$N_A: \quad \frac{N_3 + n_{fA} N_{fA}}{1 + n_{fA}} = \underline{\hspace{2cm}} \text{ lb/lb feed}$$

$$O_A: \quad \frac{O_3}{1 + n_{fA}} \qquad = \underline{\hspace{2cm}} \text{ lb/lb feed}$$

$$Cl_A: \quad \frac{Cl_3}{1 + n_{fA}} \qquad = \underline{\hspace{2cm}} \text{ lb/lb feed}$$

$$F_A: \quad \frac{F_3}{1 + n_{fA}} \qquad = \underline{\hspace{2cm}} \text{ lb/lb feed}$$

$$Br_A: \quad \frac{Br_3}{1 + n_{fA}} \qquad = \underline{\hspace{2cm}} \text{ lb/lb feed}$$

$$I_A: \quad \frac{I_3}{1 + n_{fA}} \qquad = \underline{\hspace{2cm}} \text{ lb/lb feed}$$

$$S_A: \quad \frac{S_3 + n_{fA}S_{fA}}{1 + n_{fA}} \quad = \underline{\hspace{2cm}} \text{ lb/lb feed}$$

$$P_A: \quad \frac{P_3}{1 + n_{fA}} \qquad = \underline{\hspace{2cm}} \text{ lb/lb feed}$$

12. Calculate the stoichiometric oxygen requirement for the afterburner feed, based on the combustion reactions described in Section 4.3.2.1.

$$C_A \times 2.67 \frac{\text{lb } O_2}{\text{lb C}} \qquad\qquad = \underline{\hspace{3cm}} \text{ lb } O_2/\text{lb feed}$$

$$\left(H_A - \frac{Cl_A}{35.5} - \frac{F_A}{19} \right) \times 8.0 \frac{\text{lb } O_2}{\text{lb H}} = \underline{\hspace{3cm}} \text{ lb } O_2/\text{lb feed}$$

$$S_A \times 1.0 \frac{\text{lb } O_2}{\text{lb S}} \qquad\qquad = \underline{\hspace{3cm}} \text{ lb } O_2/\text{lb feed}$$

$$P_A \times 1.29 \frac{\text{lb } O_2}{\text{lb P}} \qquad\qquad = \underline{\hspace{3cm}} \text{ lb } O_2/\text{lb feed}$$

$$\frac{-O_A \text{ (in feed)}}{} \qquad\qquad = - \underline{\hspace{3cm}} \text{ lb } O_2/\text{lb feed}$$

$$(O_2)_{stoich(A)} = \sum = \underline{\hspace{3cm}} \text{ lb } O_2/\text{lb feed}$$

13. Calculate the combustion gas mass flows, based on the stoichiometric oxygen requirement.

CO_{2_A}: C_A x $3.67 \frac{lb\ CO_2}{lb\ C}$ = _____ lb CO_2/lb feed

H_2O_A: $\left[\left(H_A - \frac{Cl_A}{35.5} - \frac{F_A}{19}\right) \times 9.0 \frac{lb\ H_2O}{lb\ H}\right]$

$\qquad\qquad\qquad\qquad\qquad$ + H_2O_A (in feed) = _____ lb H_2O/lb feed

N_{2_A}: $\left[(O_2)_{stoich(A)} \times 3.31 \frac{lb\ N_2}{lb\ O_2}\ (in\ air)\right]$

$\qquad\qquad\qquad\qquad\qquad$ + N_A (in feed) = _____ lb N_2/lb feed

HCl_A: Cl_A x $1.03 \frac{lb\ HCl}{lb\ Cl}$ = _____ lb HCl/lb feed

HF_A: F_A x $1.05 \frac{lb\ HF}{lb\ F}$ = _____ lb HF/lb feed

Br_{2_A}: Br_A = _____ lb Br_2/lb feed

I_{2_A}: I_A = _____ lb I_2/lb feed

SO_{2_A}: S_A x $2.0 \frac{lb\ SO_2}{lb\ S}$ = _____ lb SO_2/lb feed

$P_2O_{5_A}$: P_A x $2.29 \frac{lb\ P_2O_5}{lb\ P}$ = _____ lb P_2O_5/lb feed

_____

Afterburner combustion products = CP_A = $\sum$ = _____ lb/lb feed

14. Calculate the ratio of total afterburner feed to total kiln feed.

Liquid waste to kiln: m_1 = _____ lb/hr
Solid waste to kiln: m_2 = _____ lb/hr
Auxiliary fuel to kiln: $(m_1 + m_2)n_{fK}$ = _____ lb/hr

Liquid waste to afterburner: m_3 = _____ lb/hr

Auxiliary fuel to afterburner: $m_3 n_{fA}$ = _____ lb/hr

$$n_{AK} = \frac{(m_1 + m_2)(1 + n_{fK})}{m_3 \, n_{fA}} = \underline{\hspace{2cm}} \text{ lb afterburner feed/lb kiln feed}$$

15. Calculate the total combustion gas mass flows, based on stoichiometric oxygen requirements.

CO_2: $\dfrac{CO_{2_K} + CO_{2_A} \, n_{AK}}{1 + n_{AK}}$ = _____ lb/lb feed

H_2O: $\dfrac{H_2O_K + n_{AK} \, H_2O_A}{1 + n_{AK}}$ = _____ lb/lb feed

N_2: $\dfrac{N_{2_K} + n_{AK} \, N_{2_A}}{1 + n_{AK}}$ = _____ lb/lb feed

HCl: $\dfrac{HCl_K + n_{AK} \, HCl_A}{1 + n_{AK}}$ = _____ lb/lb feed

HF: $\dfrac{HF_K + n_{AK} \, HF_A}{1 + n_{AK}}$ = _____ lb/lb feed

Br_2: $\dfrac{Br_{2_K} + N_{AK} \, Br_{2_A}}{1 + n_{AK}}$ = _____ lb/lb feed

I_2: $\dfrac{I_{2_K} + n_{AK} \, I_{2_A}}{1 + n_{AK}}$ = _____ lb/lb feed

SO_2: $\dfrac{SO_{2_K} + n_{AK} \, SO_{2_A}}{1 + n_{AK}}$ = _____ lb/lb feed

P_2O_5: $\dfrac{P_2O_{5_K} + n_{AK} \, P_2O_{5_A}}{1 + n_{AK}}$ = _____ lb/lb feed

Combustion products = CP = $\sum$ = _____ lb/lb feed

16. Identify the total excess air rate for the system (i.e., to be maintained in the afterburner).

$$EA = \underline{\hspace{2cm}} \%$$

17. Calculate the additional nitrogen and oxygen present in the combustion gases due to excess air feed.

$$(O_2)_{EA} = EA \times \frac{(O_2)_{stoich(K)} + n_{AK}\,(O_2)_{stoich(A)}}{1 + n_{AK}} = \underline{\hspace{2cm}} \text{ lb } O_2/\text{lb waste}$$

$$(N_2)_{EA} = 3.31 \frac{\text{lb } N_2}{\text{lb } O_2} \text{ (in air)} \times (O_2)_{EA} = \underline{\hspace{2cm}} \text{ lb } N_2/\text{lb waste}$$

18. Calculate the total combustion gas flow.

$$\text{Combustion gas flow} = CG = CP + (O_2)_{EA} + (N_2)_{EA} = \underline{\hspace{2cm}} \text{ lb/lb feed}$$

19. Calculate the mass fraction of each combustion gas component.

CO_2: $\dfrac{CO_2}{CG}$ $= \underline{\hspace{2cm}}$ lb/lb gas

H_2O: $\dfrac{H_2O}{CG}$ $= \underline{\hspace{2cm}}$ lb/lb gas

N_2: $\dfrac{N_2(\text{from } 15) + (N_2)_{EA}}{CG}$ $= \underline{\hspace{2cm}}$ lb/lb gas

O_2: $\dfrac{(O_2)_{EA}}{CG}$ $= \underline{\hspace{2cm}}$ lb/lb gas

HCl: $\dfrac{HCl}{CG}$ $= \underline{\hspace{2cm}}$ lb/lb gas

HF: $\dfrac{HF}{CG}$ $= \underline{\hspace{2cm}}$ lb/lb gas

Br_2: $\dfrac{Br_2}{CG}$ $= \underline{\hspace{2cm}}$ lb/lb gas

I_2: $\dfrac{I_2}{CG}$ $= \underline{\hspace{2cm}}$ lb/lb gas

SO_2: $\dfrac{SO_2}{CG}$ = _____ lb/lb gas

P_2O_5: $\dfrac{P_2O_5}{CG}$ = _____ lb/lb gas

20. Identify those components that constitute less than 1-2% of the combustion gas. These components can be eliminated from further consideration in heat and material balance calculations. In most cases, CO_2, H_2O, N_2, and O_2 will be the only combustion gas components that need to be considered.

21. Calculate the volumetric flow of the major combustion products from the kiln at standard conditions of 68°F and 1 atm.

CO_2: $\left(\dfrac{CO_2}{CG}\right)$ x CG ÷ 0.114 lb/scf = _____ scf/lb

H_2O: $\left(\dfrac{H_2O}{CG}\right)$ x CG ÷ 0.0467 lb/scf = _____ scf/lb

N_2: $\left(\dfrac{N_2}{CG}\right)$ x CG ÷ 0.0727 lb/scf = _____ scf/lb

O_2: $\left(\dfrac{O_2}{CG}\right)$ x CG ÷ 0.083 lb/scf = _____ scf/lb

Other: $\left(\dfrac{Other}{CG}\right)$ x CG ÷ (0.00259 M) lb/scf = _____ scf/lb

where M = molecular weight

_____

Total flow, q = $\sum$ = _____ scf/lb feed

q x $(m_1 + m_2)$ $(1 + n_{fK})$ $(1 + n_{AK})$ ÷ 60 = _____ scfm

WORKSHEET 4-5. PROCEDURE TO CALCULATE EXCESS AIR RATE FOR A SPECIFIED TEMPERATURE AND FEED COMPOSITION

1. Identify the following input variables:

   From Worksheet 4-2, Step #5

   $(O_2)_{stoich}$ = _____ lb/lb feed

   From Worksheet 4-2, Step #6

   CO_2 = _____ lb/lb feed
   H_2O = _____ lb/lb feed
   N_2 = _____ lb/lb feed
   Other major component(s) = _____ lb/lb feed

   From Worksheet 4-3

   NHV_{waste} = _____ Btu/lb waste

   From proposed operating conditions

   Operating temperature, T = _____ °F

   Air preheat temperature, T_{air} = _____ °F
   (if applicable)

   If auxiliary fuel is to be burned in conjunction with the waste, also identify the following from Worksheet 4-2.

   n_f = _____ lb fuel/lb waste
   HV_f = _____ Btu/lb fuel

2. If air preheating is employed, calculate the corresponding enthalpy input to the incinerator. If the combustion air is not to be preheated, proceed to Step #3.

   $\Delta H_1' = 1.06(T_{air} - 77)(O_2)_{stoich}$
   = _____ Btu/lb feed

   $\Delta H_1 = \Delta H_1'(1 + EA)$

3. Calculate the heat generated by combustion of the waste or waste/auxiliary fuel mix.

   $$\Delta H_2 = \frac{NHV_{waste} + n_f \, HV_f}{1 + n_f}$$

   = _____ Btu/lb feed

4. Calculate the heat loss through the walls of the incinerator, assuming 5% loss.

4-92

$Q = 0.05\ \Delta H_2$

$\qquad = \underline{\hspace{2cm}}$ Btu/lb feed

5. Calculate the enthalpy of the combustion products leaving the incinerator.

$0.26(CO_2 + N_2)(T - 77) \quad = \qquad \underline{\hspace{2cm}}$ Btu/lb feed

$0.49\ H_2O(T - 77) = \qquad \underline{\hspace{2cm}}$ Btu/lb feed

Other $x\ \overline{C}_{p\ other}\ (T - 77) = \qquad \underline{\hspace{2cm}}$ Btu/lb feed

$\overline{\phantom{Other\ x\ \overline{C}_{p\ other}\ (T - 77)}}$

$\Delta H_3 = \sum = \underline{\hspace{2cm}}$ Btu/lb feed

6. Calculate the enthalpy of excess air leaving the incinerator.

$\Delta H_4{}' = 1.1(T - 77)(O_2)_{stoich}$

$\qquad = \underline{\hspace{2cm}}$ Btu/lb feed

$\Delta H_4 = \Delta H_4{}' \times EA$

7. Calculate the excess air percentage as follows:

$$EA = 100\left(\frac{\Delta H_1{}' + \Delta H_2 - Q - \Delta H_3}{\Delta H_4{}' - \Delta H_1{}'}\right)$$

$\qquad = \underline{\hspace{2cm}}$ %

WORKSHEET 4-6. PROCEDURE TO ESTIMATE THE MAXIMUM ACHIEVABLE GAS RESIDENCE TIME
AFTER THE DESIRED OPERATING TEMPERATURE HAS BEEN ACHIEVED

1. Identify the following input variables:

Volume of the incinerator chamber, V = _____ ft^3

Combustion gas flow rate, q = _____ scfm

Operating temperature, T = _____ °F

2. Calculate the gas flow in actual cubic feet per second at operating temperature.

$$q' = \frac{q}{60} \left(\frac{T + 460}{528} \right)$$

= _____ acf/s

3. Calculate the maximum achievable gas residence time in the incinerator after the desired operating temperature has been achieved.

$$\theta_{max} = \frac{V}{q'}$$

= _____ s

WORKSHEET 4-7. PROCEDURE TO CALCULATE SUPERFICIAL GAS VELOCITY AT OPERATING TEMPERATURE

Identify the following input variables:

Gas flow rate at operating temperature, q' = _____ acf/s
  (See Worksheet 4-6)

Cross-sectional area of the incinerator chamber, A = _____ ft^2

Calculate:

Superficial gas velocity, v = q'/A

= _____ ft/s

WORKSHEET 4-8. PROCEDURE TO CALCULATE THE MAXIMUM ACHIEVABLE EXCESS AIR RATE
FOR A ROTARY KILN OPERATING AT A SPECIFIED TEMPERATURE WITH A
SPECIFIED FEED COMPOSITION

1. Identify the following input variables:

From Worksheet 4-4, Step 6

$(O_2)_{stoich(K)}$ = _____ lb O_2/lb kiln feed

From Worksheet 4-4, Step 7

$CO_2{}_{(K)}$ = _____ lb/lb feed

$H_2O_{(K)}$ = _____ lb/lb feed

$N_2{}_{(K)}$ = _____ lb/lb feed

Other major combustion product(s) = _____ lb/lb feed

From Worksheet 4-4, Step 2

Liquid waste feed fraction, n_1 = _____ lb liquid/lb waste
Solid waste feed fraction, n_2 = _____ lb solid/lb waste

From Worksheet 4-3

Liquid waste heating value, NHV_1 = _____ Btu/lb
Solid waste heating value, NHV_2 = _____ Btu/lb

From proposed operating conditions

Kiln operating temperature, T_K = _____ °F
Air preheat temperature, T_{air} = _____ °F
    (if applicable)

If auxiliary fuel is to be burned in the kiln along with the wastes
during normal operation, identify the following from Worksheet 4-4:

n_{fK} = _____ lb fuel/lb waste
HV_{fK} = _____ Btu/lb fuel

4-96

2. If air preheating is employed, calculate the corresponding enthalpy input to the kiln. If the combustion air is not preheated, proceed to Step 3:

$$\Delta H_1{}'_{(K)} = 1.06 \ (T_{air} - 77)(O_2)_{stoich(K)} = \underline{\hspace{2cm}} \text{ Btu/lb feed}$$

$$\Delta H_1{}_{(K)} = \Delta H_1{}'_{(K)} \ (1 + EA_K)$$

3. Calculate the maximum heat generated in the kiln by combustion of the wastes or waste/auxiliary fuel mix:

$$\Delta H_2 \quad = \frac{n_1 NHV_1 + n_2 NHV_2 + n_{fK} HV_{fK}}{1 + n_{fK}} = \underline{\hspace{2cm}} \text{ Btu/lb feed}$$

4. Estimate the heat loss through the walls of the kiln, assuming 5% loss:

$$Q_{(K)} = 0.05 \ \Delta H_2{}_{(K)} = \underline{\hspace{2cm}} \text{ Btu/lb feed}$$

5. Calculate the enthalpy of the combustion products leaving the kiln:

$$0.26 \left(CO_2{}_{(K)} + N_2{}_{(K)} \right) (T_K - 77) \qquad = \underline{\hspace{2cm}} \text{ Btu/lb feed}$$

$$0.49 \ H_2O_{(K)} \ (T_K - 77) \qquad = \underline{\hspace{2cm}} \text{ Btu/lb feed}$$

$$Other_K \left(\frac{lb}{lb \ feed} \right) \times \overline{C}_p \ other \ (T_K - 77) = \underline{\hspace{2cm}} \text{ Btu/lb feed}$$

$$\rule{6cm}{0.4pt}$$

$$\Delta H_3{}_{(K)} = \sum = \underline{\hspace{2cm}} \text{ Btu/lb feed}$$

6. Calculate the enthalpy of excess air levaing the kiln:

$$\Delta H_4{}'_{(K)} = 1.1 \ (T_K - 77) \ (O_2)_{stoich(K)} = \underline{\hspace{2cm}} \text{ Btu/lb feed}$$

$$\Delta H_4{}_{(K)} = \Delta H_4{}'_{(K)} \ EA_K$$

7. Calculate the excess air percentage as follows:

$$EA_K = 100 \left(\frac{\Delta H_1{}'_{(K)} + \Delta H_2{}_{(K)} - Q_K - \Delta H_3{}_{(K)}}{\Delta H_4{}'_{(K)} - \Delta H_1{}'_{(K)}} \right) = \underline{\hspace{2cm}} \%$$

WORKSHEET 4-9. PROCEDURE TO CALCULATE EXCESS AIR IN A ROTARY KILN AFTERBURNER FOR A SPECIFIED AFTERBURNER TEMPERATURE AND OVERALL FEED COMPOSITION

1. Identify the following input variables:

From Worksheet 4-4, Steps 6 and 12

$(O_2)_{stoich(K)}$ = _____ lb O_2/lb kiln feed

$(O_2)_{stoich(A)}$ = _____ lb O_2/lb afterburner feed

From Worksheet 4-4, Step 15

CO_2 = _____ lb/lb feed

H_2O = _____ lb/lb feed

N_2 = _____ lb/lb feed

Other major combustion product(s) = _____ lb/lb feed

From Worksheet 4-4, Step 14

Afterburner/kiln feed ratio, n_{AK} = _____ lb afterburner feed/lb kiln feed

From Worksheet 4-3

Afterburner waste heating value, NHV_3 = _____ Btu/lb

From proposed operating conditions

Afterburner temperature, T_A = _____ °F

Air preheat temperature, T_{air} = _____ °F
    (if applicable)

If auxiliary fuel is to be burned in the afterburner along with liquid wastes during normal operation, identify the following from Worksheet 4-4:

n_{fA} = _____ lb fuel/lb afterburner waste feed

HV_{fA} = _____ Btu/lb fuel

From Worksheet 4-8,

$\Delta H_{2(K)}$ = _____ Btu/lb kiln feed

4-98

2. If air preheating is employed, calculate the corresponding enthalpy input to the kiln and afterburner combined. If the combustion air is not pre-heated, proceed to Step 3:

$$\Delta H_1' = 1.06 \ (T_{air} - 77) \left[(O_2)_{stoich(K)} + (O_2)_{stoich(A)} \right] = \underline{\hspace{1cm}} \text{ Btu/lb feed}$$

$$\Delta H_1 = \Delta H_1' \ (1 + EA)$$

3. Calculate the heat generated in the kiln and afterburner by combustion of the total waste/auxiliary fuel feed:

$$\Delta H_{2(A)} = \frac{NHV_3 + n_{fA} HV_{fA}}{1 + n_{fA}} = \underline{\hspace{2cm}} \text{ Btu/lb afterburner feed}$$

$$\Delta H_2 = \frac{\Delta H_{2(K)} + n_{AK} \Delta H_{2(A)}}{1 + n_{AK}} = \underline{\hspace{2cm}} \text{ Btu/lb feed}$$

4. Estimate the heat loss through the walls of the kiln and afterburner, assuming 5% loss:

$$Q = 0.05 \ \Delta H_2 = \underline{\hspace{2cm}} \text{ Btu/lb feed}$$

5. Calculate the enthalpy of the combustion products leaving the afterburner:

$$0.26 \ (CO_2 + N_2) \ (T_A - 77) \qquad = \underline{\hspace{2cm}} \text{ Btu/lb feed}$$

$$0.49 \ H_2O \ (T_A - 77) \qquad = \underline{\hspace{2cm}} \text{ Btu/lb feed}$$

$$\text{Other} \left(\frac{lb}{lb \ feed} \right) \times \overline{C}_p \ \text{other} \ (T_A - 77) = \underline{\hspace{2cm}} \text{ Btu/lb feed}$$

$$\overline{}$$

$$\Delta H_3 = \sum = \underline{\hspace{2cm}} \text{ Btu/lb feed}$$

6. Calculate the enthalpy of excess air leaving the afterburner:

$$\Delta H_4' = 1.1 \ (T_A - 77) \left[(O_2)_{stoich(K)} + (O_2)_{stoich(A)} \right] = \underline{\hspace{2cm}} \text{ Btu/lb feed}$$

$$\Delta H_4 = \Delta H_4' \ EA$$

7. Calculate the excess air percentage in the afterburner:

$$EA = 100 \left(\frac{\Delta H_1' + \Delta H_2 - Q - \Delta H_3}{\Delta H_4' - \Delta H_1'} \right) = \underline{\hspace{2cm}} \%$$

WORKSHEET 4-10. PROCEDURE TO ESTIMATE SOLID WASTE RETENTION TIMES IN ROTARY KILNS

Identify the following input variables:

Kiln length, L	= _____	ft
Kiln diameter, D	= _____	ft
Slope of kiln, S	= _____	ft/ft
Rotation velocity, N	= _____	rpm

Calculation:

$$\theta_s = 0.19 \ (L/D)/SN = \underline{\hspace{2cm}} \ \text{min}$$

WORKSHEET 4-11. PROCEDURE TO CALCULATE AUXILIARY FUEL CAPACITY REQUIREMENTS
FOR STARTUP AT DESIGN AIR FLOW FOR WASTE COMBUSTION

1. Identify the following input data from the proposed operating conditions,
    Section 4.3.2, and/or Section 4.3.3.

    Auxiliary fuel type: _____

    Fuel heating value, NHV = _____ Btu/lb

    Desired operating temperature, T_{out} = _____ °F

    Average proposed waste feed rate, m_w = _____ lb/hr

    Stoichiometric oxygen requirement for waste,
    $(O_2)_{stoich(w)}$ = _____ lb O_2/lb waste

    Proposed excess air rate, EA = _____ %/100

2. Identify the stoichiometric oxygen requirements and combustion product
    yields for the auxiliary fuel from the following table.

Fuel	$(O_2)_{stoich(f)}$, lb/lb fuel	Combustion products yields, lb/lb fuel		
		CO_2	H_2O	N_2
Residual fuel oil (e.g., No. 6)	3.16	3.18	0.92	10.5
Distillate fuel oil (e.g., No. 2)	3.32	3.20	1.11	11.0
Natural gas	3.67	2.54	2.04	12.2

3. Calculate the enthalpy of the fuel combustion gases.

$$h_i = \sum n_{if} \overline{C_{pi}} (T_{out} - 77)$$
$$= \left[0.26(CO_2 + N_2) + 0.49 \ H_2O \right] (T_{out} - 77)$$
$$= \underline{\hspace{3cm}} \ Btu/lb \ fuel$$

4. Calculate the heat output from the unit associated with design air flow
    for waste combustion.

$$Q_1 = 1.12 \ m_w \ (O_2)_{stoich(w)} \ (1 + EA) \ (T_{out} - 77)$$
$$= \underline{\hspace{3cm}} \ Btu/hr$$

5. Calculate "enthalpy" of air consumed in fuel combustion.

$$h_2 = 1.12 \, (O_2)_{stoich(f)} \, (T_{out} - 77)$$

$$= \text{_____} \text{ Btu/lb fuel}$$

6. Calculate the heat of fuel combustion, less 5% heat loss through the refractory walls.

$$h_3 = 0.95 \, NHV_f = \text{_____} \text{ Btu/lb fuel}$$

7. Calculate the required auxiliary fuel capacity.

$$m_f = \frac{Q_1}{h_3 + h_2 - h_1} = \text{_____} \text{ lb fuel/hr}$$

8. If necessary for comparison with the reported auxiliary fuel rating, calculate the required auxiliary fuel capacity in Btu/hr.

$$Q_f = m_f \, NHV_f = \text{_____} \text{ Btu/hr}$$

WORKSHEET 4-12. PROCEDURE TO ESTIMATE PARTICULATE CONCENTRATION AND
EMISSION RATE FROM LIQUID INJECTION INCINERATORS

1. Identify the following input data:

   Ash content of waste, ASH = _____ wt%

   Average waste feed rate, m_w = _____ lb/hr

   Volumetric combustion gas flow rate, q = _____ scfm

   Volumetric fraction of oxygen in the gas, $(O_2)_v$ = _____

2. Calculate the particulate emission rate, based on the ash content of the
   waste

   m_p = ASH x m_w = _____ lb/hr

3. Correct the volumetric combustion gas flow rate to zero percent excess
   air.

   $q_a = q \left[1 - 4.77(O_2)_v \right]$ = _____ scfm

4. Calculate the particulate loading in the gas at zero percent excess
   air.

   $c_p = 117 \dfrac{m_p}{q_a}$ = _____ gr/scf

4-103

WORKSHEET 4-13. INTERNAL CONSISTENCY CHECK FOR PROPOSED CONDITIONS
OF GAS VELOCITY, LIQUID TO GAS RATIO, AND PRESSURE
DROP FOR VENTURI SCRUBBERS

1. Identify the following input data:

Proposed liquid to gas ratio, $\dfrac{Q_L}{Q_G}$ = _____ gal/1,000 ft^3

Proposed gas velocity (at the throat), U_G = _____ ft/s

Cross-sectional throat area, A = _____ ft^2

Gas density (downstream of throat), ρ_a = _____ lb/ft^3

ρ_a may be estimated from the ideal gas law:

$$\rho_a = \frac{M\ P}{RT}$$

where   M = average molecular weight of gas (normally about 30)
        P = absolute pressure (atm)
        R = gas constant = 0.73 atm ft^3/°R lb mol
        T = absolute temperature (°R)

2. Calculate the pressure drop, ΔP

$$\Delta P = \frac{(U_G)^2\ \rho_a A^{0.133}}{1270}\left(\frac{Q_L}{Q_G}\right)^{0.78} = \underline{\hspace{3cm}} \text{ in. WG}$$

WORKSHEET 4-14. PROCEDURE TO CALCULATE THE NUMBER OF PLATES
                REQUIRED FOR A SPECIFIED GASEOUS POLLUTANT
                REMOVAL EFFICIENCY[a]

1. Identify the desired removal efficiency for pollutant i.

   E_i = _____ %/100

2. From Table 4-19 or other sources, identify the average Murphree vapor
   phase efficiency for the plate tower

   E_{MV} = _____ %/100

3. Calculate the required number of plates

   $$N_\rho = \frac{\ln (1 - E_i)}{\ln (1 - E_{MV})} = \underline{\hspace{4cm}}$$

---

[a]This procedure is only applicable for gaseous pollutants that are highly
soluble or chemically reactive with the scrubbing liquid.

WORKSHEET 4-15. PROCEDURE TO CALCULATE THE MAXIMUM LIQUID TO GAS RATIO FOR PLATE TOWERS

1. Identify the inlet temperature to the tower and the tower diameter.

   T = _____ °F + 460 = _____ °R

   d = _____ ft

2. Identify the volumetric fraction of each major component in the gas.

   Y_{CO_2} = _____

   Y_{H_2O} = _____

   Y_{N_2} = _____

   Y_{O_2} = _____

   Y_{other} = _____

3. Calculate the average molecular weight of the gas

   $$\overline{M} = 44Y_{CO_2} + 18Y_{H_2O} + 28Y_{N_2} + 32Y_{O_2} + M_{other} Y_{other}$$

   = _____ lb/lb mol

4. Calculate the gas density

   $$\rho_G = 1.37 \frac{\overline{M}}{T(°R)} =$$ _____ lb/ft³

5. Determine the scrubber liquor density

   $$\rho_L =$$ _____ lb/ft³

6. Determine the Souders-Brown constant, K, from Reference 6 or other sources. (For 24-in. tray spacing, use K = 0.17)

7. Calculate the maximum liquid-to-gas ratio

$$\left(\frac{Q_L}{Q_G} \right)_{max} = \frac{630}{Kd} \left(\frac{\rho_G}{\rho_L - \rho_G} \right)^{0.5} = \underline{\hspace{3cm}} \text{ gal/1,000 ft}^3$$

WORKSHEET 4-16.   PROCEDURE TO CALCULATE PRESSURE DROP BETWEEN
THE INCINERATOR AND INDUCED DRAFT FAN

1. Identify and/or calculate the following input data relevant to the
    combustion gas:

    a)   From Section 4.3.2,

        Approximate waste feed rate, m   = _____ lb/hr
        Combustion gas mass flow, CG   = _____ lb/lb waste
        CG x m   = _____ lb/hr
        Combustion gas volumetric flow, q_{std} = _____ scfm

        Volumetric fraction of each major component in the gas

        Y_{CO_2} = _____

        Y_{H_2O} = _____

        Y_{N_2} = _____

        Y_{O_2} = _____

        Y_{other} = _____

    b)   Calculate the average molecular weight of the gas

        $$\bar{M} = 44\ Y_{CO_2} + 18\ Y_{H_2O} + 28\ Y_{N_2} + 32\ Y_{O_2} + M_{other}\ Y_{other}$$

        = _____ lb/lb mol

2. Calculate the actual gas flow rate and gas density at the <u>entrance</u> to
    each gas conditioning or air pollution control device and <u>the fan</u> using
    the following equations:

    $$q = q_{std}\left(\frac{T°F + 460}{528}\right),\ acfm$$

    $$\rho_{gas} = 137\left(\frac{\bar{M}}{T°F + 460}\right),\ lb/ft^3$$

4-108

Location (inlet)	q, acfm	ρ_{gas}, lb/ft^3
Quench tower		
Scrubber		
Demister		
Fan		
Other (specify) _____		

Approximate gas temperatures at these locations need to be determined.

3. From manufacturer specifications, estimate the pressure drop across each gas conditioning device for the gas flow rates calculated in the preceding step.

Location	ΔP, in. H$_2$O
Quench tower	
Scrubber	
Demister	
Other (specify) _____ _____	
TOTAL	

4. For the segments of ductwork entering the aforementioned devices, determine the inner diameter (D), the cross-sectional area of the duct (A_d), the cross-sectional area of the device <u>preceding</u> the duct (A_p), the length of straight duct (L_s), the radius of curvature of any bends in the duct (R), and the gas velocity through the duct.

If the duct is square, use the length of a side as the equivalent diameter. If the duct is rectangular, calculate an equivalent diameter by the following equation:

$$D = \frac{2\ ab}{a + b}, \text{ where a and b are width and depth of the duct.}$$

Figure 4-15 in Section 4.4.4 shows how radii of curvature can be estimated.

Gas velocities can be calculated by the following equation:

$$V = \frac{q}{60A_d}, \text{ ft/s}$$

Location (inlet duct)	D, in.	A_d, ft^2	A_p, ft^2	A_d/A_p	L_s, ft	R, in.	V, ft/s
Quench tower							
Scrubber							
Demister							
Fan							
Other (specify) _____							

4-109

5. Calculate the pressure drop across each straight length of ductwork using Figure 4-13 in Section 4.4.4. and the known diameters of the ducts, combustion gas mass flow rate, average molecular weight of the gas, and temperatures at the specified locations.

   Figure 4-13 yields pressure drop values per length of straight duct. These can be converted to total pressure drops by the following calculation:

   $$\Delta P = \left(\frac{\Delta P}{L} \right) L_s, \text{ in } H_2O$$

Location (inlet duct)	ΔP, in. H_2O
Quench tower	
Scrubber	
Demister	
Fan	
Other (specify) _____	_____

6. Estimate the pressure drop across any bends in the ductwork.

   Figure 4-14 in Section 4.4.4 shows L_e/D values as a function of R/D for 90° bends,

   where L_e = equivalent length, in.
   - D = diameter, in.
   - R = radius of curvature, in.

   L_e/D values can be converted to pressure drops by the following calculation:

   $$\Delta P' = \Delta P \left(\frac{L_e}{D} \right) \left(\frac{12D}{L_s} \right), \text{ in. } H_2O$$

   where $\Delta P'$ = pressure drop across the bend in the duct, in. H_2O

   For 45° bends, $\Delta P'$ is about 65% of that calculated for a 90° bend. For 180° bends, $\Delta P'$ is about 140% of that calculated for a 90° bend. Thus,

   $$\Delta P'_{(45°)} = 0.65 \ \Delta P'_{(90°)}$$

   $$\Delta P'_{(180°)} = 1.4 \ \Delta P'_{(90°)}$$

```
        Location
        (inlet duct                          ΔP', in. H₂O

        Quench tower
        Scrubber
        Demister
        Fan
        Other (specify) _____        _____

            TOTAL
```

7. Estimate the additional pressure drops due to sudden contraction of flow at the entrance to each duct.

$$\Delta P' = .003 \ K_c \ \rho_{gas} \ V^2, \text{ in. } H_2O$$

where $\Delta P'' =$ pressure drop due to contraction, in H_2O

$\rho_{gas} =$ gas density, lb/ft^3

$V =$ gas velocity, ft/s

$K_c =$ sudden contraction-loss coefficient

K_c is a function of the ratio of the duct cross-sectional to the cross-sectional area of the preceding vessel, A_d/A_p. Table 4-21 in Section 4.4.4 shows this relationship.

```
        Location
        (inlet duct)                         ΔP", in. H₂O

        Quench tower
        Scrubber
        Demister
        Fan
        Other (specify) _____        _____

            TOTAL
```

8. Calculate the total pressure drop across the system by summing the totals from Steps 3, 5, 6, and 7

$$\Delta P_{total} = \underline{\hspace{2cm}} \text{ in. } H_2O$$

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CHAPTER 5

OVERALL FACILITY DESIGN, OPERATION, AND MONITORING

CONTENTS

CHAPTER 5

OVERALL FACILITY DESIGN, OPERATION, AND MONITORING

5.1 INTRODUCTION

Incineration is one controlled combustion process used in the ultimate disposal of unusable hazardous wastes that result from industrial and chemical manufacture. Careful selection of equipment and processes for the incineration of chemical wastes is essential to ensure that the basic obligations of safe handling and proper ultimate disposal are met in a satisfactory manner. In addition to fulfilling social obligations, an effective system will satisfy regulatory needs with minimum, adverse community reaction.

Prior to incineration, the handling, storage, and feeding of hazardous wastes require special care to ensure safety and reduce exposure. During incineration and while the facility operates, certain parameters must be monitored by the operators to assure that proper conditions are maintained in day-to-day operation.

Although the problems are substantially reduced, incineration of hazardous waste materials alone does not eliminate all of the disposal problems associated with hazardous waste. Most incinerators produce combustion products that must be properly removed prior to discharging gas products to the environment. These products include ash or inert residues from such things as silica oxides and/or metals. Captured gas products, such as HCl, when reacted with caustic solutions in the scrubber, can also produce dissolved and suspended solids. These solutions from the quench process and scrubber reactions must be carefully disposed of to ensure the entire sequence of combustion is safe. Whenever these wastes are of a nonhazardous nature, standard procedures can be used for their treatment and ultimate disposal. However, in some cases the secondary wastes can be hazardous themselves and require special handling.

5.1.1 Purpose

The purpose of this chapter is to provide the permit writer with engineering back-up information to supplement the guidance criteria necessary to judge the capability of the overall incineration facility to technically and practically process and monitor hazardous wastes safely and effectively.

This chapter discusses overall facility layouts, requirements common to all facilities, site and combustor specific requirements, material and process flows, waste receiving procedures, waste and other storage, material handling equipment, emergency and safety procedures and provisions, personnel safety, monitoring for the incineration process itself, monitoring of the air

pollution control system, monitoring of waste handling and treatment systems, monitoring and controlling parts of the overall facility that may become fugitive emission sources, proper handling and disposal of quench/scrubber water and ash, and sampling and analysis of wastewaters and ash.

5.1.2 Hazardous Waste Incinerator Facility Design

The overall facility design of hazardous waste incinerators is significantly influenced by the category of waste involved; i.e., solids, liquids, or sludges. The systematic approach to facility design, therefore, requires investigation of the composition of each class of waste to define the equipment and operating procedures for each of the following elements:

1. Safety (toxicity, fire explosion)
2. Transportation and unloading
3. Segregation of wastes during storage
4. Storage
5. Handling and feeding
6. Monitoring
7. Fugitive emission control
8. Scrubber/quench water treatment
9. Residue handling and disposal
10. Secondary problems (e.g., stream pollution, runoff, ground-water contamination).

The overall success of an incinerator facility depends upon the successful integration of storage, feeding, and firing equipment; often these are areas which do not receive as much attention as is necessary. In the case of hazardous waste incineration it is crucial that these areas require special attention.

Figure 5-1 is a block diagram of a typical incinerator facility layout. In an overall facility evaluation, the key areas are the facilities and equipment before and after the combustor; i.e., waste receiving, waste storage, waste blending, transfer between these areas, equipment feeding waste to the incinerator, handling and treatment of quench and scrubber waters, and ash disposal.

5.2 INCINERATOR FACILITY SITE SELECTION AND OPERATION

5.2.1 Site Selection Concerns

The Guidance Manual for Location Standards contains guidance for complying with general (i.e., applicable to all facilities) location standards ¶264.18. Flood plains, holocene faults, and endangered and threatened species are discussed.

The selection of a site for a hazardous waste incineration facility is a phased decision process which has occurred prior to making a permit application. Site screening is the process of identifying and evaluating a parcel of land for its suitability as a hazardous waste disposal site. Specific site-screening criteria which the permit applicant has addressed include geologic, hydrogeologic, topographic, economic, social, and political aspects. While many sites may exist which meet technical, economic, and ecological criteria,
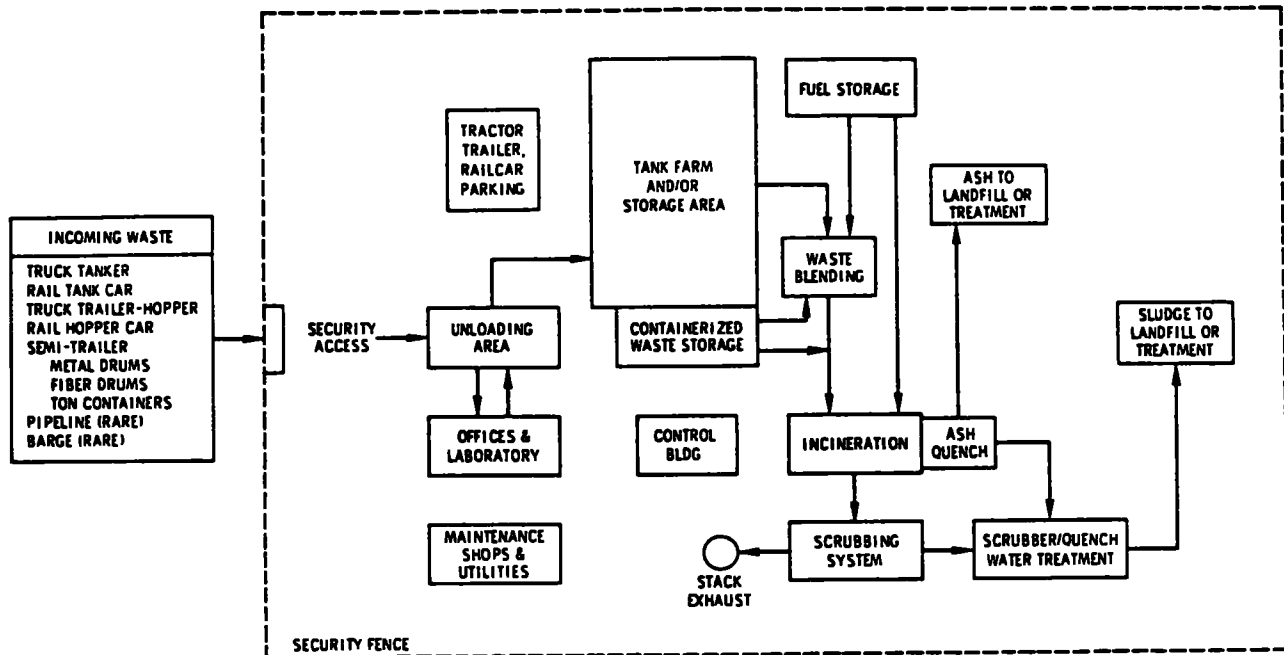
Figure 5-1. Typical incinerator facility layout.

public acceptance or rejection may ultimately decide the fate of the facility [1].

The main geological constraints that can render a site unsuitable for a hazardous waste incinerator facility are historical or predicted seismic activity, landslide potential, soil slump of solifluction, and volcanic or hot spring activities.

The main topographic constraints are susceptibility to flooding, erosion, and offsite drainage runoff. The site will need sufficient area for the construction of a runoff-holding pond (or diversion to an existing holding pond) to retain surface runoff which may contain hazardous substances in solution. Because of the holding pond and flood protection criteria, siting in flood plains is not normally acceptable.

The primary climatic features which can adversely affect an incineration site are the amount of annual or seasonal precipitation and incidence of severe storms. Copious precipitation will cause surface runoff and water infiltration through the soil. Runoff, that amount of rainfall that does not infiltrate the soil, depends on such factors as the intensity and duration of the precipitation, the soil moisture content, vegetation cover, permeability of the soil, and slope of the site. Normally, the runoff from a 10-year storm (recurrence interval of only once in 10 years) or annual spring thaw, whichever is greater, is containable by the site's natural topography. If not, berms, dikes, and other runoff control measures must be constructed to modify the site.

5-3

Ecological site features are those elements determined through earlier studies and environmental impact statements (EIS) which determine whether ecosystems at the site are in a delicate balance. Whether a site is a habitat for rare and endangered species; or used seasonally by migratory wildlife is also a factor determined for final site selection.

Cultural site features are those elements that are a direct result of human activities which modify and affect the site's desirability as a hazardous waste incineration facility--access, land-use, and aesthetics. Land areas zoned for nonresidential uses and adequate buffer zones are generally preferred for siting a hazardous waste management facility. The site ideally needs to contain sufficient land area to provide a concentric ring of unoccupied space as a buffer zone between active storage, treatment, and disposal areas, and the nearest area of human activity. Vegetation, topography, distance, and artificial barriers are all potential means to screen facility activities from line-of-sight observations from commercial, residential, or recreational areas.

One of the most difficult problems faced by a hazardous waste incineration facility applicant has been that of gaining public approval from a community for construction of the facility. No matter how thoroughly the above parameters have been examined in the facility site selection, public acceptance or rejection probably decides the fate of the facility. Public awareness of the planned facility, early planning input, and active participation by political leaders, public officials, environmental groups, as well as other public interest groups and adjacent industry have led to successful facility sitings in the past.

5.2.2 Operation of the Facility

Preplanning of the proper operation of a hazardous waste incineration facility is necessary to protect and prevent adverse effects of the facility on the public health or to the environment. Proper facility operation, on a day-to-day basis, includes plans and manuals of operation for handling wastes, safety at the site, monitoring of operating parameters, monitoring to assure protection of the environment, and operator training. These plans are developed within the operating company (and corporate structure) and are done in cooperation with other neighboring or similar organizations and with governmental agencies. It may not always be possible for all of them to fully cooperate or participate, but through planned action each organization is made aware of certain available assistances.

5.2.2.1 Operations Plan--
An operations plan includes the following:

(1) Classification of wastes to be handled and estimated quantities

(2) Methods and processes utilized

   (a) Facility capacity
   (b) Detailed description of each process

(3) Storage and disposal procedures

    (a) Plans for receipt, checking, processing, segregating incompatible wastes, and odor control
    (b) Life of facility based on projected use

(4) Monitoring Procedures

    (a) Monitoring of incinerator operating parameters
    (b) Monitoring and recording of incoming wastes
    (c) Leachate control and groundwater monitoring
    (d) Security system
    (e) System for monitoring water and air pollution affecting area outside the site
    (f) Air pollution control device monitoring

(5) Administrative Procedures

    (a) Hours of operation/day and days/week
    (b) Security procedures including entry control, hours manned, lighting, and other procedures to prevent unauthorized entry
    (c) Procedures planned and equipment available in case of break-downs, inclement weather, or other abnormal conditions.
    (d) Description of recordkeeping procedures, types of records to be kept, and use of records by management to control the operation.
    (e) List of general qualifications of key operating personnel
    (f) Maintenance and inspection schedules

5.2.2.2 Operations Manual--
Once in operation, the incinerator facility will maintain operation guides or manuals, covering the routine workings of the plant. An operations guide can include:

(1) A scaled engineering drawing, pictorial flow diagram, or scale model of the plant, showing all major components by name and function.
(2) A set of formal drawings at the plant for reference by operational and maintenance personnel
(3) Equipment manuals
(4) Equipment catalogs
(5) Spare parts lists
(6) Job or task functions for each assignment during a typical shift

5.2.2.3 Emergency Manual or Handbook--
An emergency manual or handbook is prepared which specifies the plan-of-action for any type of emergency the incinerator facility may reasonably expect to encounter. These include weather extremes (severe cold, heavy snowfall, hail damage, hurricanes, tornadoes, high winds, or lightning damage), floods, earthquakes, power outages, bomb scares, fires and explosion, and spills (See Section 5.2.2.5). The typical remedial actions for emergency situations presented in Table 5-1 cover many of the items that can be included in the

TABLE 5-1. HAZARDOUS WASTE INCINERATOR MALFUNCTIONS AND REMEDIAL OR EMERGENCY RESPONSES

No.	Malfunction	Type incinerator[a]	Malfunction indication	Response
1	Partial or complete stoppage of liquid waste feed delivery to all liquid burners	L C	(a) Flowmeter reading out of specified range (b) Pressure build-up in feed lines (c) Change in combustion zone temperature (d) Feed pump failure, zero amps	Halt waste feed, start trouble-shooting and maintenance in affected system. Reinitiate or increase auxiliary fuel feed to maintain combustion zone temperatures; continue operation of air pollution control devices (APCD)
2	Partial or complete stoppage of liquid waste to only one burner	L C	As in (a), (b) and (c), above	Halt waste feed to affected burner only
3	Partial or complete stoppage of solid wastes feed to rotary kiln	RK C	(a) Drop in RK combustion temperature (b) Power loss in waste feed conveyor or other feed system	As in 1, above
4	"Puffing", or sudden occurrence of fugitive emissions from RK due to thermal instability or excessive feed rate of wastes to RD, or failure of seals	RK C	(a) Pressure surge in kiln (rapid change in manometer level) (b) Visible emission from air seals at either end of kiln	(a) Halt feeding of any solid waste to kiln for 10-30 min, but continue combustion (b) Evacuate unneeded personnel from immediate vicinity of kiln (c) Reevaluate waste prior to further incineration

TABLE 5-1 (continued)

No.	Malfunction	Type incinerator[a]	Malfunction indication	Response
5	Failure of forced air supply to liquid waste feed or fuel burners	L RK C	(a) Flowmeter reading for air supply off scale (b) Automatic flame detector alarm activated (c) Zero amps or excessive current draw on blower motor(s)	(a) Halt waste and fuel feed immediately (b) Start trouble shooting immediately and restart as soon as possible (c) Continue operation of APCD's but reduce air flow at induced draft fan by "damping" accessory
6	Combustion temperature too high	L RK C	(a) Temperature indicator(s) at instrument control panel (b) Annunciator or other alarm sounded	(a) Check fuel or waste feed flow rates; reduce if necessary (b) Check temperature sensors (c) Check other indicators in combustor, if multiple sensors used (d) Automatic or manual activation of combustion chamber vent (sometimes called an "emergency stack cap")

TABLE 5-1 (continued)

No.	Malfunction	Type incinerator[a]	Malfunction indication	Response
7	Combustion temperature too low	L RK C	(a) - as above (b) - as above	(a) Check other indicators in combustor, if multiple sensors are used (b) Check fuel or waste feed flow rates; increase if necessary (c) Check sensor accuracy
8	Sudden loss of integrity of refractory lining	L RK C	(a) Sudden loud noise (b) Partial stoppage of air drawn into combustor, resulting in decreasing combustion temperatures, increased particulate emissions, and development of hot spots on external of combustor shell	Shut down facility as quickly as possible
9	Excess opacity of stack plume	L RK C	Visual, or instrument opacity readings which are above maximum allowable operating point	(a) Check combustion conditions, especially temperatures O_2 (excess air) and CO monitor (b) Check APCD operation (c) Check nature and feed rates of wastes being burned (d) Check ESP rapping interval, cycle duration and intensity

TABLE 5-1 (continued)

No.	Malfunction	Type incinerator[a]	Malfunction indication	Response
10	CO in exhaust gas in excess of 100 ppm, or in excess of normal CO values	L	CO indicator	Check and adjust combustion conditions, especially temperature and excess air (O_2 in stack gas), and adjust accordingly
11	Indication of or actual failure of Induced Draft Fan	L RK C	(a) Motor overheating (b) Excessive or zero current (amps) (c) Total stoppage of fan (d) Δp drop across blower inlet and outlet	(a) Switch to standby fan, if available (b) If two induced draft fans are used in series, reduce operational levels immediately, stop the failing unit, and operate at reduced rate on one fan only, until maintenance can be completed (c) If there is only one fan, and the fan failure appears serious, shift into an emergency shutdown mode for entire incinerator

TABLE 5-1 (continued)

No.	Malfunction	Type incinerator[a]	Malfunction indication	Response
12	Increase in gas temperature after quench zone, affecting scrubber operation	L RK C	(a) Partial or total loss of water supply to quench zone (b) Increase of combustion temperatures	(a) Check water flow to quench zone. Prepare for limited operation rate until water supply is restored (b) Check combustion conditions, especially temperature
13	Partial or complete stoppage of water or caustic solution to scrubber(s)	L RK	(a) Decrease in Δp across scrubber, as indicated by manometers, or other instruments (b) Zero or increased amps on water or solution pumps (c) Flowmeter readings out of specified range (d) Large increase in acid components in stack gas as detected by NDIR or other type instruments	(a) Halt waste feed, start troubleshooting and maintenance in affected system (b) Start up redundant pumps, if available (c) Check recycle water or solution tank levels (d) If using alkaline solution, switch to water supply if available (e) Check for deposition of solids from recycled liquors in pump lines (f) Use emergency (standby) water supply which will feed water by gravity until the whole system can be shutdown

TABLE 5-1 (continued)

No.	Malfunction	Type incinerator[a]	Malfunction indication	Response
14	Deposition of solids in scrubber from recycled wastes or caustic solution, or from excess solids emissions from combustor	L RK C	(a) Buildup of Δp across scrubber as indicated by manometers or other instruments. (b) Increased hold-up of liquor in packed or tray towers, up to and including flooded condition. This can also be detected by liquid level indicators.	This requires a shutdown to clean out the tower and internals. The shutdown can be scheduled if the deposit buildup is gradual and is monitored.
15	pH of recycled scrubber liquor not in spec	L RK C	(a) Continuous, or spot-checking pH indicator shows actual pH to be outside of desired operating range (d) Drop in scrubber efficiency with excess acid gas in stack gas	(a) Check for adequate supply and metering of alkaline agent (b) Check accuracy of pH meter and alkaline solution metering pump associated with recycling of scrubber liquor
16	Failure of demister operation	L RK C	Increased Δp, as measured by manometer, due to solids accumulation in demister element	Back-wash element

a. L = Liquid injection; RK = Rotary kiln; C = Combination liquid injection and rotary kiln.

emergency handbook, but other items may be needed as dictated by the anticipated emergencies and the available resources.

5.2.2.4 Leak Detection and Repair Plan--
Any facility that processes hazardous air pollutants as described under Section 112 of the Clean Air Act must develop a Leak Detection and Repair Plan (LDRP) to aid in reducing fugitive emissions [2]. The LDRP must be certified by the owner of the facility as meeting the fugitive emission criteria established by the EPA under the Clean Air Act. The plan is to be reviewed and updated, as required, once every three years, or within 90 days of a major modification at the facility. At the minimum, the LDRP:

(1) Develops a schedule and recordkeeping program for routine surveillance and/or monitoring of fugitive emissions.

(2) Establishs a written plan for detection and repair of leaks, and a reasonable schedule for repair.

(3) Provides a written plan for sampling procedures, housekeeping (e.g., small spill cleanup) and onsite waste handling.

(4) Develops recordkeeping procedures for all aspects of the LDRP and saves these records for one year.

(5) Establishes a written plan for specifying sufficient personnel to fulfill the LDRP, and provides a training program with a written manual.

5.2.2.5 Hazardous Chemical Spill Handling Plan--
Most plants' safety, disaster or operating plans and manuals do not fulfill the requirement for a spill-handling plan. The key to adequate spill-handling is decision-making. None of the above manuals or procedures supply the information required to make the decisions necessary to cope with the spill of a hazardous material. Thus, a chemical-spill-handling plan will fill an information need, but will not program decisions.

In a spill-handling plan, the decisions that must be made in a spill incident are defined. First, the plant or plant superintendent must accept the fact that a spill has occurred, based on information from his monitoring systems. The most immediate steps are those aimed at the protection of human life. If the information obtained about the location and nature of the leak/spill shows that the threat to life is "immediate and great," the decision should be to "shut down - all persons immediately take cover." Otherwise, the decision should be to "cleanup the area."

The "immediate cover" for persons is a spill response usually described by the plant disaster/emergency plan, whereas the protection of employees during the "cleanup the area" procedure is ordinarily contained in a safety plan. It is the lack of information between these two extremes that the spill-response plan fills.

Once a spill-response leader has been chosen, the decision-making process continues toward containment actions and disposition procedures. Figure 5-2 diagrams the decision-making process and information needed in a spill-handling situation, as well as the requirements for improving the spill response.

A spill-handling plan is written as an easy-to-consult document for decision-making, and includes:

(1) Monitoring all possible spills of materials

INFORMATION REQUIREMENTS   DECISION PROCESS   IMPROVEMENTS
                                                            REQUIREMENTS

SPILL-MONITORING   IS THERE A SPILL ?   NO   REVIEW AND/OR
INFORMATION   DON'T KNOW IMPROVE SPILL
                                                              MONITORING

                          YES

PLANT-EQUIPMENT CONTENTS   IS IT AN   YES   REVIEW AND/OR USE
AND MATERIAL-HAZARD   IMMEDIATE   DISASTER PLAN
INFORMATION   THREAT TO LIFE ?

                          NO

SPILL-RESPONSE CHAIN-   IS   NO   REVIEW SPILL RESPONSE
OF-COMMAND INFORMATION   THE LEADER   CHAIN OF COMMAND
                           AVAILABLE?

                          YES

                          WHAT CONTAINMENT   NONE   IMPROVE
                          ACTION SHOULD BE   AVAILABLE   CONTAINMENT
                          TAKEN ?   DEVICES

EQUIPMENT AVAILABLILITY   WHAT DEPOSTION   NONE   IMPROVE
AND MATERIAL-HAZARD   ACTION SHOULD BE   AVAILABLE   DEPOSITION
INFORMATION   TAKEN ?   CAPABILITY

                          ACTION

Figure 5-2. Spill-response diagram illustrating the interrelating information available, decisions to be taken, and improvements needed [3].

(2) Identifying of all plant equipment and other contents it may have (can be separated into convenient process groupings or modules)

(3) Describing hazards of materials that would comprise potential spills

(4) Designating the chain of command during a spill incident

(5) Specifying equipment available for containment, and disposition alternatives in response to a spill.

Every spill-handling plan has seven relatively independent parts that fulfill the five needs mentioned above. These parts are kept as autonomous as possible to facilitate the upgrading of each one. The seven parts are:

(1) List of contacts for spill emergencies, including plant/shift individuals, safety personnel, environmental control personnel, and government agency contacts, with home and office telephone numbers.

(2) Process flowsheets, showing primarily those pieces of equipment containing sufficient volume of material to constitute a potential spill problem.

(3) Site map.

(4) Chemical-effects list for all hazardous materials located within the boundaries of the plant.

(5) Monitoring checklist, consisting of a matrix indicating how equipment is monitored for potential spills.

(6) Containment alternatives matrix, describing the series of containments that occur in sequential order for various process equipment.

(7) Chemical-disposition alternatives, including a listing of equipment that are considered alternative places of material disposition for recovery, treatment, ultimate disposal.

5.2.2.6 Facility Security

Incineration facility security is management's responsibility. Basic security problems are protection of property and controlling access to the facility. Security procedures for hazardous waste disposal facilities are described in the Federal Register, Vol. 45, No. 98, Part 265 - Interim Status Standards for Owners and Operators of Hazardous Waste Treatment, Storage, and Disposal Facilities, Subpart B - General Facility Standards, 265.14 Security, pg. 33235, May 19, 1980.

5.2.2.7 Operator Practices and Training

Operator practices and training of personnel ensure the smooth, efficient running of a hazardous waste incineration facility. Some of the areas covered under practice and training include:

(1) Selection of personnel, pre-employment physicals, periodic examinations
(2) Training; e.g., supervisory, operator, emergency
(3) Operating manual use; e.g., development of the manual, process description, material specifications, safety considerations
(4) Instruction of personnel
(5) Start-up and shut-down procedures; e.g., problems of start-up, normal shut-down, emergency shut-down
(6) Maintenance and inspection
(7) Preparation for emergencies; e.g., recognition, alarms, simulated emergencies, disaster drills

Operator training procedures and rules are described in the Federal Register (as cited in Section 5.2.2.6), 265.16 - Personnel Training.

5.2.2.8 Loss Prevention Program

A loss prevention program embodies many of the facets of an emergency handbook, operations manual, and personnel training. Usually, loss prevention encompasses a whole facility concept and can include other concerns such as:

(1) Accident prevention
(2) Industrial Health and Hygiene
(3) Environmental Control
(4) Fires and explosions
(5) Fire prevention measures
(6) Explosion prevention measures

5.3 WASTE RECEIVING AREA

The type and nature of hazardous waste received at an incinerator facility will dictate the design and equipment of the waste receiving area. The physical types of hazardous waste which may be received are:

(1) Liquid
(2) Containerized materials, liquid and solids
(3) Dry solid materials
(4) Wet solid materials
    (a) Pumpable
    (b) Nonpumpable.

The types of receiving equipment for unloading can be divided into three general areas:

(1) Pumpable liquid transfer
(2) Container transfer
(3) Bulk solids transfer.

Figure 5-3 shows a generalized flow diagram of handling procedures for incineration of hazardous wastes. Careful consideration must be given to the layout, safety, and recordkeeping arrangements of the waste receiving area. Unloading material offers one of the greatest spill or toxic exposure
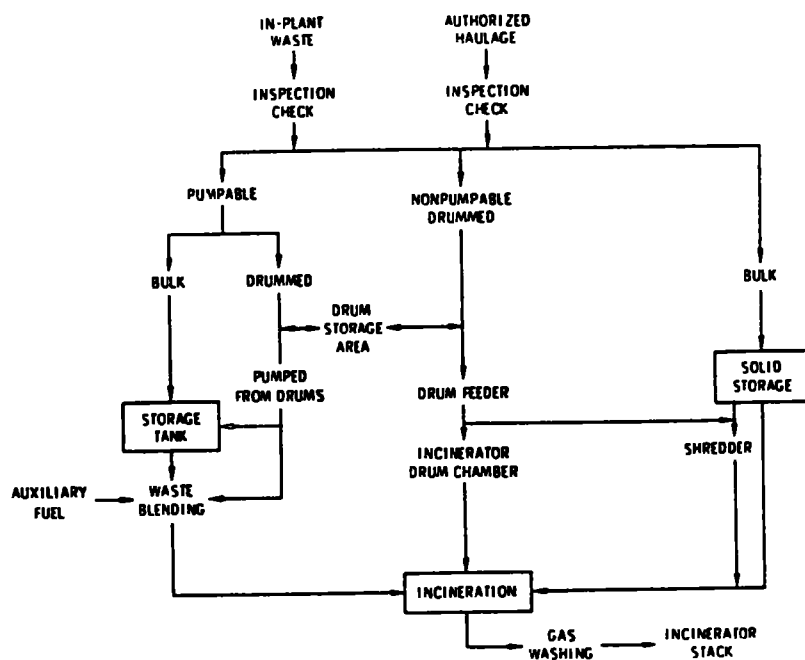
Figure 5-3. Flow diagram showing handling procedures
for incineration of hazardous wastes.

potentials at a hazardous waste facility. For recordkeeping, the waste
receiving area poses the first interface with the transporter and manifest
system.

5.3.1 Typical Operations and Layouts

A detailed flow sheet is a useful guide in laying out receiving areas, partic-
ularly those handling hazardous materials. The nature of the materials and
handling procedures can be studied and provisions made to eliminate or control
hazards.

Access to the incinerator facility will most likely be by truck or rail. (An
inspection procedure will be required for all incoming waste.) Figure 5-4
illustrates a receiving area layout of a facility designed to accommodate both
forms of transport. Most receiving areas for liquids will consist of a dock-
ing area, pumphouse, and storage facilities. For solid materials the pump-
house is replaced with mechanical or pneumatic conveyor devices. For receipt
of containers, a suitable docking area with conveyors and inspection appropri-
ate to the hazardous nature of the containers is necessary. Later sections
describe
in greater detail some of the equipment, handling procedures, and safety re-
quirements for each form of hazardous waste received.
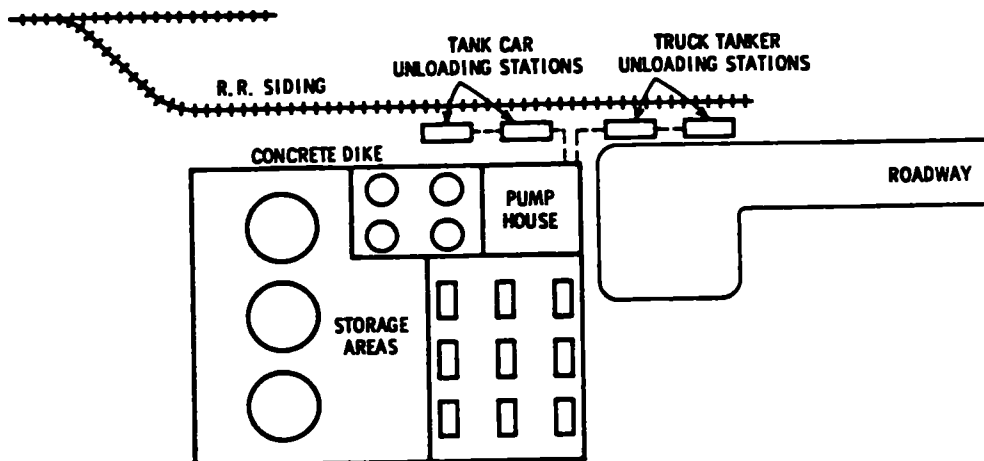
Figure 5-4. Layout for liquid receiving area.

5.3.2 Laboratory for Waste Verification and/or Characterization

Analytical data should be made available for all wastes to be incinerated.
The physical and chemical properties and the combustion characteristics of
each chemical waste or general classification of wastes, will be determined
before incineration. Only after such analysis can successful waste disposal
be carried out safely and without violation of air or water pollution
regulations as set forth by state and federal agencies.

A minimal but complete laboratory facility requires a working area, including
office facilities, of about 2,400 sq ft. Provisions are made for air, water,
gas, and electricity, preferably both AC and DC. The laboratory furniture in-
cludes benches, sinks, fume hood, shelving, glassware racks and a refrigerator.
Good lighting and air-conditioning are also important. Identification of
laboratory equipment needed for analyses of chemical wastes follows. Specific
requirements depend on the types of wastes to be processed and type of inciner-
ator used. If the equipment for sophisticated analytical methods is not
available in-house, the analyses can be performed by commercial analytical
laboratories.

   (1) Typical laboratory equipment to determine physical properties:

      (a) Specific gravity balance - specific gravity of liquids.

      (b) Brookfield viscosimeter - viscosity measurement of liquids and
         sludges.

      (c) Imhoff cones and centrifuge with graduated tubes -measurement
         of percent solids by volume.

      (d) Sieving machine for screen analysis (to 100 micron) and HIAC
         particle counter (100-5 micron) - particle size measurement.

(e) Cleveland open cup flash point tester - flash and fire point determinations.

(f) Oven and balances - percent solids and moisture by weight.

(g) Gas chromatograph-mass spectrometry and infrared apparatus to identify organic substances which may be toxic.

(h) Differential thermal analyzer - explosion characteristics and fusion temperature.

(i) Juno meter or equivalent - sensitive to alpha, beta and gamma rays for radioactivity.

(2) Laboratory equipment to determine chemical properties.

(a) Muffle furnace, oven, balances - for percent ash by weight.

(b) Orsat, fyrite techniques for flue gas analyses to provide data for excess air calculations.

(c) pH meter and automatic titrator - acidity and alkalinity measurement.

(d) Emission spectrograph for concentration and presence of metals.

(e) Atomic absorption spectrometer for concentration of metals and elements.

(f) Optical microscope for particulate characterization down to the sub-micron size. Electron microscope may be required for some sub-micron determinations.

(3) Laboratory equipment to determine combustion properties:

(a) Calorimeter for heating value and combustibility.

(b) Orsat (previously listed) for CO_2, CO, O_2, H_2 and N_2 analysis.

(c) Flue gas analyzer (previously listed) for analysis at various excess air rates.

(d) Mass spectrometer (previously listed) for hazardous products of combustion.

Reliable, bench-scale, chemical incineration equipment is generally unavailable. The present practice appears to follow the line of waste characterization, physical, chemical and combustibility analysis followed by a test burn in pilot or plant scale equipment.

5.3.3 Liquids Unloading

Liquids will arrive in bulk in tank cars or tank trucks by either truck or rail. Standard rail tank cars vary in capacity from 6,000 to 26,000 gallons and tank trucks carry up to 10,000 gallons. Figures 5-5 and 5-6 illustrate typical tank cars with parts and nomenclature identified.

The unloading stations are not normally located near important buildings or facilities. The site is arranged so that escaping liquid will flow to a safe location by utilizing the natural grade or by providing diversionary dikes or drains. (For more information, see Section 5.3.3.1). When possible, 50 feet or more of clear space is provided between unloading stations and buildings.

Hazardous liquids and "pumpable" materials are transferred through piping by pump, gravity flow, or compressed-gas displacement. Pumping systems are most commonly used and have an inherent safety advantage in that they can easily be arranged so that the flow of liquid ceases when the pump is stopped. Either direct-displacement or centrifugal pumps can be purchased in a wide variety of capacities suitable for a wide range of liquids.

The safest method of unloading tank cars or trucks is through the top by means of a pump, as shown in Figures 5-7 and 5-8, which also illustrate provisions for grounding and bonding to prevent static electricity discharges. Many tank cars are equipped with permanent unloading connections in the dome. For cars not so equipped, special covers are available to replace the dome cover during unloading. Bottom unloading, unloading by siphoning, or unloading by air pressure is undesirable, since accidental movement of the tank car during unloading may result in the escape of the entire contents of the car. Bottom unloading may be tolerated under favorable conditions if a remote control or a heat-actuated automatic shutoff is provided at the tank car connection.

Tank trucks are usually unloaded from the bottom by gravity or by pumps mounted on the vehicle. These methods are considered acceptable.

For the best methods when transferring liquid wastes:

(1) Positive-displacement pumps are preferred

(2) Centrifugal pumps are suitable for flammable-liquid service but cannot be used as shutoffs.

Positive-displacement pumps are preferred because, unlike centrifugal pumps, they afford a reasonably tight shutoff and prevent siphoning when not in operation. A relief valve is provided downstream of positive-displacement pumps, of sufficient capacity to prevent excess pressure in the system. The relief-valve discharge is then piped back to the supply source or to the suction side of the pump. With liquids having closed-cup flash points of 0°F or lower, the relief valve should be piped to the storage tank; otherwise the churning action of the pump might cause dangerous overheating.

Centrifugal pumps are suitable for flammable-liquid service but cannot be used as shutoffs, since they usually must take suction under a head. Submerged or
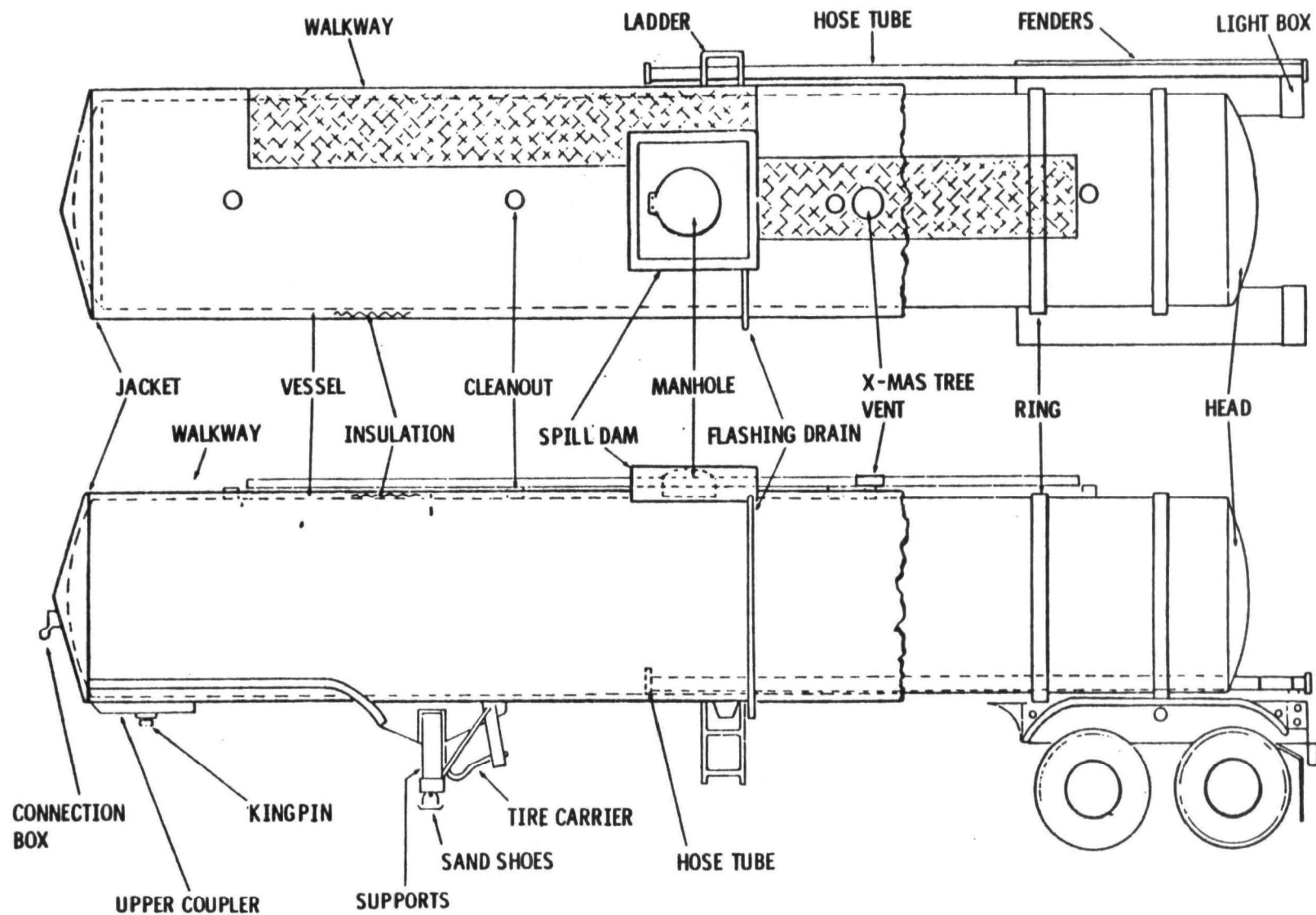
Figure 5-5. Typical tank trailer (car) with parts identified [4].
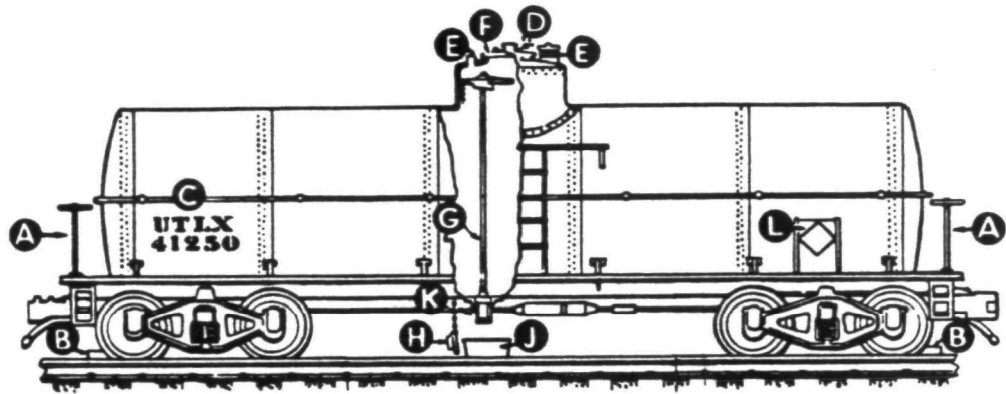
A. CAR BRAKE
B. WHEEL BLOCK
C. IDENTIFICATION NUMBER
D. CAR SEAL

E. SAFETY VALVE
F. DOME COVER
G. OUTLET LEG VALVE
H. OUTLET LEG CAP

J. DRAIN PAN
K. OUTLET NOZZEL
L. "FLAMMABLE" CARD

Figure 5-6. Typical tank car with parts identified [5].
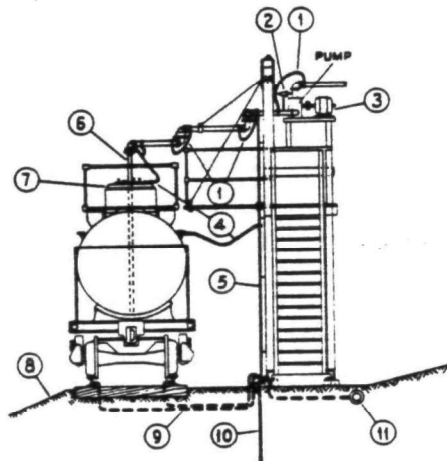
1. BONDING WIRE ATTACHED WITH GROUND CLAMP
2. RELIEF-VALVE BYPASS
3. EXPLOSIONPROOF MOTOR
4. INSULATED FLEXIBLE GROUNDING CABLE ATTACHED TO TANK CAR WITH GROUND CLAMP; NOT SMALLER THAN NUMBER 4
5. NO. 4 STRANDED CABLE SECURED TO PLATFORM COLUMN
6. NONFERROUS TUBE
7. SAFETY-DOME COVER
8. GROUND SLOPING AWAY FROM IMPORTANT FACILITIES
9. BARE-COPPER CONDUCTOR
10. GROUND ROD DRIVEN TO PERMANENT MOISTURE LEVEL
11. WATER MAIN, IF AVAILABLE

Figure 5-7. Tank car unloading station [6].

DOWNSPOUT SHOULD EXTEND TO NEAR BOTTOM OF TANK WHEN LOADING.

PIPE CLAMP

PLACE PIPE CLAMP ON EVERY PIPE & CONNECT TO COMMON GROUND

BARE STRANDED WIRE

WEIGHT

BUCKET BOX

WIRE

TRUCK GROUND

CONNECTION IS TO BE MADE BEFORE MANHOLE IS OPENED

FOR USE ON TRUCKS NOT EQUIPPED WITH GROUNDING PLUG

5/8" X 8'-0" GROUND ROD WITH CLAMP
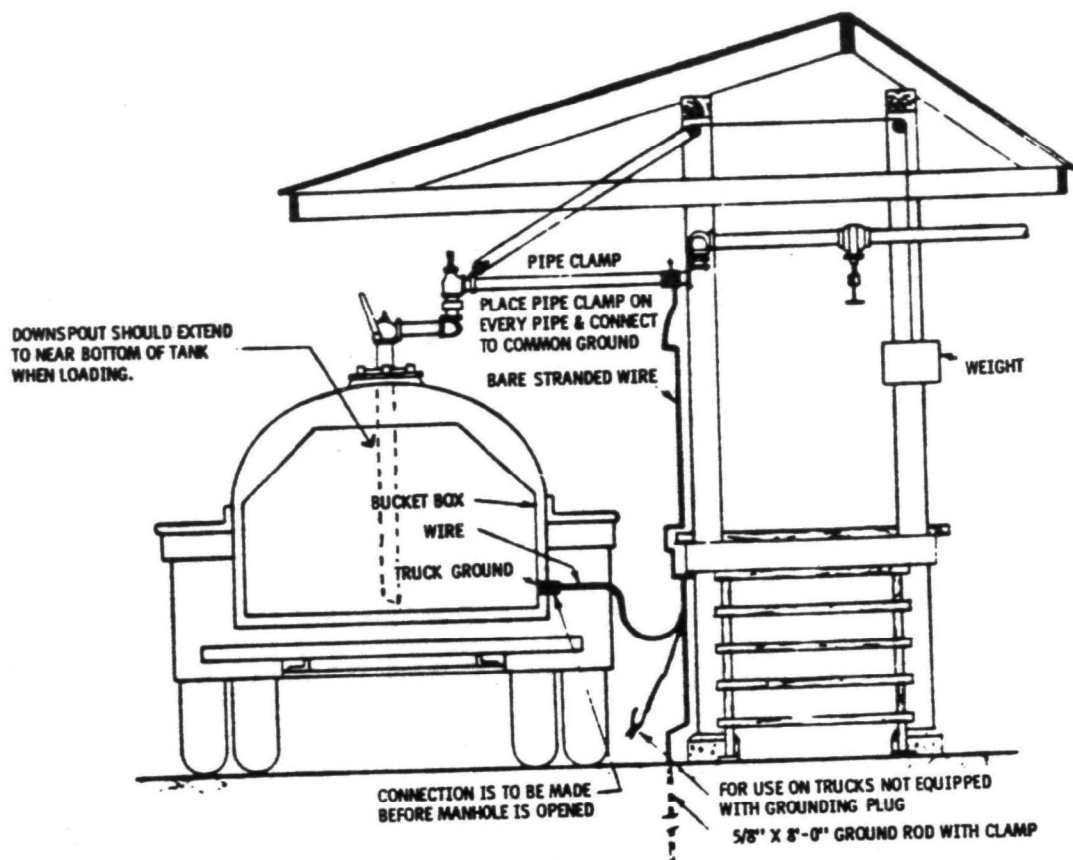
Figure 5-8. Bonding and grounding of a flammable liquid
tank truck and loading rack [5].

deep-well (vertical-shaft) centrifugal pumps mounted on tanks are satisfactory
if the pump and bearings are cooled by the liquid being pumped. This is to
prevent dry rotating parts from operating in the vapor space of the tank.

A gravity feed system has the disadvantage of being more difficult to arrange
for prompt automatic or manual shutoff than unloading by pumping. Another
disadvantage is that gravity usually maintains constant pressure on the system,
whereas pumps can be easily arranged to permit pressurizing only during demand.
If very volatile liquids cause vapor lock when pumped by conventional methods,
gravity transfer may be necessary; it is required for many processing
operations.

Some of the safety precautions for a gravity feed system are:

(1) Installation of emergency shutoff valves in all gravity transfer
     systems.

(2) Location of such valves as close to the source as possible.

Inert gas transfer methods, owing to the compressible nature of the transfer
medium, have the same disadvantage as the gravity system. In the event of

5-22

breakage or leakage, flow from the system will be continuous. Such systems also introduce the complication of pressure storage tanks.

Among the disadvantages of the inert gas transfer methods are these:

(1) A considerable amount of liquid may be discharged in the event of pipe failure or careless valve operation.

(2) Because vapor-air explosions are extremely violent at high pressure, transfer by compressed air should be avoided.

(3) Tanks for inert gas transfer systems have to be constructed, installed, and tested in accordance with ASME or other recognized codes for unfired pressure vessels.

(4) The gas pressure is regulated at the minimum needed to force the liquid through the transfer system, and a relief valve with a slightly higher setting downstream must normally be installed.

(5) Provisions need to be made for automatically shutting off the supply of inert gas and for bleeding the gas pressure from the flammable-liquid system in event of fire.

Transfer can be made by nitrogen, carbon dioxide, or other inert gases. The system is under constant pressure, and the compressibility of the transfer medium results in discharge of considerable liquid if there is pipe failure or careless valve operation.

A schematic diagram illustrating the inert gas transfer method is shown in Figure 5-9.

Fail-safe transfer lines primarily intended for use in transferring hazardous liquids between a mobile transporter and storage facility have been developed [7]. The operating principle is based on measurement of flow rate at the inlet and outlet of the transfer line, and detection of a leak through comparison of the two rates.

The system consists of four items: an inlet assembly, a flexible hose, an outlet assembly, and a control module. It is designed to transfer hazardous fluids, and to automatically close both the inlet and outlet valves upon detection of a leak. It will also cause the inlet and outlet valves to close if electrical power is lost, the valve operating air pressure is out of toler-ance, or if any cable is severed. Figure 5-10 shows a simplified diagram of the system.

The inlet and outlet assemblies are shown in Figure 5-11. They are identical, except that a strainer is included on the inlet assembly only. The transfer hose is a 2-inch diameter, 50 ft. length of steel-reinforced steam hose, designed to carry about 100 gpm. The control module is housed in an explosion-proof junction box, consisting primarily of a simple hardwired computing device [7].

1. INERT GAS SUPPLY LINE
2. MANUAL CONTROL VALVE
3. GAS COMPRESSOR
4. PRESSURE-REGULATOR VALVE
5. SOLINOID-OPERATED THREE-WAY TWO-PORT VALVE. WHEN CIRCUIT TO SOLINOID IS COMPLETED, VALVE INLET IS CONNECTED TO OUTLET TO SUPPLY INERT GAS TO TANK. SHOWN WITH CIRCUIT TO SOLINOID BROKEN; VALVE DISCHARGE IS CONNECTED TO DRAIN TO RELIEVE PRESSURE ON TANK.
6. RELIEF VALVE
7. LIQUID-LEVEL DIAL INDICATOR
8. FILL CONNECTION
9. STRAINER
10. SOLINOID VALVE. INTERLOCKED SO THAT IT WILL BE OPEN ONLY WHEN VALVE 5 ON INERT GAS SUPPLY LINE IS IN THE POSITION SHOWN AND VALVE 11 ON DELIVERY LINE IS CLOSED.
11. SOLINOID VALVE. ARRANGED FOR MANUAL CONTROL AND FOR AUTOMATIC SHUTOFF IN EVENT OF FIRE AT PROCESS.

Figure 5-9. Compressed inert gas transfer method [6].
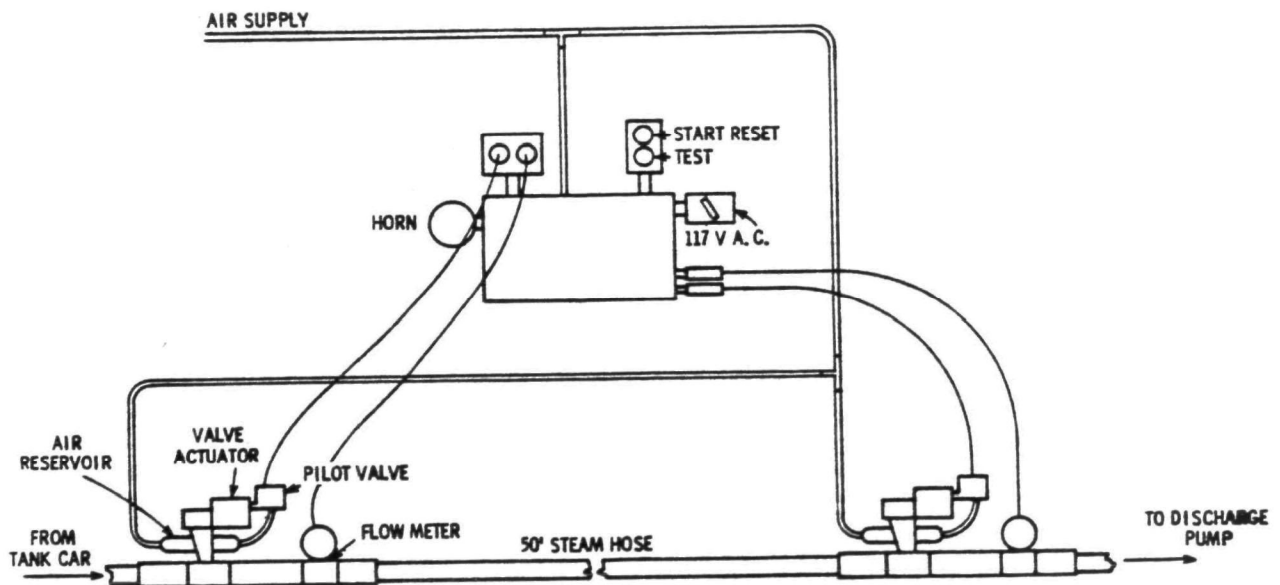
Figure 5-10. Fail safe transfer line for hazardous fluids [7].
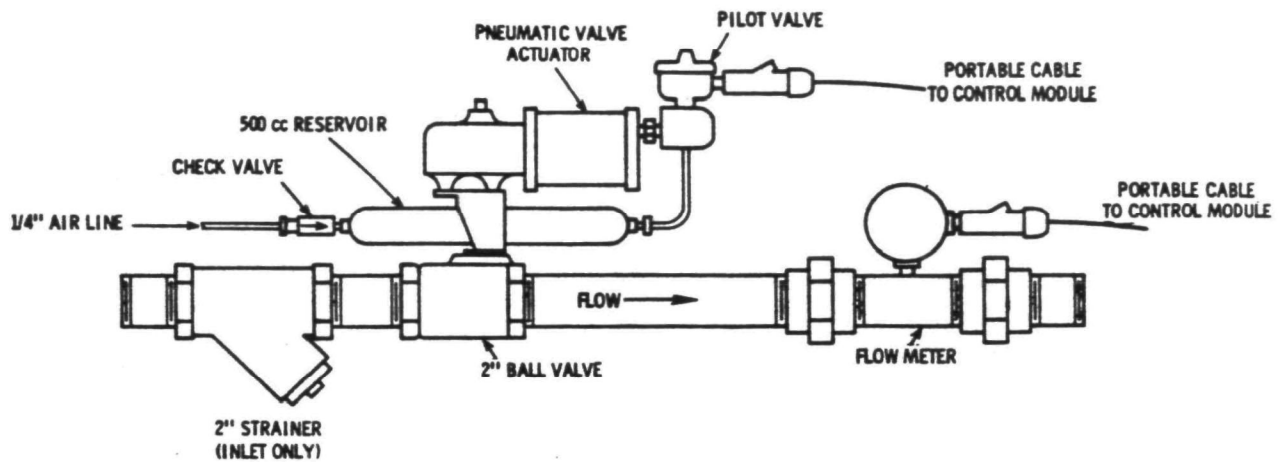
Figure 5-11. Fail safe transfer line inlet and outlet assemblies [7].

The device will reliably detect leaks of 0.5% or greater. Average fluid loss before valve actuation (closing at 85 gpm and 0.5% leak rate setting) was 250 mL. It should be noted that the extremely low fluid loss before shutdown is only a measure of the device reaction time and not of the total fluid loss that may be experienced in the event of a leak. Fifty feet of 2-inch hose holds about 8 gal of fluid; all of which could be lost through the leak after shutdown.

5.3.3.1 Safety/Emergency Provisions--
Hazardous fluid unloading and transfer operations offer one of the highest likelihoods of accidents; i.e., fire, spills, or worker exposure. Technical bulletins of the Chemical Manufacturers Association (CMA) and the American Petroleum Institute (API) provide excellent guidance for the unloading of tank cars and tank trucks [8-11].

Some of the design provisions and procedures for safely unloading hazardous liquids include:

(1) The condition of the cars is examined, and any leaks are to be reported immediately.

(2) Before unloading starts the area is checked to be sure it has no exposed lights, fires, or other sources of ignition.

(3) Vents on tank cars are protected by flame arresters.

(4) In all cases, personnel should be thoroughly trained and have been given written instructions suitable for each material they will handle.

5-25

(5) Adequate personal, protective equipment have been furnished for those involved in the loading and unloading of tank cars. For materials that are corrosive to the skin or that may be absorbed through it, full protective clothing with face masks, rubber gloves, rubber shoes, etc., is required. When materials that have toxic vapor or gas are unloaded, personnel should be equipped with airline respirators or self-contained breathing equipment. Protective equipment not available at the site should be obtained even though this may mean some delay in making the transfer.

(6) First aid and medical procedures are worked out in advance and posted in the unloading area. Where unusually toxic substances are handled, medical personnel will have information on the characteristics of the material and on the medical management needed for any material they may encounter.

(7) Fire extinguishers of adequate type for the material handled are distributed throughout the area.

(8) Personnel responsible for unloading stay in the immediate vicinity of the operation at all times, and ascertain that all conditions are normal.

(9) An emergency shower and an eyewash device is available at each loading location. Preferably, these devices are tied to an alarm system that would bring help to any man making use of them.

(10) Safe access to the top of the vehicle is one general safety requirement for liquid unloading. This is particularly important for top unloading, but it may also be necessary for operations such as gauging or sampling. Thus, loading racks with suitable ladders, platforms, gangways, or even railings permanently affixed to the vehicle are usually required.

(11) Keeping liquid-unloading facilities usable in adverse weather conditions, such as icing, may be difficult, but every effort must be made to keep them safe. Good general illumination, especially at night, is far preferable to providing the operator with an extension light, which he might drop.

(12) Steel pipe and swing joints or flexible hose of the standard metal type are usually used for connections to tank cars or tank trucks. Metal-reinforced rubber hose of a type resistant to the material being handled is acceptable but less desirable. See Section 5.13 on materials compatibility.

(13) Each line and connection should be clearly identified to avoid intermixing materials.

(14) Liquids that require heat within the tank car for pumping purposes should be received only in cars equipped with heater coils. The minimum steam pressure necessary to being the liquid to a fluid

state is used. A regulator adjusted to this pressure is installed in the steam line, and a relief valve with a slightly higher setting is provided downstream.

(15) Some tank cars and tank trucks have interior linings of rubber or plastic of various kinds. When such cars are being unloaded, special care must be taken to prevent damage to the lining.

(16) Pumps are preferably located outdoors so that fire at the pump will not expose property of appreciable value. They should not be located inside diked areas. Pumps are sometimes located in small detached noncombustible pump houses or in cutoff rooms of main buildings. When they are located indoors and handle flammable liquids with flash points below 110°F, positive low-level exhaust ventilation of 1.0 ft^3/min-ft^2 of pumproom floor area is recommended. Natural ventilation is acceptable for less hazardous liquids.

(17) Where flammable liquids are handled in a pump house, motors can be partitioned and sealed off from the rest of the pump house, or can be of a type approved for use in flammable atmospheres. It is a good operating and safety practice to have a well-marked master cutoff switch outside the building. However, consideration is normally given to locating flammable liquid pumps outside of buildings whenever feasible.

(18) As a fail-safe precaution, an interlocked warning light or physical barrier system is often provided in unloading areas to prevent vehicular departure before complete disconnect of flexible or fixed transfer lines.

5.3.3.2 Spill and Runoff Containment--

Drainage from the unloading area is collected or diverted to allow runoff of any spills or runoff from rainfall to permit recovery or at least proper disposal. The basic objective of secondary containment is to prevent the discharge of hazardous materials to waterways, sewer systems, or groundwaters. Containment systems which fail under rainstorm conditions are considered inadequate. To the extent feasible, such containment is designed to hold 110% of the largest unit handled (or largest unit contents plus the maximum 24-hr/10-yr rainfall event, if greater).

For tank trucks a system of containment curbs are used for unloading areas, using ramps to provide truck access into the confines of the containment curb.

A lined trenching system encompasses the railroad tank car unloading area. The trench is designed to carry away any spill or runoff to a catchment basin or holding pond for later treatment. Figure 5-12 illustrates a containment curb type spill catchment system, depressed area form.

5.3.3.3 Static Electricity Prevention--

Static electricity is generated when fluid flows through a pipe or from an orifice into a tank. The principal hazards created by static electricity are those of fire and explosion, which are caused by spark discharges containing
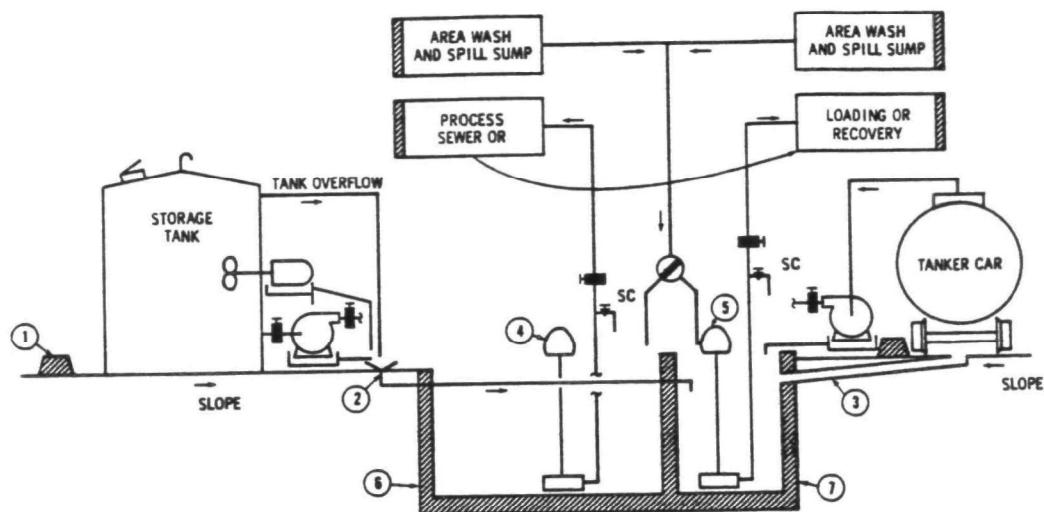
ITEM	DESCRIPTION OF PROTECTION	OPERATION/EQUIP. PROTECTED	HAZARD
1	DIKE	TANKS	SPILLS, WASHING
2	RAISED DRAIN	OVERFLOW, DRIPS	CONC. SPILLS
3	TRENCH DRAIN	TANKCAR	UNLOAD, SPILLS
4, 5	SUMP PUMP	PROCESS SEWER	SLUG DISCHARGE
6	DILUTE SUMP	TANK MAT	SPILLS
7	CONC. SUMP	PROCESS SEWER	DISCHARGE

Figure 5-12. Containment curb type spill catchment system, depressed area form [12].

sufficient energy to ignite any flammable or explosive vapors or dust present. A point of great danger from a static spark is the place where a flammable vapor may be present in the air, such as a delivery hose nozzle.

The terms "bonding" and "grounding" often have been used interchangeably because the terms are poorly understood. Bonding is done to eliminate a difference in potential between objects. Grounding is done to eliminate a difference in potential between an object and ground. Figures 5-7 and 5-8 (Section 5.3.3) illustrate bonding and grounding of tank cars during unloading operations. Figure 5-13 shows rail joint bonding and track grounding.
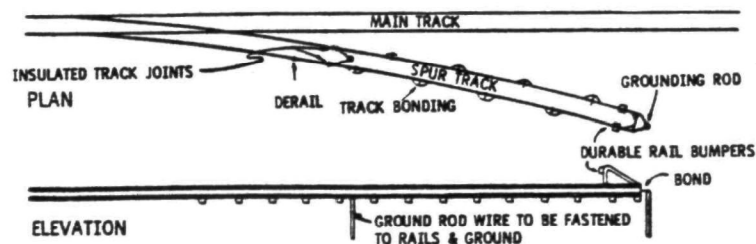
Figure 5-13. A tank car unloading siding showing rail joint bonding, insulated track joint, detail, and track grounding [5].

When unloading tank cars through open domes, it is best to use a downspout long enough to reach the tank bottom. Generally, tank cars need not be

separately grounded because the resistance of the natural ground through the tank car wheels and rails, and the resistance of piping, flexible metallic joints, or metallic swivel joints, are considered sufficiently low to protect against static electricity. For detailed information and exceptions to this generality, consult NFPA Standard No. 77, "Recommended Practice on Static Electricity."

5.3.4 Container Unloading

For hazardous wastes, the choice of container will usually be made from among various types of drums, barrels, and special bulk units. As is true in any bulk handling problem, the first step is to obtain information on the type of container which will be received with respect to its handling properties. Since it contains a hazardous waste, the container must then meet the regulations for its transportation set forth by the Department of Transportation and RCRA.

Containerized hazardous waste is most likely to arrive for unloading via rail boxcar or truck semitrailer. Due to economics of transportation, the carrying capacity of a trailer or boxcar will most likely be near the maximum. A 55-gal drum is the most popular form of container; a boxcar can carry 360 55-gal drums per carload.

In addition to liquid waste, certain dry materials require the strength, water tightness, weatherability, and general ruggedness of a steel drum. Standard specifications for steel drums have been established by the Department of Transportation; a typical specification is shown in Table 5-2. The heavier gage drums find use in transporting liquids.

The process for unloading trailers or cars differs by the waste and hauler. Drummed material may be placed on pallets or may rest on the bed of the trailer. In the latter case, the hauler may be involved with unloading and may manually handle the cargo. A common delivery condition for cargo touching the truck bed is "tail gate delivery", whereby the truck driver moves the packaged cargo to the tailgate of the trailer, and the recipient removes it.

Alternative methods include industrial trucks with drum-loading attachments, or fork-lifts for containers on pallets. Type EE battery-powered industrial trucks have the additional safeguards (electrical equipment enclosed to prevent emission of sparks) needed to work in hazardous locations; Type EX trucks, which are of explosion-proof or of dust tight construction, are also recommended.

After removal steel drums can be handled by gravity conveyors. However, steel drums should not be transported on wheel conveyors, because the chime, or lip, at the drum bottom gets hung up on the wheels. If roller conveyors are used, the rolls need to extend at least 2 in. beyond the outside surface of the chime, unless the drums are centered by guard rails. Drum loads up to 250 lb can be handled on a conventional 1.9-in. roller conveyor having rollers spaced at 3 in. and positioned at a 1-1/2 in. pitch.

TABLE 5-2. TYPICAL STEEL DRUM SPECIFICATION FOR HAZARDOUS MATERIALS [13][a]

Capacity, gal	Inside diameter	Inside height	Outside diameter	Overall height	Steel gage, body
55[c]	22 1/2	32 11/16	23 27/32	34 13/16	16
55[c]	22 1/3	32 11/16	23 27/32	34 13/16	18
30[d]	18 1/4	27 5/16	19 19/32	29	18

	Steel gage, cover	Steel gage, bottom	Steel gage, ring	Tare weight (approx.)[b]	DOT spec.
55[c]	16	16	12	64.5	17C
55[c]	16	18	12	55.5	17H
30[d]	18	18	12	37.5	17C & 17H

[a]All dimensions given in inches. Dimensions are within normal manufacturing tolerances of ± 1/16 in. (± 1/8 in. on height).

[b]Container weights shown are approximate and may vary within the allowable limits for manufacturers standard gage.

[c]On the 55-gal drum, a third rolling hoop, directly below the top rim, gives strength and rigidity to meet specifications.

[d]These drums meet Department of Transportation Specifications DOE 17H and DOT 17C for storage and shipment of hazardous materials. They also meet Rule 40 of the Uniform Freight Classification, and Rule 26C of the National Motor Freight Classification; DOT 17H drums also comply with ANSI standards.

Because of the difference in weights between empty and full drums, a roller pitch as high as 5 in. can be specified for empties, while a pitch of 3 in. may be sufficient for full drums. Both live-roller conveyors and belt-on-roller conveyors can also be used to convey drums.

A host of other special containers have been made for storing, shipping, and handling hazardous materials. Some of these units are designed to hold 2,000 lb or more; some designs include metal-walled containers equipped with specialized filling and discharge openings and rubberized containers. A major factor to be looked at when a facility receives these types of units is the total system concept of handling, with appropriate machinery and design taken into account.

Once a container has been unloaded, three possible options exist for distributing the contents:

(1) Place the container in storage.
(2) Pump the contents (liquid) into another storage tank.
(3) Dump the contents (bulk solids) into another receiver.

5.3.5 Bulk Solids Unloading

Hazardous waste bulk solids for incineration will arrive for unloading in hopper cars - both truck and rail. Due to the hazardous nature of the material transported, the hopper cars must be the covered type, typically with bottom unloading ports. Three types of unloading systems are used:

(1) gravity,
(2) pressure differential, and
(3) fluidized.

Figure 5-14 shows examples of fluidized unloading ports. Fluidized unloading is preferable for hazardous wastes when possible, because gravity unloading necessitates having a pit located under the rail spur.
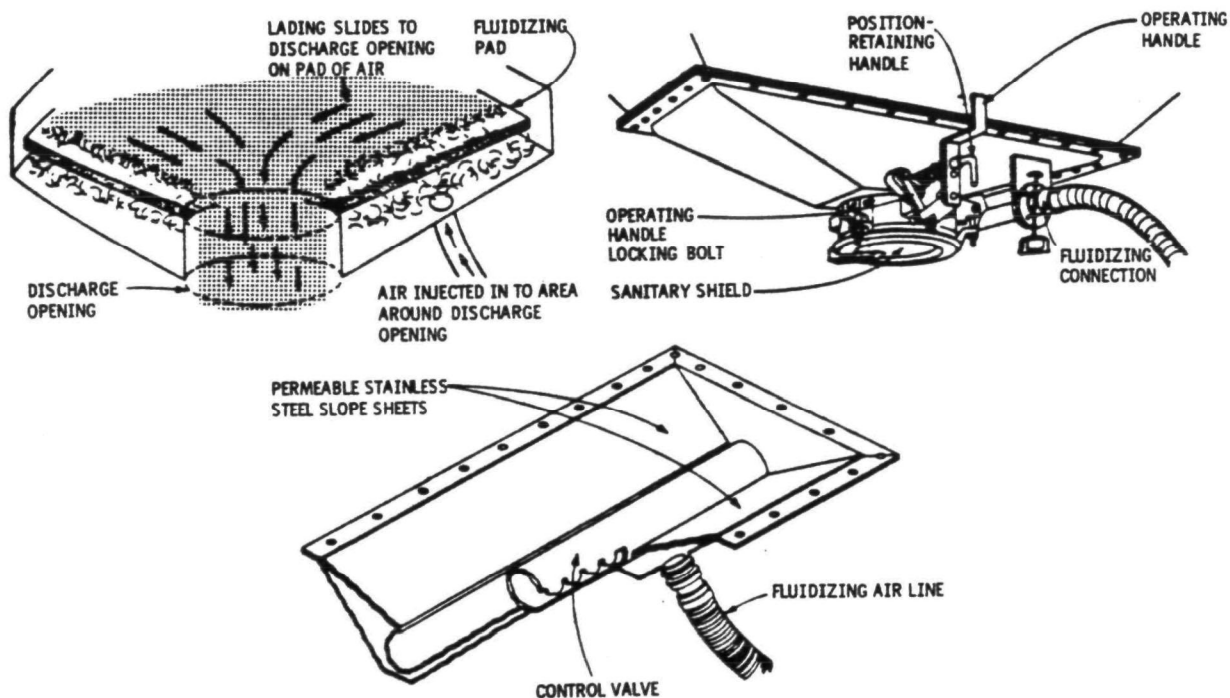
Figure 5-14. Fluidizing outlets for hopper cars [14].

5.3.5.1 Mechanical Conveyors--
When a discharge pit is used for unloading, the material is then conveyed to storage via one or more of three methods:

(1) screw conveyor,
(2) belt conveyor, and
(3) bucket elevator.

The screw conveyor is one of the oldest and most versatile conveyor types. It consists of a long pitch, steel helix flight mounted on a shaft, supported by bearings within a U-shaped trough. Screw conveyors are generally easy to maintain and inexpensive to replace.

Belt conveyors consist of an endless belt moving horizontally or on an incline. Almost all belt conveyors for bulk solids use rubber-covered belts whose inner carcass provides the strength to pull and support the load. Belt conveyor slopes are limited to a maximum of about 30° with those in the 18-20° range more common. In an evaluation of a materials-handling system involving belt conveyors, the number of belt transfer points should be reduced to a minimum to cut degradation, dust, and cost. Elevation of all belt lines a few feet above ground will ease inspection, maintenance, and cleanup. Belt conveyors emit dust almost exclusively at the transfer points. Placing enclosures around transfer points can give effective dust control. A few simple rules are normally followed for dust control:

(1) Reduce the number of belt transfers point to a minimum

(2) Be generous in sizing enclosures

(3) Arrange enclosures in easily removable sections

(4) Provide access doors on enclosures

(5) Install skirting and curtains at openings.

Bucket elevators are the simplest and most dependable units for making vertical lifts. They can be totally enclosed to reduce fugitive dust emissions.

5.3.5.2 Pneumatic Conveyors--
Pneumatic conveyors are commonly used to transfer dry granular or powdered materials, both vertically and horizontally, to plant areas hard to reach economically with mechanical conveyors. The properties of a material determine whether or not it can be successfully conveyed pneumatically. The material must pass through piping and auxiliary equipment without clogging, degradation, or segregation, and be readily disengaged from the conveying air. Materials from fine powders through 1/4-in. pellets can be handled.

Pneumatic systems can be completely enclosed to prevent contamination, material loss, and dust emissions. Furthermore, some materials are better protected from adverse reactions when they are conveyed using an inert gas or dried air.

Pneumatic conveying systems can provide smooth, controlled, hands-off unloading of bulk rail cars. The unloading procedure begins with the insertion of a material pickup probe into the rail car's discharge port. The probe controls the material-to-air ratio, and probe kits are designed to fit all rail cars.

They consist of housing with slotted probes of varying lengths, designed to reach different areas or compartments across the rail car. An air intake filter is clamped to the car's discharge port opposite the material pickup connection, and a car hatch filter attaches to the top of the rail car to relieve vacuum created in the car by the material flow. Figure 5-15 illustrates pneumatic unloading of a railcar.
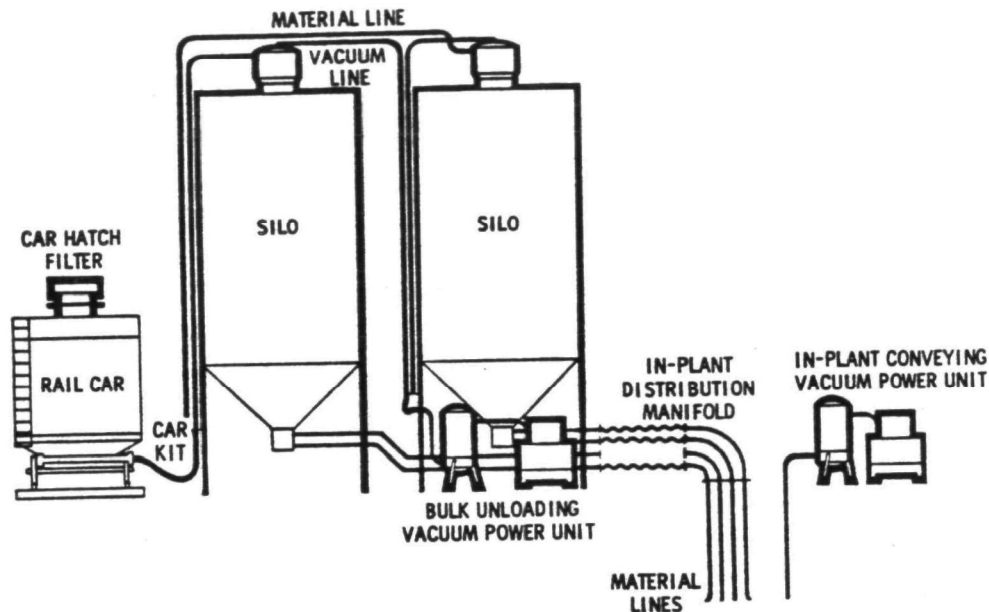
Figure 5-15. Diagram of pneumatic railcar unloading.

5.4 WASTE STORAGE AREA

The manner in which a waste is handled on-site is dependent on the nature of the waste (corrosivity, explosivity, etc.), plant storage facilities, and heat content of the fuel. Wastes received for incineration at a disposal facility are either incinerated directly (in some cases via pumping directly from the tank truck), or stored until they can be handled more conveniently. A plant operator may want to store some of the incoming wastes with higher heating values to possibly blend with other wastes which have heating values too low to support combustion alone.

For further information on storage of hazardous waste in tanks, piles or containers, see The Permit Writer's Manual on each of those topics (prepared by Fred C. Hart Assoc., Inc.).

Storage capacity is based on:

- Seasonal inventory buildup
- Redundancy or excess incinerator capacity
- Maintenance schedules and downtime
- Operating schedules (i.e., number of shifts vs. inshipment rates)
- Amounts and nature of waste blending to be done.

Depending on the type of incinerator installation, storage facilities may be required to hold both liquid and solid hazardous wastes. If an incinerator cannot burn solids, facilities for solid storage are obviously not necessary.

A hazardous waste storage area is designed to address three problem areas:

  (1) Segregation of incompatible corrosive and reactive waste types;

  (2) Fire hazards due to flammable liquids and solids; and

  (3) Toxic hazards to prevent human exposure during storage, transfer, and spill possibilities.

The safety and emergency design provisions for storing hazardous liquid wastes are described in Section 5.4.3.

5.4.1 Types of Storage

5.4.1.1 Liquid storage--

Liquid/fluid waste storage includes temporary holding tanks, batching tanks, main storage tanks, and transfer pumps (pumps and valving are discussed in Section 5.5). Holding tanks provide initial storage of wastes prior to final deposition of the material. Other tanks can store specific waste categories which have been analyzed, require segregation, and are ready for incineration. Batching tanks are used to prepare an 8-hr shift waste feed for the incinerator. Also, tanks may be needed to store fuel oil (or bottled gas) for incinerator ignition and auxiliary burners.

Container nomenclature is vague but, ordinarily, "tank" means a container designed to withstand pressures from atmospheric up to about 15 psig, whereas "vessel" refers to a container which can withstand external or internal pressures exceeding 15 psig.

There are several basic types of storage tanks, as shown in Figure 5-16. The aids to design of tanks takes the form of specifications, rules, standards, and codes.

Any of the vessels noted above can be lined or coated with corrosion-resistant materials. All weld spatter is removed, and welds ground smooth or flush, depending on the type of coating to be applied. Tank nozzles must be large enough so a coating can be applied.

Both vertical and horizontal tanks are available for storing liquids. Vertical tanks are more economical to install, and occupy less space, while horizontal tanks are easier to maintain and repair. Usually the lower maintenance generally required by horizontal tanks does not offset their higher cost and greater space requirements; hence, vertical tanks are normally recommended. If, however, it appears that future compartmentation of the tank will be likely (as with segregated waste storage), it is easier to modify a horizontal tank.
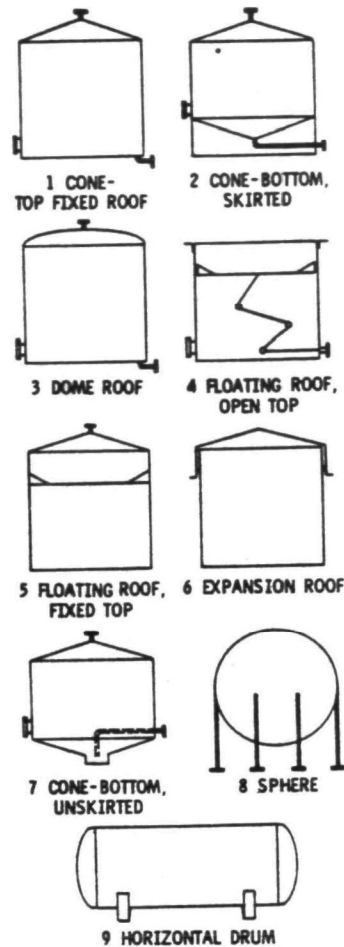
Figure 5-16. Typical shapes for storage vessels [15].

Installation and maintenance of aboveground tanks are less troublesome than for underground tanks. With underground storage, the functions of gaging, pumping, and leak detection become more difficult. With storage of hazardous wastes and liquids, underground tanks and their possibility of leakage is discouraged. Underground tanks lend themselves to accelerated corrosion and often require cathodic protection. Also, a means of containing leaked or spilled materials is necessary for most underground tanks.

Depending upon the liquid waste contained, tank storage can also require many accessory equipment features such as:

(1) Flash arrester fill pipes.

(2) Flame arrester rodding and sampling units.

(3) Conservation breather vents with pipe-away construction--used where pressure or vacuum relief is required and vapors must be piped away rather than released into the atmosphere.

(4) Tank vent condensers--designed to condense and return to the tank vapors that could escape, as shown in Figure 5-17.
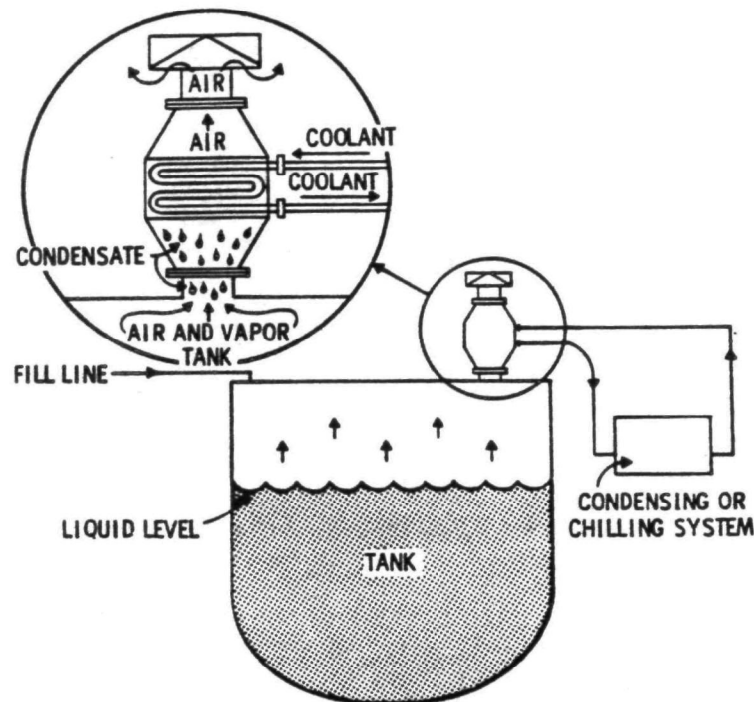
Figure 5-17. Typical tank condenser vent system.

(5) Steam-heated conservation, pressure, or vacuum relief vents--designed for use on tanks containing liquids whose vapors tend to crystallize at ambient temperatures (also with pipe-away construction).

(6) Mushroom vent with flame arrester--used where it is not necessary to conserve vapor losses, but where low flash point solvent materials must be protected against fire and explosion from exterior sources of ignition.

(7) Steam-jacketed flame arrester vents--designed for use on tanks containing hazardous liquids whose characteristics require steam heating to prevent crystallization of interior vapors; e.g., naphthalene.

(8) Manhole and emergency pressure relief vent covers--to provide emergency pressure relief as well as access for tank cleaning.

(9) Internal safety valve--intended for use where tanks are required to be equipped with valves that close automatically when subjected to fire.

(10) Integral internal heating coils--usually steam, designed to prevent freezing of tank contents.

(11) Overflow piping--usually connected to an adjacent tank to mitigate spill possibilities.

5.4.1.2 Bulk Solids Storage--
Material received as bulk solids at a hazardous waste incineration facility
can be stored in three ways:

(1) Enclosed bins or silos

(2) Concrete pits or below-grade concrete hoppers

(3) Stockpiles

Generally, solid hazardous waste materials which present a toxicity problem to
plant personnel are stored in totally-enclosed storage, such as single-outlet
bins, multiple-outlet silos, and portable bins. These enclosures protect the
hazardous material from exposure to the elements, or guard against dangers
represented by explosive, flammable, ignitable, or corrosive properties.
Table 5-3 gives a rough rating of the major types of bulk storage units in
terms of their capacities and method of reclamation or discharge.

TABLE 5-3. TYPES AND CHARACTERISTICS OF DRY BULK STORAGE [13]

Storage technique and method of reclaim or discharge	Small, under 20,000 ft^3	Med.	Large, over 700,000 ft^3
Stockpiles			
Bottom tunnel		X	X
Bucket wheel			X
Scraper truck			X
Front-end loader	X	X	
Multiple-outlet silos			
Mass flow	X	X	
Expanded flow	X	X	
Funnel flow	X	X	
Single-outlet bins			
Mass flow	X		
Expanded flow	X	X	
Funnel flow	X	X	
Portable bins			
Funnel flow	X		
Mass flow	X		
Concrete pits			
Grapple	X	X	

Multiple-Outlet Silos--Multiple-outlet silos are useful for storing small or medium quantities of material. Because they generally rely on gravity flow to discharge the solids, hopper slopes and outlet dimensions must satisfy the minimum requirements for uninhibited flow.

One of the most common problems with multiple-outlet silos is structural failure caused by nonsymmetric flow patterns. Side discharge is typically used with free-flowing materials such as grain. With this arrangement, bin failures, especially in steel structures, manifest themselves as dents in the region of the localized flow channel.

Single-Outlet Bins--Single-outlet bins are the most common type of storage units in industry. Most of them are funnel-flow type, in which the sidewalls of the hopper are sufficiently steep to maintain continuous flow. Most pyramidal hoppers and conical hoppers with slopes of 60° or less from the horizontal will display funnel flow.

Portable Bins--These special bulk units, generally limited to volumes less than 200 ft^3, are often thought of simply as large buckets used to transport homogenous material of a specified size and composition. Typically, these bins are cube-shaped, with a flat hopper leading to a central outlet about 10 in. or less in diameter.

Some of the solid material characteristics considered when designing a solids storage and retrieval system include:

  (1) Bulk density
  (2) Moisture content
  (3) Particle size
  (4) Angle of repose
  (5) Angle of slide
  (6) Temperature
  (7) Pressure differentials
  (8) Abrasiveness
  (9) Cohesiveness
 (10) Material melting point
 (11) Hygroscopicity

Many different types of bin hopper discharging devices have been developed, primarily because solid material retrieval is difficult to achieve reliably and consistently. Some of the bin hopper discharging devices are:

  (1) Manual prodding through poke holes to eliminate material "bridging" (definitely not useful for hazardous wastes)
  (2) Chain or cable elements suspended to reduce bridging
  (3) Agitators or "rotating fingers"
  (4) Sweep arms or rotary vanes
  (5) Rotary plows
  (6) Multiple screw bottoms
  (7) Bin activators or vibratory sections
  (8) Electromechanical devices, such as side vibrators
  (9) Pneumatic and hydraulic vibrators

(10) Air pads, cushions, and slides, wherein air is injected to fluidize the material.

If one word could describe the basis of all solids retrieval problems, it would be "friction." Any hopper surface which can reduce friction can minimize bridging or arching. Fortunately, for a corrosive-type hazardous solid material, the material of construction or lining of the hopper bin can solve a dual problem. Materials to be given consideration are:

(1) Stainless steel, full thickness or clad-polished
(2) Teflon sheets bonded to steel containers.

Items of safety in bin design considerations include:

(1) Access doors for inspection, routine maintenance, and firefighting
(2) Fire detection--sensors; alarming; automatic suppression systems such as CO_2, foam, or water; standpipes for connection to a water source and availability of fire hoses
(3) Detection of level and pluggage
(4) Provisions for dust control
(5) Provisions for maintenance removal of bin discharge mechanisms which are normally buried under waste.

Concrete Waste Pits--Concrete solid waste pits are in wide use in municipal and industrial waste disposal plants which handle nonhazardous wastes. Bulk solid refuse is dumped into the storage pit by packer truck, load lugger bucket, or other collection vehicles.

The storage pits are normally under an enclosure to prevent precipitation from entering, and there is an approximately 10 ft wide vestibule which trucks back into. Refuse is picked out of the pit by a bridge crane with a bucket or grapple, and the crane delivers the solid waste to an infeed system. Control of the crane and grapple is usually from an air-conditioned pulpit in which the operator sits. Control is a saturable reactor type which provides cushioned starting and acceleration. Protective zones are provided preventing the operator from drawing the grapple into a wall, pulpit, etc. Automatic control can be provided.

For fugitive dust control at each truck dumping point, there can be a down blast heater. The vestibule and pit area are designed for complete sprinkler protection of fire. Sprays in both the front and rear wall of the pit can be included to suppress dust clouds that arise when a load is dumped.

The entire pit is usually watertight and sloped to troughs and drains for dewatering. When a pit is constructed below grade, it is usually necessary to have a sump. Screening devices to prevent material from entering the sump are also used [16].

Stockpiles--Hazardous wastes are occasionally stored in piles, generally small in size. Many are in buildings or maintained outside, under cover, on concrete or other pads. They are most frequently used to accumulate waste composed of a single, dry material.

Wind dispersal is controlled by a cover or windscreen; piles inside a building are adequately protected from dispersal.

5.4.1.3 Container Storage--

Hazardous materials for incineration will often arrive in small container form (e.g., 55 gallon drums), and can be stored until used, provided the containers are in good condition and are not leaking.

Metal and fiber containers are loaded, stored, and unloaded so as to minimize the possibility of container damage. The containers are stored in a covered area, off the ground, in a manner which will preclude damage, weathering, and subsequent leakage. Storage pads of concrete or other impervious materials are used as a base to prevent ground water leaching and percolation. The area itself is provided for drainage to a treatment facility in an analogous manner to diked storage tank areas.

If some containers contain corrosive substances, these are stored so that, should leakage develop during storage, these substances will not corrode through adjacent containers. Waste segregation practices of bulk storage (liquid and solid) also prevail with indoor container storage.

All containers in storage are inspected to insure physical and mechanical integrity, and the drainage and containment systems are also inspected.

Nonstationary containers can proliferate in a storage area; hence, all containers are clearly labeled and records maintained. In this way the operator is able to quickly locate any hazardous waste.

Waste containers are sealed to prevent the escape of vapors. Gasketed closures of containers and containers themselves are normally of a material that will not be deteriorated by the waste inside the container. The container storage enclosure area is vented to allow for collection and control of any released vapors.

5.4.1.4 Tank Cars--

Hazardous waste storage can also occur in parked tank cars -- both truck and rail. Usually, the wastes are then pumped directly to the incinerator or blending tanks. As with bulk storage, the area is designed to prevent ground contamination and percolation, and diked or drained to collect spills and surface runoff. As with container storage, each tank car is clearly labeled and records maintained to quickly locate each hazardous waste.

5.4.2 Segregation of Wastes During Storage

Hazardous wastes may be segregated at an incineration facility due to waste categories for fuel value and are certain to be segregated when incompatible waste types are received. The type of incinerator and nature of wastes which can be burned will greatly influence the extent of waste segregation during storage.

Incompatible wastes are normally segregated due to corrosive and reactive effects. Examples of segregation during storage are reactive chemicals which

should be stored in air or water tight containers, oxidizers which should be isolated from flammable materials, and materials which may polymerize in the presence of accelerators. Section 5.5 on waste blending contains a ready and quick reference for determining the compatibility reactions of most binary combinations of hazardous wastes.

Wastes may also be segregated and stored to allow for fuel blending for maximal incinerator performance. Examples of the categorization of wastes which could occur and the storage requirements necessary are as follows [17]:

(1) Light hydrocarbons and nonaqueous solvents -- includes low flash point wastes such as paint thinners, aromatics (toluene, benzene, xylene, etc.) which reduce viscosity of heavier wastes and assist fuel oil in initial heating prior to firing heavy blends.

(2) Medium to heavyweight hydrocarbons -- includes still bottom residues, crankcase oils, and discarded transformer oils. Most have high flash points but relatively low ignition temperatures and moisture is generally under 10 percent. Handling these wastes may require use of insulated storage tanks and auxiliary heat to maintain proper fluidity, particularly during cold weather.

(3) Low-water-content aqueous wastes -- sludges from fatty acids production, starches, reject fatty acids, waste soluble oils, and clabberstock. These wastes may be blended in limited proportions with the heavier wastes in group 2 but require storage in insulated and heated tanks to avoid congealing and freezing of contained water during winter.

(4) Dirty solvents -- includes kerosene, soluble inks, oil-solvent residues, organic pigments. Storage tanks do not require insulation or heating.

(5) High-water-content aqueous wastes, semisolids, sludges, and low heating value liquids -- includes aqueous mixture of paint, enamel and lacquer oversprays, liquid polymers in water, paint sludges.

(6) Skimmings from wastewater treatment plants -- floatable material skimmed from settling tanks and thickeners such as spent grease.

(7) Spent earth -- from filters and contaminated areas. Due to high water content this waste can require insulated storage, auxiliary heat, and continuous agitation to maintain fluidity and prevent freezing in cold weather.

5.4.3 Safety Provisions for Storage Areas

For safe facility design in the storage area, provisions are made to protect personnel and the immediate environment from catastrophe--particularly fire hazards and material spills. Liquid and container storage are most likely to occur at a hazardous waste incineration facility, and are discussed below.

5-41

5.4.3.1 Fire Safety--
Volume 1 of National Fire Codes (National Fire Protection Association (NFPA), Boston) contains recommendations and standards in NFPA 30, "Flammable and Combustible Liquids Code," for venting, drainage, and dike construction of tanks for flammable liquids. Also possibly applicable are NFPA 327, "Standard Procedures for Cleaning or Safeguarding Small Tanks and Containers", and NFPA 43A, "Liquid and Solid Oxidizing Materials."

Many of the devices and equipment utilized to prevent fire hazards in the liquid storage area were discussed in Section 5.4.1.1. Some other considerations which apply to storage of large quantities of flammable liquids include:

(1) Instrumentation or remotely-operated valves to minimize flow of flammables.

(2) Combustible gas monitors in the storage area which have an alarm set below the lower flammable limit.

(3) Combustible gas monitors that automatically actuate a deluge system or safely shut down systems below lower flammable limit.

(4) Drainage and collection ponds (equalization basin) to carry away liquid spills resulting from a fire incident.

For the storage of drums, many safety precautions can be used for the protection of the operators who open and inspect drums prior to incineration. Safety features include:

(1) explosion-proof electrical equipment
(2) automatic fire doors
(3) a "light water" system
(4) dry chemical and CO_2 fire extinguishers
(5) special safety fork trucks with nonsparking forks
(6) air-operated pumps
(7) nonsparking tools
(8) safety showers and eyewashes
(9) safety glasses and face shields
(10) a ventilation system which makes a minimum of three air volume changes per hour in all areas and thirteen (13) air volume changes per hour in the drum pumping room or area.

For storage of bulk-solids, evidence of spontaneous heating is closely monitored. Heat-sensitive devices in silos and bins are installed, connected to a continuous temperature recorder at a central control board and arranged to sound an alarm if unsafe temperatures are produced. Excessively wet materials are not placed or permitted in storage silos or bins.

5.4.3.2 Spill/Toxicity Safety--
The most effective way of addressing a bulk liquid storage area's vulnerability to spill incidents is to prevent them from happening. Assuming that all storage tanks are properly designed, equipped with overflow alarms, and used

only for intended or compatible purposes, the possibility of spills can be substantially reduced by:

- Assuring the continual physical integrity of the vessels and their fittings (inspection and testing).

- Establishing strong administrative controls covering all loading/unloading and in-plant transfer operations (plans and procedures).

- Providing adequate secondary containment facilities (dikes, diversion ditches, equalization basins).

Physical Testing and Inspections--Spark testing (of lined storage tanks), wall-thickness testing, or other appropriate means of nondestructive physical testing or inspection are conducted on storage vessels which hold hazardous liquids.

The exterior of each bulk storage tank is also visually examined at regular intervals. Each inspection includes an examination of seams, rivets, nozzle connections, valves, and pipelines directly connected to the tank. Visible leaks of waste from tank seams and rivets are then promptly corrected. Foundations and/or tank supports are also subject to inspection.

New and old tank installations are, as far as practical, fail-safe engineered or updated to a fail-safe engineered installation. Design considerations are given to providing the following devices:

(a) High liquid-level bell or horn alarms with an audio signal at a constantly manned operating or listening station; in smaller plants an audible air vent may suffice.

(b) Low liquid-level alarms with an audio signal at a constantly manned operation or listening station; such alarms can also have a non-bypassing reset device that can be readjusted to a given operating level following tank fill or liquid removal.

(c) High liquid-level pump cutoff devices set to stop flow at a predetermined tank content level.

(d) Direct audible or code signal communication between the tank gauger and the pumping station.

(e) At least one fast response system for determining the liquid level of each bulk storage tank such as digital computers, telepulse, or direct vision gauges.

Tanks are then not knowingly used if the "head" or "top" is in a corroded-through condition. Action is taken to drain such tanks and repair the defective member as promptly as possible.

Partially buried tanks for the storage of oil or hazardous materials are normally avoided, unless the buried section of the shell is adequately coated

to prevent rapid corrosion of metallic surfaces buried in damp earth, especially at the earth/air interface.

Buried storage tanks represent a potential for undetected spills. A buried installation, when required, is wrapped and coated to retard corrosive action. In addition, the earth is subjected to electrolytic testing to determine if the tank should be further shielded by a cathodic protection system. Such buried tanks are also subjected to regular hydrostatic testing. In lieu of the above, arrangements can be made to expose the outer shell of the tank for external examination at least every five years. Alternatively, a means of conducting examinations of the tank at regular intervals can be provided, e.g., down-hole television.

Tank Overfill--A variety of engineering practices suited to the nature of any hazardous material stored are used to prevent tank overfilling, a major source of spill incidents. The following general principles can be used in designing a system of protection against tank overfill:

(1) Tanks are gauged before filling.
(2) Overflow pipes are connected to adjacent, compatable waste storage tanks, or to secondary containment.
(3) Fail-safe devices and level alarms have been tested and insured in place.
(4) Provisions to prevent static electricity discharge have been implemented.

Protection of Integral Heating Coils--Many liquids in storage require auxiliary heating to remain in a fluid state. This is normally accomplished economically by integral steam coils inside the storage tank and, often, agitation.

To control leakage through integral heating coils which may become defective through prolonged use, the following design factors are considered and applied:

(1) The past life span of internal steam coils is determined, and a regular system of maintenance and replacement that does not exceed the anticipated life span is established.

(2) The temperature and environment is carefully considered when selecting heating coil materials to reduce failure from corrosive action, prolong life, and reduce replacement costs.

(3) The steam return of exhaust lines from integral heating coils which discharge into an open watercourse is monitored for contamination, or passed through a settling tank, or skimmer, etc.

(4) The nature of the wastes is carefully considered to prevent wastes from caking on the heating coils, which reduces their efficiency as well as causing waste materials to be contained in a tank thought to be empty.

(5) The feasibility of installing an external heating system is also considered, and, if feasible, often is recommended to solve problems which may arise from implementation of (1) through (4).

Secondary Containment--All bulk storage tank installations at a hazardous waste incineration facility are planned so that a secondary means of containment is provided for the entire contents of the largest single tank. Dikes, containment curbs, and pits are commonly employed for this purpose, but they may not always be appropriate. An alternative system would consist of a complete drainage trench enclosure arranged so that a spill could collect and be safely confined in an in-plant catchment basin or holding pond.

Dikes are generally constructed of concrete, cinder blocks, and/or earth. However, dike materials are designed to be chemially resistant and essentially impervious (e.g., permeability rate no greater than 10^{-7} cm/s when subjected to a head of 1 ft of water) to the substances contained. Acceptable engineering design criteria for a dike will enable it to withstand a sudden massive release.

Some of the important design guidelines for dike construction include [18]:

(1) Single storage tank -- The capacity of diked area is at least adequate to hold the entire tank contents plus a reasonable allowance for precipitation. Local regulations may contain more stringent requirements. An alternative design goal is for the diked area to contain the volume of the tank plus 1 ft of freeboard.

(2) Clustered storage tanks -- The capacity of the diked area is adequate to hold the entire contents of the largest tank plus a reasonable allowance for precipitation. Again, local regulations may be more stringent.

(3) To the extent feasible, dike walls generally do not exceed a height of 6 ft above interior grade. A greater height might require the observance of tank entry procedures including safety harnesses, oxygen deficiency checks, standby observers, and other precautions each time it is necessary to enter the diked area.

(4) For earthen dikes, a slop of 2.5:1 is preferred. Earthen dike walls 3 ft or more in height are generally designed with a flat walkway section at the top not less than 2 ft wide.

(5) Dikes may also need to be constructed to provide necessary ramps for vehicles needing access to the storage areas.

(6) The disposal of rainwater and other liquids from within diked areas is normally accomplished by a manually activated pump or siphon system. Such accumulated stormwater must be removed in order to maintain adequate volume for a maximum spill. Figure 5-18 shows a diversion structure which serves this purpose. Of course, retained drawoff water and the rainfall accumulated are checked (analyzed) before release.
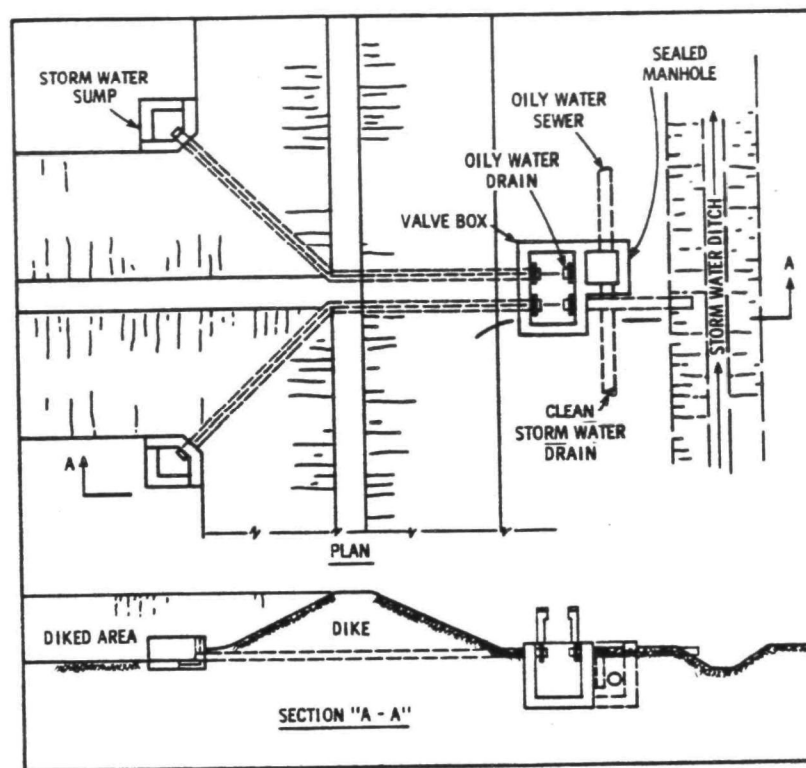
Figure 5-18. Dike drain detail Type "A" diversion box [19].

(7) For hazardous and toxic liquids, the ground area within the dike
     and curbing are designed to be essentially impermeable. This can be
     achieved by use of concrete, asphalt, or suitable clays. Neutraliz-
     ing materials for the stored chemical waste such as limestone or
     clam shells for acidic wastes are sometimes used as a ground cover,
     although neutralizing ground covers need to be replaced promptly
     after a spill or incident.

(8) Generally, it is recommended that there be no discharge or loading
     pipes through the dike wall. However, construction design has to
     conform to state and local regulation, and some local fire regula-
     tions (applicable to flammable liquids) require a valved pipe through
     the dike wall, while others prohibit this installation. If a drain-
     age valve through the dike wall is required, it is kept locked in
     the closed position when not in use and a chemically resistant seal
     is installed around the pipe passing through the wall.

(9) The storage tanks located immediately adjacent to the dike itself
     are oriented so that no manholes face the dike. This is considered
     desirable, so that, if a manhole fails, the resulting discharge
     from a full tank will not be aimed over or at the dike. Where
     this design is not feasible, appropriate baffles are installed
     to deflect potential leaks and cause them to drop within the
     contained area.

(10) If storage tanks located immediately adjacent to the dike are equipped with fill lines which enter the tank near the bottom, and if the fluid pumped has suspended abrasive material, the discharge into the tank should be on the dike side, discharging against the tank side away from the dike. Alternatively, a baffle plate located inside the tank opposite the pump discharge in the area apt to be abraded, may be provided.

The final defense in the prevention and containment of liquid and solid spills is at the end of the plant storm-drain system. Here, an automatic system monitors the storm drain for acidity or alkalinity (pH), turbidity, total oxygen demand (TOD), and flow (variance from normal).

If any of the parameters are sensed beyond normal limits, a diversion gate automatically move into position to divert the discharge to a holding pond. Such a system provides protection against a spill that goes beyond the process area, dikes, and into the storm drains. Discharges diverted to the holding pond are removed to a process area for recycle, treatment, or disposal.

Container Storage--Containers with a capacity of less than 45 gallons are stored out-of-doors, when possible, in rows no more than 30 feet in length, five feet in width, and six feet in height. Containers which have a capacity of 45 gallons or more are stored in rows no more than 30 feet in length and two containers in width and should not be stacked. A minimum of five feet between rows of containers of hazardous wastes is usually maintained.

If exposure of the containers to moisture or direct sunlight (see Section 5.5) will create a hazardous condition or adversely affect the containers' ability to hold the hazardous waste, the containers are then stored in an area with overhead roofing or other covering that does not obstruct the visibility of the container labels.

The area under or around the container storage area is built to be able to collect or hold any spilled material; e.g., collection drains, trenches, or dikes.

5.5 WASTE BLENDING AND/OR PROCESSING BEFORE INCINERATION

The methods by which hazardous wastes are removed from storage, prepared for incineration, and fed to the incinerator are dependent on the nature of the waste and type of incinerator. Figure 5-3 in Section 5.3 illustrates the various pathways from storage to final feed into the incinerator. Careful design consideration is given:

(a) To the layout for liquid waste blending, pumping and associated pipework, and

(b) To the handling and feeding arrangements for nonpumpable sludges, solids, and containerized wastes, where applicable.

Operating experience has shown that these are areas that do not receive as much attention as is necessary; the overall success of an incineration

facility depends upon the successful integration of storage, feeding, and firing equipment.

5.5.1 Waste Compatibilities

The "combination of wastes" often presents many problems for the management of hazardous wastes. In some instances, the combination or mixture of two or more types of the wastes produces undesirable or uncontrolled reactions resulting in adverse consequences. These reactions may cause any one or more of the following:

    (1) Heat generation, fire, and/or explosions,
    (2) Formation of toxic fumes,
    (3) Formation of flammable gases,
    (4) Volatilization of toxic or flammable substances,
    (5) Formation of substances of greater toxicity,
    (6) Formation of shock and friction sensitive compounds,
    (7) Pressurization in closed vessels,
    (8) Solubilization of toxic substances,
    (9) Dispersal of toxic dusts, mists, and particles, and
  (10) Violent polymerization.

Available data indicate that hazardous wastes are ill-defined, complex mixtures generated by a great variety of sources. No two types of wastes appear to be identical, for even a single process appears to produce different types of wastes. Laboratory analyses of wastes seem to be non-existent or cursory due to the high costs and complexity of analytical methods required. Characterization of the wastes by the analysis of the processes and the materials used appear to give inaccurate descriptions of the resulting wastes. The data indicate that each waste is unique and that individual reactivities may be best assessed by identifying respective chemical constituents.

For further information on compatability of hazardous waste refer to the Guidance Manual entitled, "Treatment Trial Tests and Hazardous Waste Compatability".

While empirical data exist concerning the consequences of reactions between pure substances under laboratory conditions (mostly binary combinations), very little work has been done in the field of waste combination reactions. Very seldom are wastes pure substances. They are usually sludges, emulsions, suspensions, or slurries containing many different compounds.

The chance of combining noncompatible wastes within a specific category can be minimized in several ways. First, the problem is restricted to pumpable wastes since nonpumpable scrap is often handled in individual drums or bin containers and is not mixed prior to incineration. Secondly, a single manufacturing location normally uses compatible solvents. Thus, with knowledge of the generator in hand (manifest system), the greatest chance that noncompatible wastes will be combined occurs at the incineration facility. Basically, proper labelling at the waste generation source and the experience and knowledge in liquid segregation of the incinerator operators will greatly minimize the problem.

It is evident from the existing data that the largest and most common dangers inherent from imcompatible reactions involve strong acids or bases. For this reason, it is desirable that acids and bases be neutralized to within a pH range of 4.5 to 9 before being mixed with other wastes (sometimes acidic and basic wastes are mixed in a controlled manner to achieve pH neutrality). Even within this restricted pH range, acids should be segregated from acid-soluble sulfide and cyanide salts.

With the above inclusions, an example of a compatibility matrix is depicted in Figures 5-19 and 5-20. If it is not feasible to neutralize acid wastes and/or caustics to within the prescribed pH range, then the matrix in Figure 5-20 is used.

Figure 5-19. Compatibility matrix for neutralized hazardous wastes [1].

Figure 5-20. Compatibility matrix when wastes cannot be neutralized [1].

5.5.2 Liquid Feed and Blending Equipment

Liquid blending or mixing of hazardous wastes is done as part of an overall liquid feed system, which includes a feed pump, usually some recirculation to the mix vessel, and associated piping to the incinerator.

An example of a mixing vessel is shown in Figure 5-21. For hazardous waste blending, the vessel is always closed-top rather than open-top to prevent splashing and vapor escape. Impeller mixer drives, both direct drive and gear drive, are available. The shaft length and number or configuration of impellers must be based on the geometry of the tank and viscosities of the waste. Generally, fuel blending requires a mild agitation or intensity of blending, and the use of baffles increases the turbulence and mixing characteristics.

Where conditions warrant extreme safety, the blending and feeding process can be augmented by the use of a pneumatic compressed air (or gas mixer motor, inert gas blanketing of the mixing vessel, and pneumatically-driven diaphram feed pump. The pumps used to transfer the wastes from storage to blending can also be pneumatic diaphram pumps.
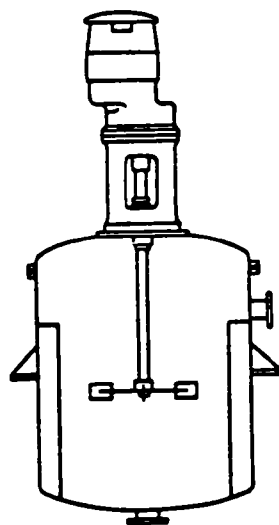
Figure 5-21. Example of a baffled
mixing vessel [14].

If the type of incinerator can handle a slurry feed, the piping system should
be designed to handle slurries. A slurry piping system has a minimum diameter
of 4-6 times the particle size being pumped. All piping is recirculated to
prevent settling, and possibly, mechanically comminuted to destroy any
agglomerations which would cause plugging problems. A careful monitoring of
the pump discharge pressure allows the operator to determine whether the feed
pump is being influenced by the mixer (entrained air), as a check of slurry
density, and to point to plugging problems. Figure 5-22 shows a slurry
injection and monitoring system.
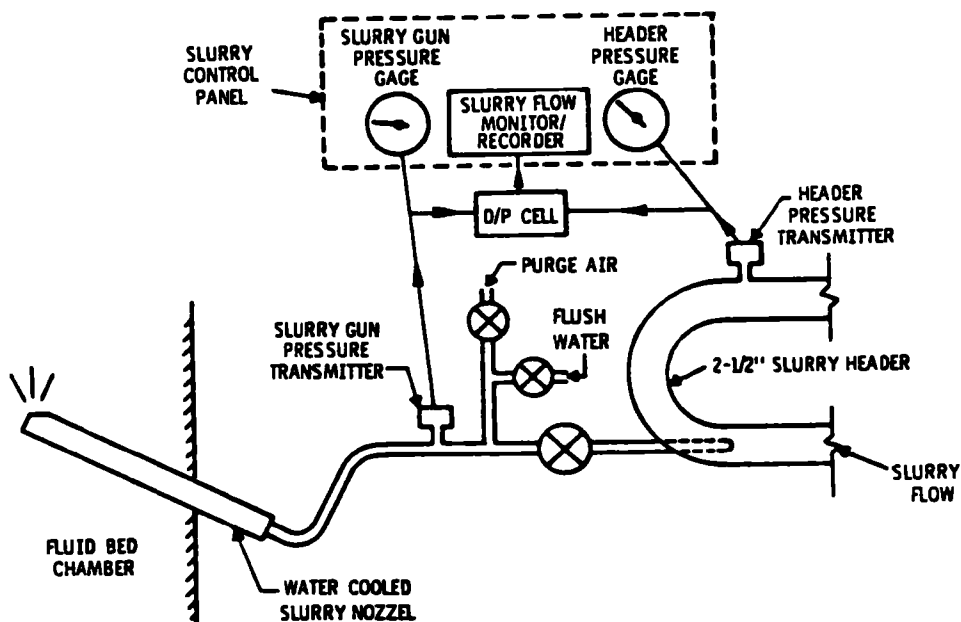
Figure 5-22. Slurry injection and monitoring system.

When slurries cannot be fed to an incinerator, the feed lines to the mixing tanks are filtered to prevent solids from reaching the burner nozzles.

Liquid streams can carry impurities of every sort. Furthermore, they may be highly viscous, which makes handling and atomizing difficult. Liquids should generally have a viscosity of 10,000 SSU or less to be satisfactorily pumped and handled in pipes. For atomization, a viscosity of 750 SSU is the maximum. Viscosity can usually be controlled by steam heating with tank coils or in-line heaters, but careful notice of the flash points must be taken. If pre-heating is not feasible, a lower viscosity and miscible liquid may be added to reduce the viscosity of the mixture.

A feed system may have two or more recirculating loops installed, chiefly to keep any solids remaining in the liquid mixture from settling and plugging pipelines. Figure 5-23 illustrates an example of multiple recirculation.

GV- GATE VALVE OR GLOBE VALVE
PRV-PRESSURE RELIEF VALVE HEARTH
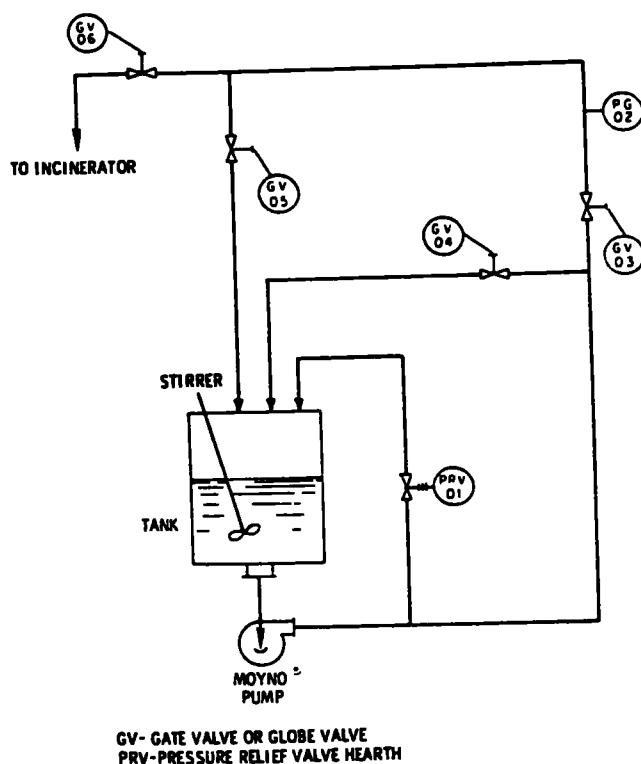
Figure 5-23. Liquid feed system with redundant recirculation.

5.5.3 Pumps and Piping

Pump and piping materials of construction are designed to be suitable for the liquids encountered (See Section 5.13). While centrifugal pumps can be used to feed liquids and/or slurries, positive displacement-type (PD) pumps are preferred. Unlike centrifugal pumps, they afford a reasonably tight shut-off and prevent siphoning when not in operation. Table 5-4 displays the materials of construction for positive displacement pumps. Figure 5-24 provides a pump classification chart.

TABLE 5-4. MATERIALS OF CONSTRUCTION FOR POSITIVE DISPLACEMENT PUMPS

| | Plunger pump | | Diaphragm pump |
| | | | Diaphragm |
Pump body	Plunger	Lantern ring	or bellows
Steel	Stainless steel	Stainless steel	Elastometer
Iron	Ceramic	Allow 20	Teflon
Stainless steel	Monel	Hastelloy "C"	Polyethylene
PVC		PVC	Buna N
Alloy 20		Alumina-ceramic	Neoprene
Monel			Viton
Carpenter 20			Resistant steels

| | Check valves | |
Valve body	Ball	Ball seat
Steel	Stainless steel	Stainless steel
Stainless steel	PVC	PVC
PVC	Hastelloy "C" to "D"	Alloy 20
Alloy 20	Alumina-ceramic	Monel
Hastelloy "C"		Hastelloy "C"
Monel		
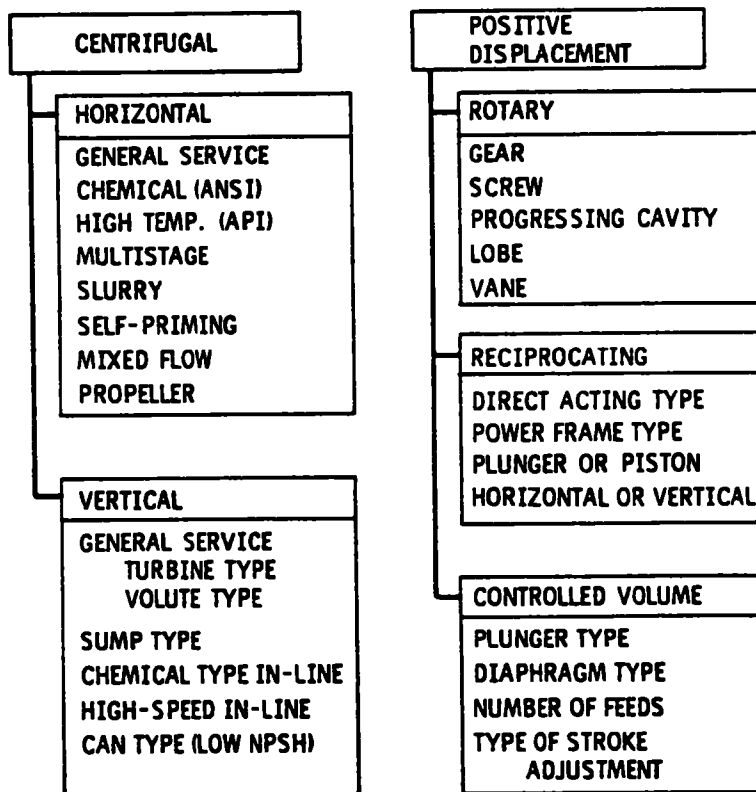
Figure 5-24. Pump classification chart.

5-52

A relief valve is usually provided downstream of PD pumps, of sufficient capacity to prevent excess pressure in the system. The relief valve discharge is then piped back to the supply source or to the suction side of the pump.

5.5.3.1 Positive-Displacement Pumps--

Positive-displacement pumps have as their principle of operation the displacement of the liquid from the pump case by reciprocating action of a piston or diaphragm, or rotating action of a gear, cam, vane, or screw. The type of action may be used to classify positive-displacement pumps as reciprocating or rotary. Figures 5-25 and 5-26 depict some typical pumps of each type. When a positive-displacement pump is stopped, it serves as a check valve to prevent backflow.
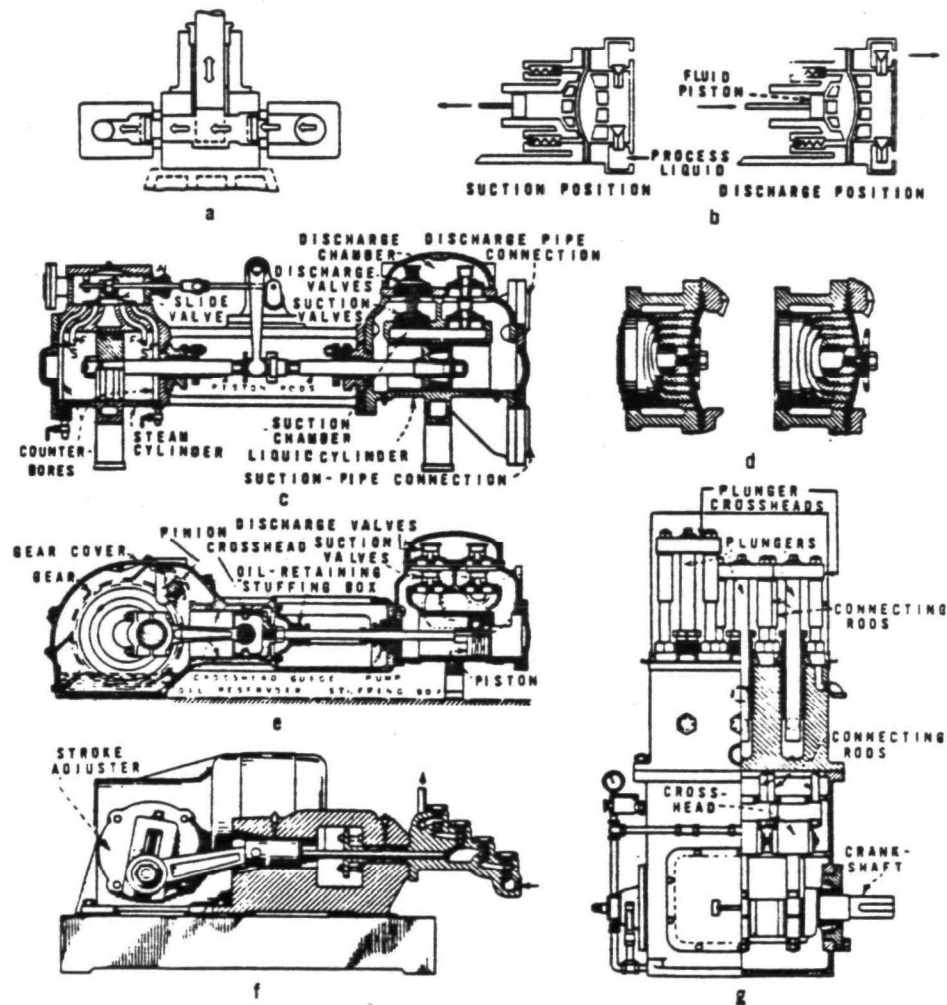
Figure 5-25. Reciprocating pumps: (a) Principle of reciprocating pump, (b) principle of fluid-operated diaphragm pump, (c) direct-acting steam pump, (d) principle of mechanical diaphragm pump, (e) piston-type power pump, (f) plunger-type power pump with adjustable stroke, (g) inverted, vertical, triplex power pump [20].
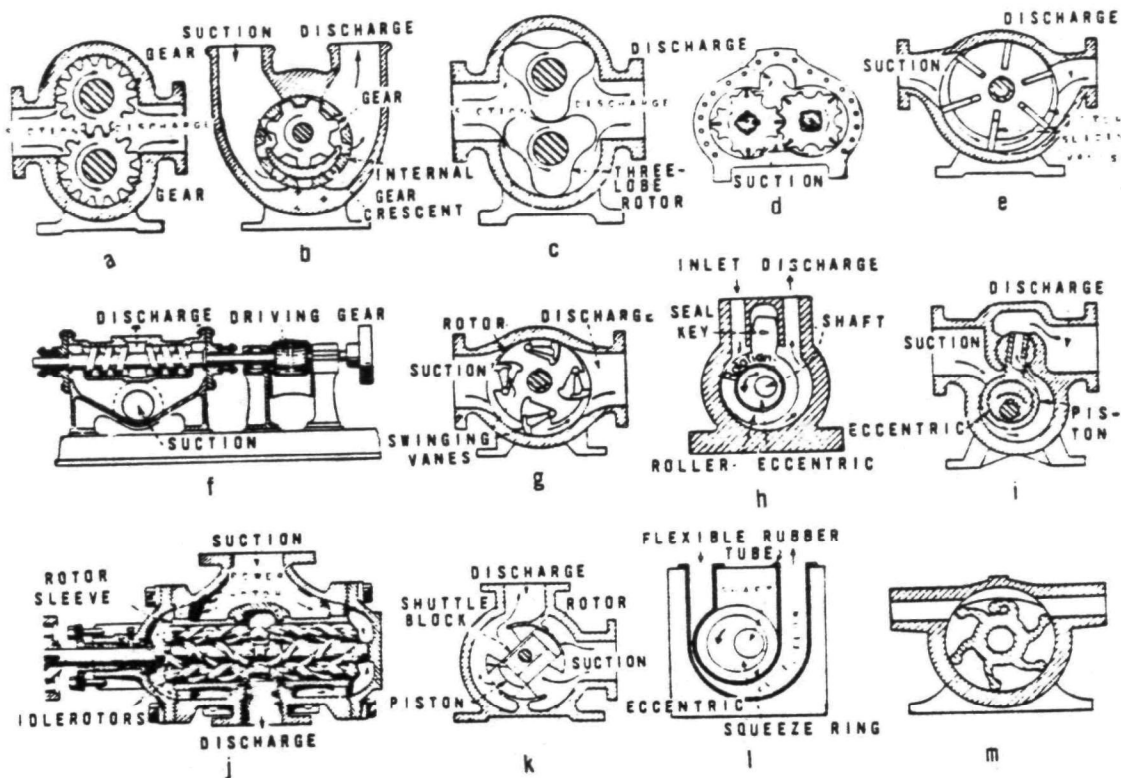
Figure 5-26.   Rotary pumps: (a) External-gear pump, (b) internal-gear pump,
(c) three-lobe pump, (d) four-lobe pump, (e) sliding-vane pump,
(f) single-screw pump, (g) swinging-vane pump, (h) cam or
roller pump, (i) cam-and-piston pump, (j) three-screw pump,
(k) shuttle-block pump, (l) squeegee pump, (m) neoprene vane
pump [20].

5.5.3.2 Centrifugal Pumps--
Centrifugal pumps operate by the principle of converting velocity pressure
generated by centrifugal force to static pressure. Velocity is imparted to
the fluid by an impeller that is rotated at high speeds. The fluid enters at
the center of the impeller and is discharged from its periphery. Unlike
positive-displacement pumps, when the centrifugal type of pump is stopped
there is a tendency for the fluid to backflow. Figure 5-27 depicts some
centrifugal pumps.

Power for driving the various types of pumps is usually derived from electric
motors or pneumatic drives. Most rotary pumps are driven by electric motor.

5.5.3.3 Pump Emission Control--
Operation of various pumps in the handling of fluids can result in the release
of air contaminants. Both reciprocating and centrifugal pumps can be sources
of emissions.
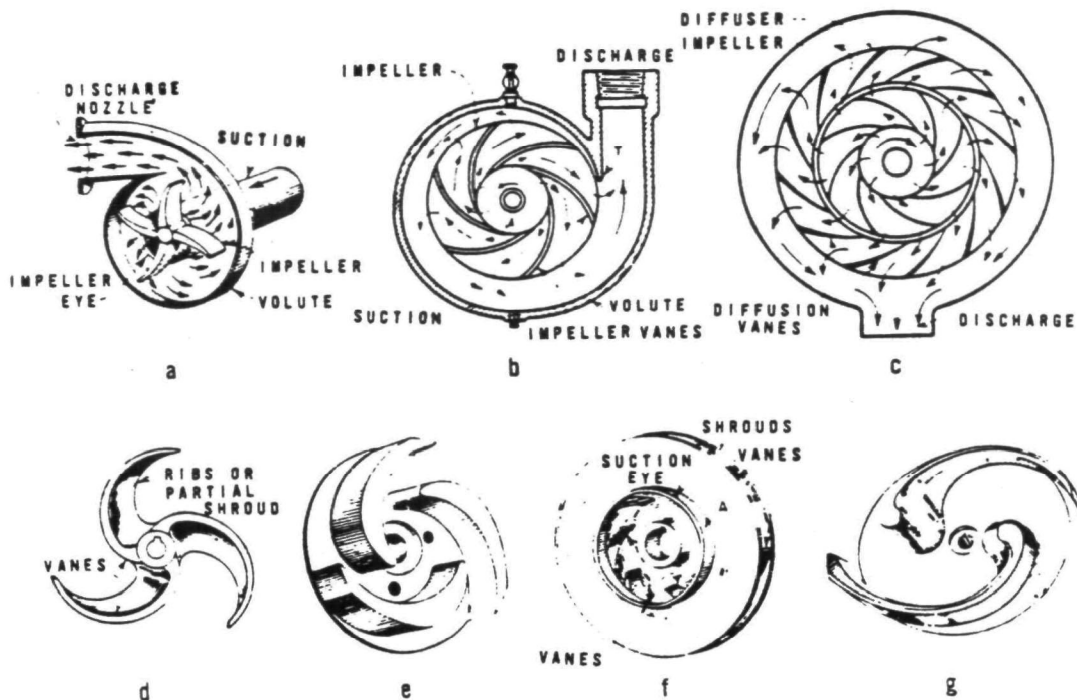
Figure 5-27.   Centrifugal pumps: (a) Principle of centrifugal-type pump,
                (b) radial section through volute-type pump, (c) radial section
                through diffuser-type pump, (d) open impeller, (e) semi-
                enclosed impeller, (f) closed impeller, (g) nonclog impeller
                [20].

The opening in the cylinder or fluid end through which the connecting rod
actuates the piston is the major potential source of containants from a recip-
rocating pump. In centrifugal pumps, normally the only potential source of
leakage occurs where the drive shaft passes through the impeller casing.

Several means have been devised for sealing the annular clearance between pump
shafts and fluid casings to retard leakage. For most applications, packed
seals and mechanical seals are widely used.

Packed seals can be used on both positive displacement and centrifugal type
pumps. Typical packed seals generally consist of a stuffing box filled with
sealing material that encases the moving shaft. The stuffing box is fitted
with a takeup ring that is made to compress the packing and cause it to tight-
en around the shaft. Materials used for packing vary with the fluid's tempera-
ture, physical and chemical properties, pressure, and pump type. Some
commonly used materials are metal, rubber, leather, and plastics.

Lubrication of the contact surfaces of the packing and shaft is effected by a
controlled amount of product leakage to the atmosphere. This feature makes
packing seals undesirable in applications where the liquid can cause a pollu-
tion problem. The packing itself may also be saturated with some material

such as graphite or oil that acts as a lubricant. In some cases cooling or quench water is used to cool the impeller shaft and the bearings.

The second commonly used means of sealing is the mechanical seal, which was developed over a period of years as a means of reducing leakage from pump glands. This type of seal can be used only in pumps that have a rotary shaft motion. A simple mechanical seal consists of two rings with wearing surfaces at right angles to the shaft. One ring is stationary while the other is attached to the shaft and rotates with it. A spring and the action of fluid pressure keep the two faces in contact. Lubrication of the wearing faces is accomplished by a thin film of the material being pumped. The wearing faces are precisely finished to ensure perfectly flat surfaces. Materials used in the manufacture of the sealing rings are many and varied. Choice of materials depends primarily upon properties of fluid being pumped, pressure, temperature, and speed of rotation. The vast majority of rotating faces in commercial use are made of carbon.

Emissions to the atmosphere from centrifugal pumps may be controlled in some cases by use of the described mechanical-type seals instead of packing glands. For cases not feasible to control with mechanical seals, specialized types of pumps, such as canned, diaphragm, or electromagnetic, are required.

Another specialty category is the sealed pump, which has no external seal or potential leakage. The two major types are the canned-rotor and the magnetic. Sealed pumps are used where no leakage can be tolerated, or where pump seal failure might cause major trouble. Such pumps are available in a limited range of sizes, most are low-flows, and all are of single- or two-stage construction. They have been used for both high-temperature and very low-temperature liquids. High-suction-pressure applications avoid the need for a troublesome high-pressure stuffing box. The centrifugal-type pumps follow the same hydraulic performance rules as conventional centrifugal pumps. Because of their small size, these pumps show a rather low efficiency but, in dangerous applications, efficiency must often be sacrificed for safety.

5.5.3.4 **Pump and Piping Safety**--
The primary objectives of pumping and piping systems are to prevent escape of liquid and to keep to a minimum the quantity lost if the liquid does escape. Inherent safety and freedom from human failure can, to a considerable extent, be built into a hazardous/flammable liquid system. Some design recommendations which help to attain the above objectives are listed below:

(1) Complete automatic sprinkler protection is provided in indoor areas where pumps, piping, tanks, and other parts of hazardous liquid transfer systems are located. In well-drained areas, sprinkler discharge of 0.30 gpm/sq ft of floor area is usually recommended to prevent structural and equipment damage.

(2) Indoor piping is located either overhead or in trenches in the floor. Overhead piping is normally installed close to ceilings or beams or along walls at least 6 ft above floor level. If piping is located in a trench in the floor, the trench is covered with removable steel plates and a trapped drain installed to a point of safe

discharge. Positive-exhaust ventilation is provided in the trench, or the trench is backfilled with sand for liquids having closed-cup flash points below 110°F.

(3) Provisions are made to clean out the piping and equipment when long or scheduled shutdowns occur. This is usually done by purging with steam. The condensate is then collected and treated as a wastewater.

(4) Pipe materials are used which are chemically resistant to the liquid handled, which have adequate design strength to withstand the maximum service pressure and temperature, and which, when possible, are resistant to mechanical damage or thermal shock. Cast-iron, soft-rubber, or thermoplastic pipe or fittings of low melting point are never used.

(5) If corrosive liquids or high standards of purity make special pipe necessary, the use of stainless steel, nickel alloys, or other materials having high resistance to heat and mechanical damage or steel pipe with tin, glass, plastic, rubber, lead, or other lining is preferred to more fragile piping. If problems of corrosion, contaminations, or sanitation are the controlling factor, the use of carbon, graphite, glass, porcelain, thermosetting-plastic, or hard-rubber pipe is acceptable. Where specifically needed for the liquid being handled, aluminum alloy, aluminum bronze, or lead pipe is acceptable. Extra care is then used in locating, guarding, and supporting specialty piping against mechanical injury.

(6) Each waste material pipeline is clearly marked by lettering (coded or otherwise), color banding, or complete color coding to indicate the product transferred therein. The coding normally conforms with company policy or standard plant practice which, in turn, should conform with state or federal requirements.

(7) Each oil or hazardous material product-fill line which enters a tank below the liquid level has a one-way flow check valve located as closely as possible to the bulk storage tank. In addition to confining the product to the tank, in the event of valve or pipeline failure, the check valve permits overhaul of the main shut-off valve and should aid in preventing shock loading of the pipeline and valves from a "slug" of the tank content caused by backflow into an empty fill line. The waste feed flow in suction lines is controlled by use of a positive displacement pump.

(8) Buried pipelines are generally avoided. When they do occur however, buried installations have a protective wrapping and coating and are cathodically protected if soil conditions warrant. A section of the line is then exposed and inspected regularly. This action is normally recycled until the entire line has been exposed and examined on a regularly established frequency. An alternative would be the use of exposable pipe corridors or galleries.

(9) When a pipeline is not in service, the terminal connection at the transfer point is capped or blank-flanged, and marked as to origin.

(10) Wood-to-metal is normally avoided as a pipeline support since it is apt to retain moisture and cause pipeline corrosion which, when coupled with the abrasive action caused by the pulsating action of the line, could cause line failure with resulting leakage. Supports are generally designed with only a minimum point of surface contact that allows for the pulsating movement (expansion and contraction) inspections at which time the general condition of items, such as flange joints, valve glands and bodies, catch trays, pipeline supports, locking of valves, and metal surfaces, are assessed.

(12) Elevated pipelines are also subjected to constant review to insure that the height of vehicular traffic granted plant entry does not exceed the lowermost height of the elevated line; gate check-in and in-plant travel are routes which warrant attention in this respect.

(13) Double-walled piping and/or flange shielding may be necessary for some above-ground pipelines carrying an especially hazardous or toxic waste stream if the pipeline intersects critical locations such as highways, driveways, railroads, or small watercourses. An example is illustrated in Figure 5-28.

(14) As far as practical, all pumps feeding the blender are located as close as possible to the storage tank.

1. A SHIELD PREVENTS SPLASHING IF THE FLANGE FAILS.

2. OUTER CONCENTRTIC PIPE PREVENTS ESCAPE (AND INDICATES THE FAILURE) IF INNER, LIQUID-CARRYING PIPE FAILS.
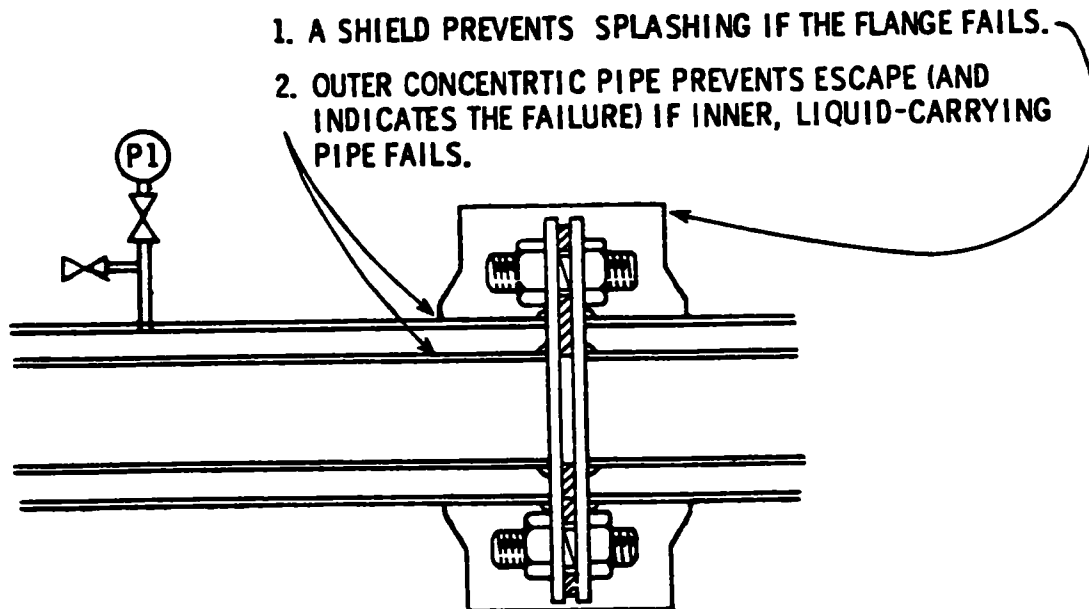
Figure 5-28. Two safeguards for piping of highly toxic liquids [21].

Many liquid wastes are solids at room temperature or become highly viscous at lower temperatures, and require heated piping to keep them in a fluid state suitable for transfer through the system. Liquids from heated tanks can usually be handled by providing adequate insulation on the pipe and fittings. The following methods of applying heat to piping systems are considered acceptable:

(1) Flammable-liquid lines are often steam-traced. The minimum steam pressure needed is used to make the liquid fluid, and a regulator is provided in the steam line with a relief valve downstream of the regulator set somewhat higher. The pipe and tracing are enclosed with noncombustible insulation.

(2) Electric heating cable is usually fastened along the pipe or wound spirally around it and the whole covered with noncombustible insulation. No splices in the cable should be made, and all connections are located outside the insulation-covered pipe. Individual thermostatic controls for each cable section should be provided and protected with a fuse or fused disconnect switches of as low a rating as practical. Outdoors, weather-proof enclosures are provided for thermostats, plug assemblies, and switches, and in all installations are located safely away from the pipelines and out of the flammable-liquid area. Accessories will introduce a hazard unless located so that the make-and-break contacts will function in a nonexplosive atmosphere.

(3) Thermal-electric conduction may be utilized by passing a low-voltage alternating current though the pipe. This method is commonly used to maintain a constant temperature in a system of piping when material in the storage tank has been previously warmed. Sufficient heat is supplied to the piping to compensate for normal heat loss in the system without raising the temperature of the liquid in transfer. Thermal-electric conduction systems is normally installed and tested as complete units by the manufacturer or his qualified agent. Sections of the piping to be heated are insulated by electrically nonconductive fittings from unheated sections to confine the current paths and to eliminate any current leakage at hazardous locations.

For thermal-electric conduction systems the following recommendations usually apply:

(a) An automatic high-temperature-limit safety cutoff switch is provided in each circuit of each system to prevent overheating of liquid in event of failure of the operating temperature-control thermostat.

(b) Each circuit is protected with fuses or fused disconnect switches of the lowest practical rating.

(c) All parts of the piping and fittings are enclosed in electrical- and thermal-insulating covering to prevent accidental grounding of the system.

(d) All switches, transformers, contactors, or other sparking units are located in a safe area away from any flammable liquid or vapor.

(e) The system is inspected and tested periodically to insure its continued safe operation. Maintenance of the installation is the responsibility of trained employees.

5.5.4 Valving and Controls

Valve functions can be defined as follows:

(1) On/off service
(2) Throttling service
(3) Prevention of reverse flow, or backflow
(4) Pressure control
(5) Special functions:
    (a) Directing flow
    (b) Sampling service
    (c) Limiting flows
    (d) Sealing vessel or tank outlets
    (e) Other.

Valve selection requires consideration of three basic and critical details:

(1) The flow control element
(2) The regulating mechanism
(3) The seal to contain the fluid within the valve.

In addition to these three important design aspects, features such as mechanical strength, materials of construction, dimensional arrangement, and types of end-connections are considered.

Valves are weak links in fluid transfer systems as regards leaks and fugitive emissions. There are three types of leakage:

(1) Process fluid escapes downstream, past flow-control element in closed position. Identified as "flow seal" leakage.

(2) Process fluid escapes to the outside of the valve, from around the stem and from the joints (bonnet) with the body. Identified as either stem-seal or bonnet-seal leakage.

(3) Air leaks into the valve body and to the process medium under vacuum.

Figure 5-29 shows a gate valve with the possible leakage areas around the stem packing, the bonnet assembly, and between the valve stem and packing gland.
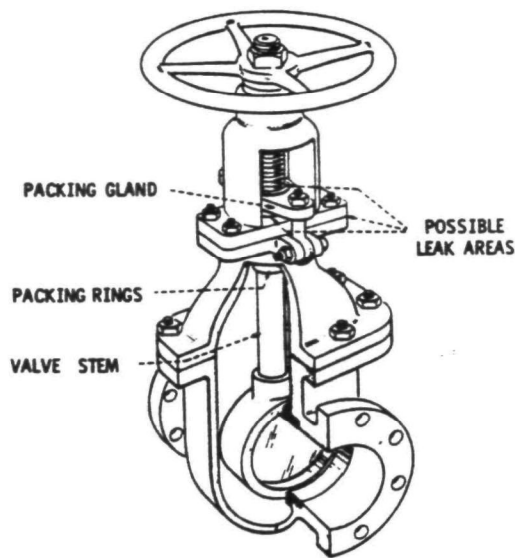
Figure 529.   Three areas of a typical gate valve that
can leak and result in fugitive emissions [2].

5.5.5 Valving and Control Safety Consideration

5.5.5.1 Safety Shutoffs--

Hazardous and flammable-liquid pumping and piping systems are equipped with emergency shutoffs to stop the flow of liquid in event of fire or accidental escape of liquid or vapor. This can usually be done by safety shutoff valves and/or positive-displacement pumps. In general, these devices are arranged for automatic operation in event of fire and for manual or automatic operation in event of accidental escape of liquid. If the location of a possible fire can be accurately determined, as would be the case at dispensing locations, remote actuation is not necessary. If a fire could occur anywhere at an extensive installation, provision for remote actuation of the main safety shutoff valve will be needed.

(1) Safety shutoff valves are needed in flammable-liquid systems in the following locations:

(a) At connections on supply and feed tanks where transfer is by gravity, centrifugal pump, inert-gas pressure, or other means that permits the maintenance of continuous pressure in the system. The possibility of siphon action through a centrifugal pump requires installation of a safety shutoff valve on the pump inlet.

(b) On feed lines where they enter important buildings or structures or on branch lines where they take off from main-supply headers. The valve is located out of doors or immediately adjacent to an exterior wall, accessible from outdoors.

5-61

(c) On feed lines at dispensing locations.

(2) Safety shutoff valves may be of the diaphragm, solenoid, or weight-
    or spring-operated fusible-element types. They generally
    incorporate some of the following design features:

    (a) Have bodies with the appropriate service rating for the maximum
    pressure and temperature to be encountered. Bodies should be of
    cast steel, except that bronze is acceptable in sizes of 2 in.
    and less if under sprinkler protection.

    (b) Close on failure of the operating electrical or air supply.

    (c) Close in the direction of the liquid flow so that system
    pressure tends to hold the valve in the closed position.

    (d) Close against a pressure of at least 150 per cent of design
    rating.

    (e) Close within 5 seconds after actuation.

    (f) Valve should not readily be bypassed, blocked, or otherwise
    made ineffective.

    (g) Have an indicator to show when the valve is open or shut,
    except on packless solenoid types.

    (h) Be manually reset, except where the valve-control circuit is
    arranged for manual resetting.

    (i) Have no direct connections between the liquid and air section
    of diaphragm valves that might permit leakage of the liquid
    past the packing into the air lines.

    (j) Have packing and lubrication, if any, resistant to the liquid
    being handled.

(3) Automatic operation of safety shutoff valves and/or direct-
    displacement pumps is normally accomplished by one of the following
    methods:

    (a) Actuation by thermal devices located at the ceiling and above
    the point of flammable-liquid use where spills may be expected.

    (b) Release of a dead-man control.

    (c) Operation of the fire-protection system. With automatic sprin-
    kler systems, actuation may be by waterflow indicators, alarm
    valves, or dry-pipe valves with hydraulic-pressure switches.
    With special fixed extinguishing systems, actuation is by
    pressure switches. Drain and alarm tests of sprinkler system

are made during idle periods or arranged that they can be made without operating the safety shutoff.

(d) If the piping contains fragile components such as rotameters and sight glasses, the safety shutoff is actuated automatically by excessive pressure drop downstream from such components.

(4) Arrange safety shutoff valves and/or positive-displacement pumps for manual shutdown by use of one or more stop buttons or switches at safe and accessible locations throughout the flammable-liquid system. In general, such stop buttons or switches are located near points of egress from the building or structure.

(5) Self-closing manual valves and dead-man controls of a type not readily blocked open are recommended as emergency safety shutoffs on small systems, where liquid transfer is intermittent, and on larger systems that lend themselves economically to such an arrangement. They require constant attendance by the operator and close automatically if he leaves.

(6) If normal flow in piping is in one direction only and the piping discharges to feed tanks, receivers, or other vessels so located that a leak in the piping upstream of these vessels could be fed by reverse flow through the piping, check valves are installed in the piping as close to the vessel as possible to prevent the reverse flow.

5.5.5.2 <u>Gages, Meters, and Gage Glasses</u>--
(1) Accessories on flammable-liquid piping systems, such as gages, meters, gage glasses, hydrometers, and sight glasses are designed to have strength equal to that of the piping system.

(2) Gage glasses are particularly susceptible to breakage. Their use is generally discouraged.

(3) Restricted orifices are used in piping to gages and instruments to reduce the amount of leakage in event of failure.

(4) Armored rotameters or instruments that read indirectly or sample a proportion of the flow in preference to those that enclose the entire stream or have the full flow directed to the glass reading chamber are also used. Vents on air releases used in conjunction with some metering devices are then piped to outdoors in order to dispose safely of flammable liquid that may be discharged if the float is inoperative.

5.5.5.3 <u>Operating Controls</u>--
(1) Operating control valves are located in hazardous and flammable-liquid piping systems so as to regulate the control and flow of liquids to connected equipment and to isolate equipment for maintenance purposes. Conventional types of valves are suitable for most liquids. Valves are used having the appropriate service rating for

the maximum pressure and temperature to be encountered and packing or lubrication resistant to the liquid being handled. Valve bodies are normally of cast steel, except that bronze is acceptable on piping 2 in. or less in size in sprinklered locations. Cast-iron bodies are usually not used. If corrosive conditions or product purity require the use of special materials of construction, stainless-steel, Monel, or lined-steel valves are preferred to those made of more fragile materials.

(2) Valving is arranged to minimize the likelihood of improper operation. Rising-stem or other valves that indicate whether open or closed are preferred. The following recommendations for valve arrangements are generally followed where applicable:

    (a) Three-way two-port valves are used at all branch lines so that flow can only proceed through one line. .

    (b) Plug-cock valves are used with a slotted guard arranged so that the handle can be removed only when the valve is in the closed position. This arrangement will prevent discharge through valves accidentally left open. One handle can serve all valves on the system.

    (c) Electrical or mechanical interlocks are provided between valves so that the position of one valve with respect to another will be automatically determined.

(3) Where the correct sequence of additions of waste materials to a blending tank is of importance, sequence locks are used on valves in pipelines.

(4) Hydraulic accumulators or safety relief valves are provided on pipelines that can be valved off with liquid trapped between valves. This prevents damage or overpressure from thermal expansion. The discharge is piped from safety relief valves to a collection point.

(5) Tanks, mixers, and other equipment to which hazardous liquid waste is transferred are arranged so as to prevent accidental overflow. The best arrangement is a trapped overflow drain leading back to the source of supply or to a point of safe collection. The capacity of the overflow drain should be at least equal to that of the fill pipe.

(6) If the equipment normally operates under pressure so that an overflow drain is not practical but overflow is possible during filling because of open manholes or sampling connections, a liquid-level control is provided to stop the liquid flow by closing a valve or stopping the pump or to sound an alarm if the maximum safe level is approached or exceeded. Float valves or switches, pressure switches, and various other liquid-level indicators are available and may be used. Mechanical interlocking of valves on overflow drain and fill

pipe can sometimes be arranged so that the overflow drain will be open when the fill-pipe valve is open.

(7) The use of accurate measuring devices, such as dispensing meters, measuring tanks, or weight tanks will assist greatly in the prevention of overflows. Dispensing meters permit a predetermined amount of liquid to pass and then automatically stop the delivery. Such meters control a spring-loaded quick-action valve that should be designed for manual starting with a hand-trip emergency shutoff.

(8) If control valves are to be remotely actuated, valves are chosen having characteristics described in recommendation 2 of Safety Shutoffs and arranged for operation in an emergency situation.

5.5.6 Solids Feeding Equipment

Waste material is pneumatically, mechanically, or gravity fed into an incinerator capable of burning solids. Normally, heterogeneous waste material must be reduced in size (shredded, pulverized, etc.) to facilitate the feed system operation and allow injection, distribution, and combustion within the incinerator.

In addition to reducing moisture content and waste material size, separation of noncombustible material such as ferrous and nonferrous metals may often be required. The former is removed using magnetic separators. Nonferrous metals are commonly removed using ballistic-type separators.

5.5.6.1 Shredders--
To reduce the size of waste materials for easier handling and feeding, shredders are used. Also, to expose all surfaces of hazardous waste containers (metal and fiber drums), it is usually necessary to shred the containers. A shredder capable of consuming 55-gallon steel drums has to be a rugged unit, capable of containing dusts and mists of toxic materials as well as particles of steel thrown around at high velocity. This type of potential danger indicates a need for a hopper feed system to enclose flying debris, with mechanical feed from a conveyor so that plant personnel need never be in the vicinity of the hopper opening during operation. The hopper is elevated for gravity feed into the shredder, which also may be above ground level and well ventilated. A suction fan can then draw fumes and dust from the shredder into the incinerator or an alternate collection device.

A shredder capable of consuming 55-gallon drums would probably have a capacity for handling material several times as fast as the incinerator. Thus, some silo storage is necessary to safely contain the shredded material. The material discharged from the silo would go directly into the incinerator.

A shredding operation normally consists of a shredding unit and a transfer network including a variety of conveyors and feeders. Several types of shredding devices exist: vertical and horizontal axis hammer mills, vertical axis grinders, and horizontal axis impactors; horizontal hammer type shredders are the most common.

Unlike most other rotating equipment (pumps, fans, turbines, etc.), there is very little design criteria for predictable performance of mixed solid waste shredders. Size, style, and power selection is on an empirical basis, and this is not likely to change in view of the infinite types and combinations of input material.

There are three basic types of horizontal shaft swing hammer type shredders:

(1) Topfeed, single direction rotor rotation
(2) Topfeed, reversible rotor rotation
(3) Controlled feed, single direction rotor rotation.

Figure 5-30 illustrates a cross-sectional view of a horizontal axis shredder.
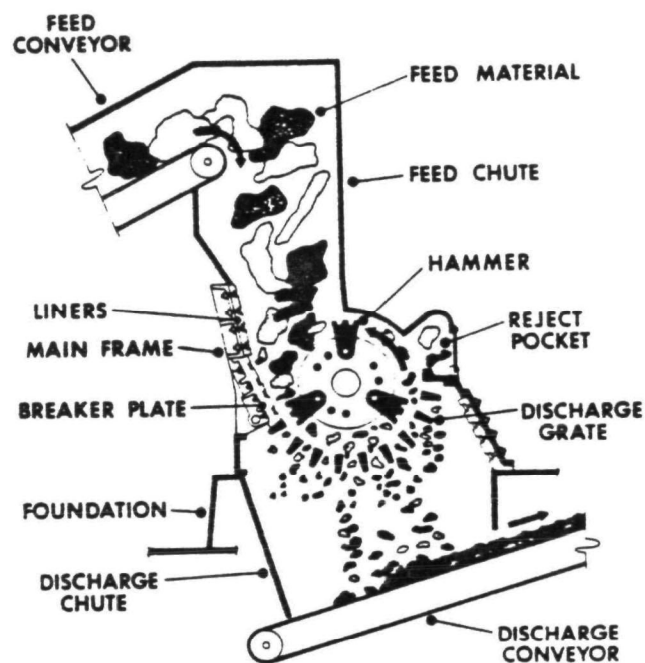
Figure 5-30. Cross-section through a nonreversible horizontal shredder [22].

5.5.6.2 Explosion Suppression and Safety Considerations for Shredders--
The primary explosion in a shredding system is a gas explosion caused by a friction spark and sometimes followed by a more violent dust explosion. Explosive dust mixtures of the type most likely to form in a solid waste shredder require a higher energy level for ignition than available from a friction spark. Explosion suppression systems have proved effective for gas and dust explosions on municipal solid waste shredders and are used on most installations. Today, most systems use a demand-inerting suppression system, whereby metal hemispherical containers release a suppressant in advance of a flame front. Such containers are connected to the shredding chamber by piping to channel the suppressant toward the interior of the chamber to provide blanket coverage. The most popular suppressant is Halon (short for

halogenated hydrocarbon), a family of chemicals which possess unique properties with regard to fire extinguishing.

Also, sufficient pressure relief area is provided in the shredder and connecting superstructures such as hoods, ducts, or any connected enclosure. Excepting the shredder, this can be by means of hinged flaps, tethered blowout panels, and flexible flaps.

In addition, other means for minimizing personal injury and building damage are [23]:

    (1)   Rigid enforcement of off-limits areas for roving personnel.
    (2)   Complete enclosure protection for the shredder operator.
    (3)   Separate or detached shredder building enclosures with blow-out sidewall and roof panels.
    (4)   Partially open walls and/or roof.

5.5.6.3 Feeders--

Critical components in any system handling bulk solids are the feeders, which, in conjunction with conveyors and other handling equipment, transfer solids at a controlled rate from storage into the process, or from point-to-point within a process. Feeders may be called upon to transfer materials from railcar to storage bin, from storage bin to conveyor, or from conveyor to the incinerator.

There are four major types of solids feeders:

    (1)   Rotary
    (2)   Screw
    (3)   Vibrating
    (4)   Belt

Many specialized feeders are also available. Table 5-5 relates feeder types to material characteristics. The most common types of feeders which will be encountered in handling hazardous solid wastes are belt feeders and screw feeders.

Both belt feeders and screw feeders have their own limitations. Steps must be taken to alleviate dusting during operation of belt feeders. Total dust control can be assured only by enclosing the feeder with the proper dust entrainment hoods. Most manufacturers furnish enclosures for belts up to about 36 inches wide. These housings can be made gas-tight for inert-gas purging. However, if the user does not monitor feeder operation, or if a poor hopper design allows powder to avalanche onto the feeder belt, or if a dust collection system has not been provided to remove particles as they become airborne, the enclosure will serve only to contain the dust so that it eventually buries the feeder.

Caution is advised when using screw feeders with sticky or very cohesive materials. Such materials can build up in short pitch sections, and conveying will cease. For these services, longer-pitch, smoothly surfaced flights, multiple screws with overlapping flights, or ribbons instead of solid flights are normally specified.

TABLE 5-5. FEEDERS FOR BULK MATERIALS

Material characteristics	Feeder type
Fine, free-flowing materials	Bar flight, belt, oscillating or vibrating, rotary vane, screw
Nonabrasive and granular materials, materials with some lumps	Apron, bar flight, belt, oscillating or vibrating, reciprocating, rotary plate, screw
Materials difficult to handle because of being hot, abrasive, lumpy, or stringy	Apron, bar flight, belt, oscillating or vibrating, reciprocating
Heavy, lumpy, or abrasive materials similar to pit-run stone and ore	Apron, oscillating or vibrating, reciprocating

Dust leakage around covers and along shaft seals is a common problem with screw feeders. "Dust tight" means little in a specification. Because this is an important requirement, "gas tight" to about one inch w.c. (water column) pressure is a term used. To ensure continued dust control, followup is normally needed during operation to make sure operators maintain seals, gaskets, and covers. Shaft seals are difficult to keep dust tight, especially if the trough is gas-purged. Even with the variety of seals offered, most will leak dust within a few hours unless shaft runout at the seal area is minimized. There is no standard industry specification covering runout; as much as 1/32 in. runout is not unusual. Manufacturers will furnish special construction for tight sealing, if this requirement is spelled out clearly in the specification.

Solid Waste Charging To Combustion Zone--The methods of feed to the combusion zone can be broken down as follows:

    (1) Batch
        (a) open charging
        (b) air lock feeders
    (2) Continuous

Batch open charging can be as simple as gravity feeding solid waste into a chute leading to the combustion zone, as in a rotary kiln incinerator.

An example of a batch air-lock feeder can be a charging hopper located above a rotary kiln inlet, charged by a grapple which is controlled from a fully air-conditioned operator cab, sealed against the bin space, using TV cameras and TV screen in a partially automatic, partially manual operation. The rotary kiln inlet is sealed from the bin space by a lock fitted with two sliding gates. When the inclined sliding gate in the drop chute of the rotary kiln inlet is closed, a horizontal sliding gate located in the charging hopper will open.

An example of a continuous solids feed is given in Figure 5-31, which illustrates a screw conveyor carrying sludge to a rotary feeder which is then pneumatically conveyed to a spin air nozzle within a fluidized bed incinerator.
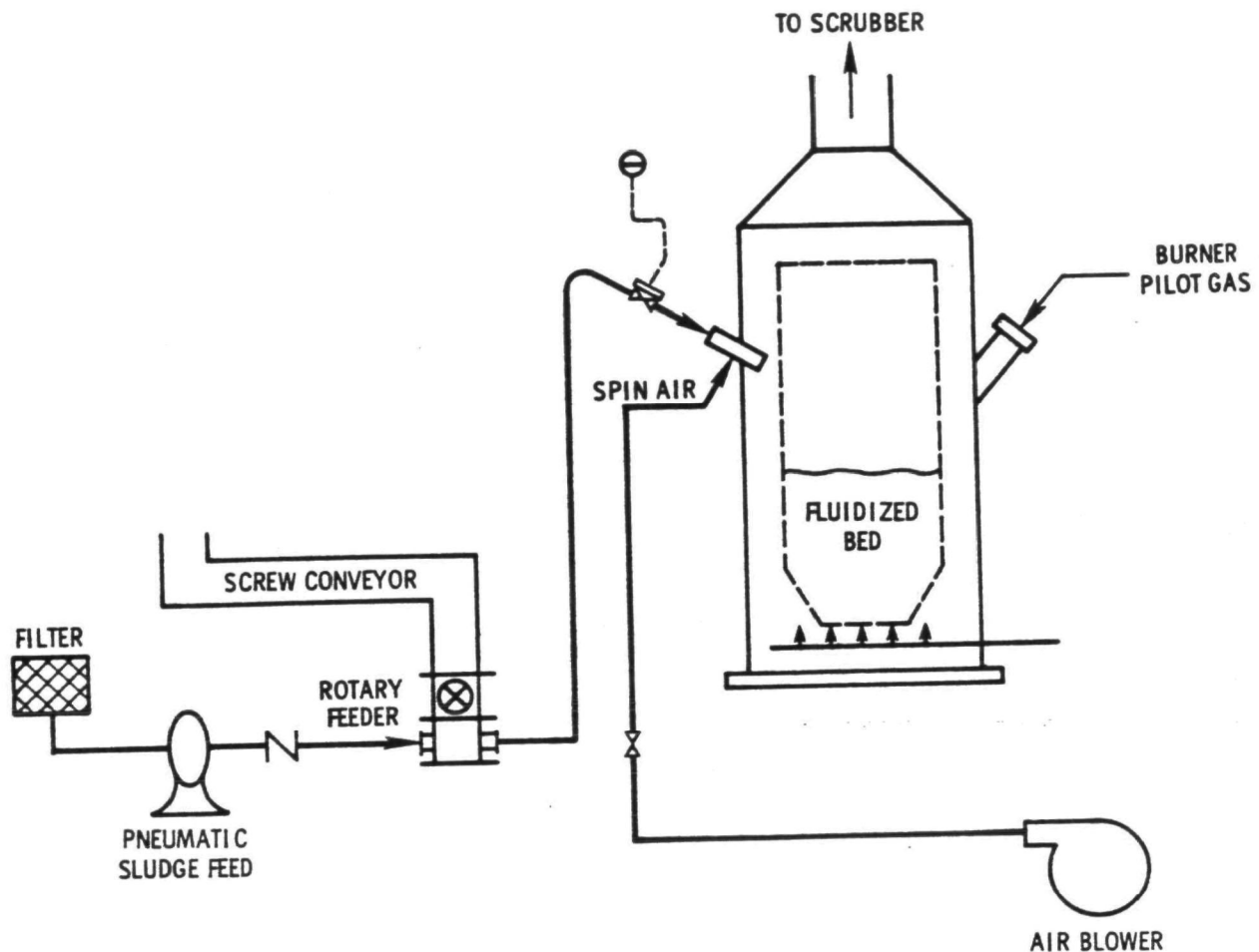
Figure 5-31. Continuous feeding of sludge to fluid bed incinerator.

5.5.6.4 Container Feeding Equipment--
For the most part, disposal technology for filled containers is appropriate for toxic materials and for materials which are not readily removable from the container. When opening the container might be harmful to operations personnel, the container should preferably be processed within a closed system. Furthermore, if the material cannot be easily poured, co-disposal of both the chemical and the container is preferable.

There are three basic types of automated container feeding equipment to incinerators:

(1) Conveyor to air-lock charging to rotary kilns.
(2) Hydraulic drum and pack-feeding mechanisms.
(3) Conveyor to air-lock vestibule with puncturing apparatus to thermal
     treatment chamber.

Figure 5-32 illustrates a schematic diagram of a rotary kiln incineration
system using air-lock charging of containers. The general practice of drop-
ping small containers into a rotary kiln without emptying them has process
disadvantages. Occasionally, there will be deflagrations with strong soot
generation and excessive thermal and mechanical loading of the kiln refractor-
ies resulting from this practice. A separate explosion vent for the charging
system is required to handle possible explosions.
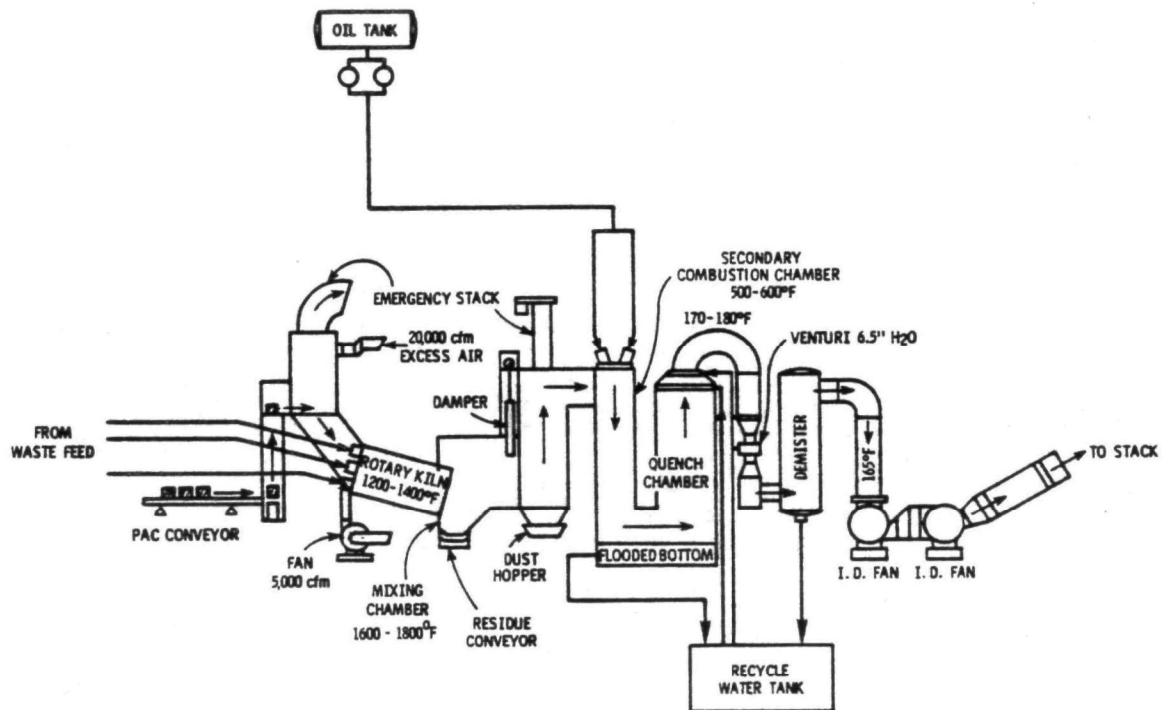
Figure 5-32. Continuous type containerized toxic
material thermal disposal process [24].

A different type of container handling, feeding, and thermal treatment system
is illustrated in Figure 5-33. The process includes a remote handling opera-
tion and a completely enclosed cannister punching operation. Containers are
then thermally cleaned in the first thermal stage with the controlled
volatilization of toxic chemicals.

The process described is excellent in the protection afforded to the operators
by the remote automated handling, punching, and thermal disposal approaches.
A wide range of containers or cannisters can be processed, including 55-gallon
drums, chemical ton containers, munition cannisters, projectiles, and cans.
Contaminated filter media have also been detoxified using the same technique.
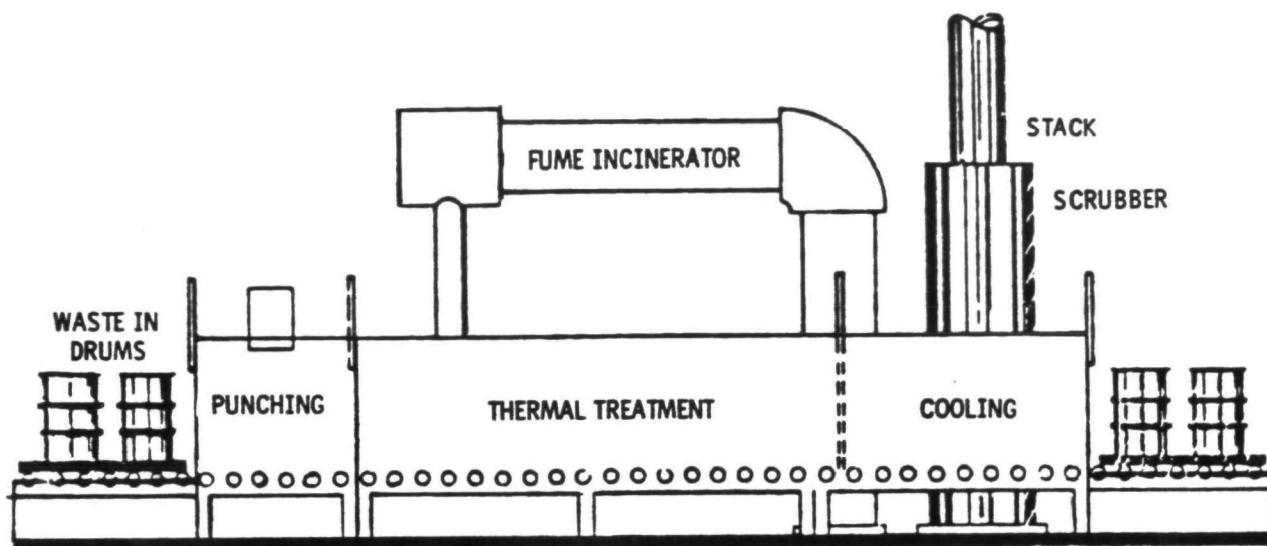
Figure 5-33. Liquid waste incinerator schematic [24].

The thermal furnace uses a containerized conveyor to transport the cannisters through the thermal process chamber, which is equipped with entry and exit vestibules with gas-tight doors at either end to facilitate the total containment of vapors which might escape from opened containers. Mechanized punching of the cannisters takes place within the entry vestibule.

5.5.7 Backup/Redundancy Provisions

The functional diagram of an incineration facility indicates that most components of the system are in a "series" configuration; each series component must be adequately functioning to avoid degraded performance. A few process components may be in a "parallel" configuration allowing a switchover to another component when problems are detected with an on-stream component. Examples are waste feed line filters which will usually have two or more units in parallel. Feed pumps are typically redundant; if plant processing rates are determined to be especially critical, redundant level monitors or extra gaging in critical storage tanks and silos, and flow monitoring cells may need backup devices to assure safety. A detailed failure mode analysis of each particular incinerator facility will identify the most likely potential malfunctions of each process element and point toward which safety systems cannot afford to fail for pointing out redundancy needs at a particular facility.

5.5.8 Waste Processing Instrumentation

An automated instrumentation system is used to transfer hazardous wastes from storage to the incinerator. Electrical and/or pneumatic systems permit observation of control, for all material handling, from a graphically illustrated control panel which shows such things as discharge valve positions, pump motor operation, storage tank and bin levels (high and low), storage tank agitator operation, and liquid or solid waste flow. Equipment operation including belt

conveyors, shredder, bucket elevator, or screw conveyors to the incinerator can also be displayed.

5.6 COMBUSTION PROCESS MONITORING

Before incineration process conditions can be controlled automatically they must be measured with precision and reliability. Instrumentation for an incineration process is essential because of the variability of the many factors involved in attaining good combustion. For example, as the heat content of the solid waste rises, changes in the combustion process become necessary. Instrumentation indicates these variations so that automatic or manual control adjustments can be made.

The uses of instrumentation and controls include means of process control, protection of the environment, protection of the equipment, and data collection. A control system must have four basic elements:

    (1)   the standard of desired performance;
    (2)   the sensor (instrument) to determine actual performance;
    (3)   the capability to compare actual versus desired performance (error), and
    (4)   the control device to effect a corrective change.

The four major factors governing incineration efficiency for a given waste feed are temperature, residence time, oxygen concentration, and the turbulence achieved. Chapter 4 discusses the significance of these factors in incinerator design and operation. Methods to determine appropriate conditions of temperature, residence time, etc., for a given waste/incinerator combination are also described in Chapter 4.

Temperature in the incinerator can be directly measured. Instrumentation is also available to directly monitor oxygen concentration in the combustion gas to insure that excess air levels are maintained. Residence time and mixing efficiency cannot be directly measured, however, so other parameters indicative of these conditions need to be measured instead.

Gas residence time in the combustion zone depends upon the volume of the combustion chamber and the volume flow rate. Since the volume of the chamber is fixed for a given unit, residence time is directly related to combustion gas volume flow rate. Therefore, measuring this flow rate is equivalent to residence time measurement for a given incinerator.

Mixing in liquid waste incinerators or afterburners is a function of burner configuration, gas flow patterns, and turbulence. Burner configuration and gas flow pattern are a function of the incinerator design and will not vary from baseline conditions. Turbulence is determined by gas velocity in the combustion chamber, which is proportional to gas volume flow rate. Therefore, combustion gas flow rate is an indicator of mixing as well as residence time in liquid injection incinerators.

In incinerators burning solid hazardous wastes, other factors need to be considered to determine solids retention time and degree of agitation. These

factors, which vary from one type of incinerator to another, are discussed in Section 5.6.4. Sections 5.6.1 through 5.6.3 discuss where and how temperature, oxygen concentration, and gas flow rate can be measured.

5.6.1 Temperature Monitoring

Incinerator temperature is monitored on a continuous basis to assure that the minimum acceptable temperature for waste destruction is maintained. This requires one or more temperature sensors in the hot zone and a strip chart recorder or equivalent recording device.

Generally, wall temperatures and/or gas stream temperatures are determined using shielded thermocouples as sensors. Thermocouples are the most commonly used contact sensors for measuring temperatures above 1,000°F. Specifically, thermocouples can measure the following thermal parameters:

a. Average gas temperature - accomplished using a shielded thermocouple with relatively large thermal capacity anchored to a relatively large mass. The metering circuit is provided with a 30-second time constant to further smooth and average the readings.

b. Instantaneous gas temperature - accomplished using a shielded thermo-couple with very small thermal capacity with the output metered by a circuit with a 1-second time constant. (Nominally, the reaction rates within the hot gas stream should be strongly temperature dependent; they thus should depend on the highest temperature to which the constituents are exposed.)

c. Open flame temperature - obtained using an unshielded low thermal mass thermocouple with the output metered by an amplifier with a 30-second time constant.

d. Average wall temperature - obtained using a shielded thermocouple imbedded in the refractory wall. (Here, the averaging is accomplished by the thermal inertia of the refractory material.)

Optical pyrometers are not recommended for these measurements due to spectral bias factors present in the combustion area which can cause unacceptable meas-urement error.

The location at which temperature measurements are taken is important, due to possible variations from one point to another in the combustion chamber. Temperatures are highest in the flame and lowest in the refractory wall or at a point of significant air infiltration. Ideally, temperatures are measured in the bulk gas flow at a point after which the gas has traversed the combus-tion chamber volume that provides the specified residence time for the unit. Generally, temperature measurement at a point of flame impingement or at a point directly in sight of radiation from the flame is not recommended. Figure 5-34 shows the approximate measurement location.
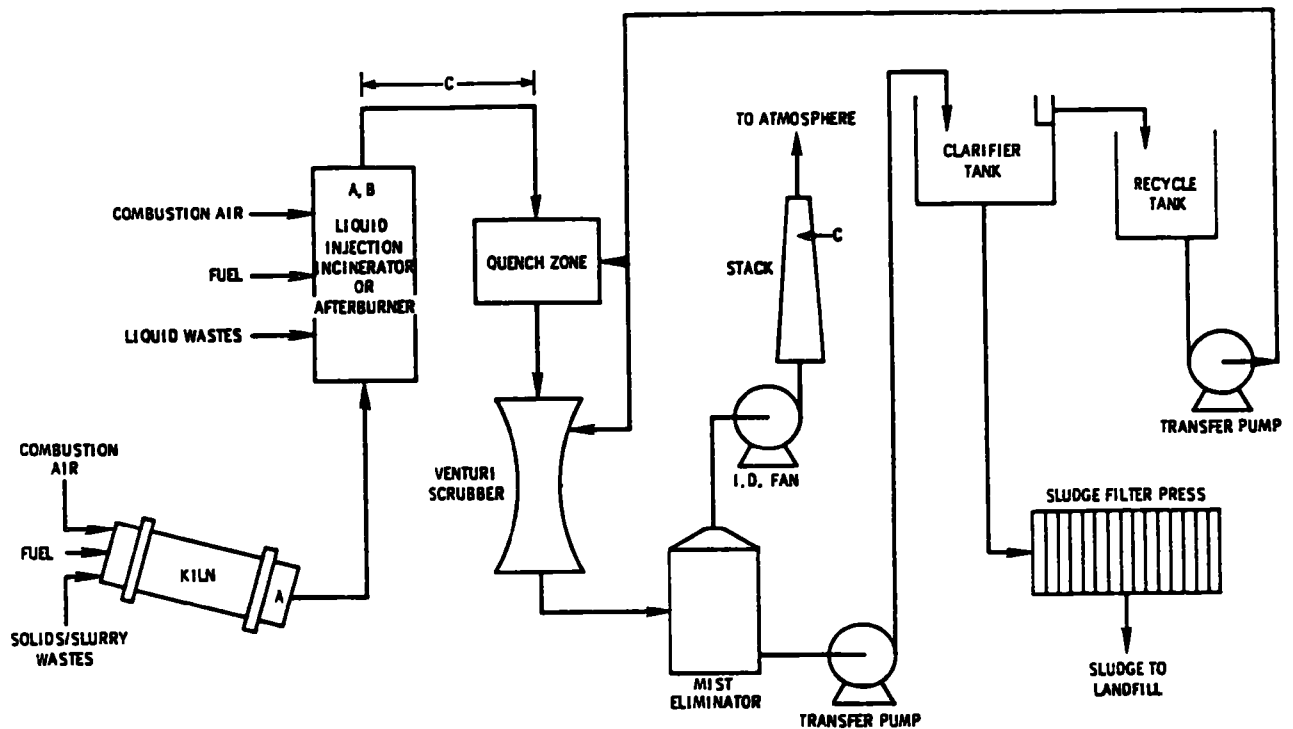
Figure 5-34. Recommended temperature measurement points.

The types of thermocouples used include J, K, E, R, S, and B. The letter symbols identifying the thermocouple types are those defined in ANSI Standard C96.1. These symbols are in common use throughout industry:

Type J - Iron versus constantan (modified 1913 calibration)

Type K - Originally Chromel-P versus Alumel

Type R - Platinum 13% rhodium versus platinum

Type S - Platinum 10% rhodium versus platinum
Type T - Copper versus constantan

Type E - Originally Chromel-P versus constantan

Type B - Platinum 30% rhodium versus platinum 6% rhodium

Table 5-6 lists the limits of error for the common thermocouple types; most manufacturers supply thermocouples and thermocouple wire to these limits of error or better.

Since the thermocouple element in a thermocouple assembly is usually expend-able, conformance to established emf-temperature relationships is necessary to permit interchangeability. Calibration of a thermocouple consists of the

5-74

TABLE 5-6. LIMITS OF ERROR FOR THERMOCOUPLES [25]

Type	Temperature range, °F	Limits of error Standard	Limits of error Special
J	32 to 530	±4°F	±2°F
	530 to 1,400	±3/4%	±3/8%
K	32 to 530	±4°F	±2°F
	520 to 2,300	±3/4%	±3/8%
R, S	32 to 1,000	±5°F	±2-1/2°F
	1,000 to 2,700	±1/2%	±1/4%
T	-300 to -75		±1%
	-150 to -75	±2%	±1%
	-75 to +200	±1-1/2°F	±3/4°F
	200 to 700	±3/4%	±3/8%
E	32 to 600	±3°F	±2-1/4°F
	600 to 1,600	±1/2%	±3/8%
B	1,600 to 3,100	±1/2%	

determination of its emf at a sufficient number of known temperatures such that with some accepted means of interpolation its emf will be known over the entire range in which it is to be used. The process requires a standard thermometer with a high-level calibration to indicate temperatures on a standard scale, a means for measuring the emf of the thermocouple, and a controlled environment in which the thermocouple and standard can be brought to the same temperature [25].

Thermocouples use one of three different types of measuring junctions-- grounded, ungrounded, and exposed. The grounded junction is the most popular. The ungrounded junction is the most rugged, but its speed of response is slower than that of the grounded type. The unprotected exposed junction responds the fastest but is more vulnerable to corrosion and mechanical damage.

A complete thermocouple assembly consists of the following:

1. A sensing element assembly, including in its most basic form two dissimilar wires joined at one end and separated by an electrical insulator

2. A protection tube, either ceramic or metal, or a thermowell. In some cases, both primary and secondary protection tubes are used

3. A thermocouple head or connector

4. Miscellaneous type hardware such as pipe nipples or adaptors to join the protection tube to the head and thermocouple glands for mounting and pressure sealing

Protection tubes and thermowells serve the double purpose of guarding the thermocouple against mechanical damage and shielding it from corrosive atmospheres. The choice of the proper material for the protection tube or thermowell is governed by the conditions of use and by the tolerable life of the thermocouple. There may be times when the strength of the protection tube is more important that the long term stability of the thermocouple. On the other hand, gas tightness, resistance to thermal shock, or chemical compatibility of the protection tube with the process may be the deciding factors [25].

The most common forms of protection tubes and thermowells and their applications are covered in the following subsections [25].

5.6.1.1 Metal Tubes--
Metal tubes offer adequate mechanical protection for base metal thermocouples at temperatures to 1,423 K (1,100°F; 1,150°C). It must be remembered that all metallic tubes are somewhat porous at temperatures exceeding 1,088 K (1,500°F; 815°C) so that, in some cases, it may be necessary to provide an inner tube of ceramic material [25].

(a) Carbon steels can be used to 973 K (1,300°F; 700°C) usually in oxidizing atmospheres.

(b) Austenitic stainless steels (300 series) can be used to 1,143 K (1,600°F; 870°C), mostly oxidizing although Types 316, 317, and 318 can be used in some reducing atmospheres.

(c) Ferritic stainless steels (400 series) can be used from 1,248 K to 1,423 K (1,800°F to 2,100°F; 975°C to 1,150°C) in both oxidizing and reducing atmospheres.

(d) High nickel alloys, Nichrome, Inconel, etc., can be used to 2,100°F (1,150°C) in oxidizing atmospheres [25].

Where the protection tube is subject to high pressure or flow-induced stresses or both, a drilled thermowell often is recommended. Although less expensive metal tubes, fabricated by plugging the end of the protection tube, may satisfy application requirements, more stringent specifications usually dictate the choice of gun-drilled bar stock, polished and hydrostatically tested as a precaution against failures [25].

5.6.1.2 Ceramic Tubes--
Ceramic tubes are usually at temperatures beyond the ranges of metal tubes although they are sometimes used at lower temperatures in atmospheres harmful to metal tubes [25].

The ceramic tube most widely used has a Mullite base with certain additives to give the best combination of mechanical and thermal shock properties [upper temperature limit 1,923 K (3,000°F; 1,650°C)] [25].

Silicon carbide tubes are used as secondary protection tubes. This material resists the cutting action of flames. It is not impermeable to gases and, where a dense tube is required, a nitride-bonded type material can be obtained so that the permeability is greatly reduced [25].

Fused alumina tubes can be used as primary or secondary protection tubes or both where temperatures to 2,253 K (3,600°F; 1,980°C) are expected and when a gas-tight tube is essential. Fused alumina tubes and insulators should be used with platinum-rhodium, platinum thermocouples above 2,200°F (1,200°C) in order to ensure long life and attain maximum accuracy. [The Mullite types contain impurities which can contaminate platinum above 2,200°F (1,220°C). The alumina tubes are more expensive than the Mullite base tubes, but types impervious to most gases to 2,088 K (3,300°F; 1,815°C) can be obtained] [25].

5.6.1.3 Metal-Ceramic Tubes--

"Cermets" are combinations of metals and metallic oxides which, after proper treatment, form dense, high-strength, corrosion-resistant tubes usable to about 1,698 K (2,600°F; 1,425°C) in most atmospheres [25].

5.6.2 Oxygen Monitoring

Oxygen concentration in the combustion gas is usually measured at a point of high turbulence, after the gas has traversed the full length of the combustion chamber. A good location for measurement is at the inlet to the duct leading from the combustion chamber to the quench zone, immediately after the gas has gone through a 90° turn. Figure 5-34 shows this location.

Oxygen measurements are made on a continuous basis. Commercially available instruments are discussed in Section 5.9. Whichever type of sensor is used, it is typically equipped with a gas conditioning system specified by the manufacturer for the gas environment in which the instrument is used.

5.6.3 Gas Flow Measurement

Gas flow rates can be measured or approximated in several ways: by insertion in the flue gas duct of an air pressure measuring element (e.g., pitot tube) or by measuring the drop in pressure across a restriction to the gas flow (e.g., baffle plate, venturi section, or orifice) downstream of the combustor. Exhaust gas flow, however, is the most difficult flow measurement application on the incinerator for many reasons:

(1) Because the gas is dusty, moist, and corrosive, pressure taps will tend to plug. For this reason it is extremely important that the connection to the duct be made sufficiently large and with cleanout provision.

(2) If the two pressure sensing points are at widely different temperatures, the resulting difference in density of the gas in the connecting lines to the instrument will create an error in measurement. For this reason, avoid measurement across spray chambers or other locations where gas temperature changes radically [26].

(3) If taken across a restriction to gas flow, the fouling tendencies of the dirty gas will cause the restriction to increase with time, thereby changing the differential measurement for a given rate of flow [26].

For the reasons stated above, the usefulness of this measurement as an indication of quantitative flow is limited and care should be taken in this application [26].

Flow measurements are performed at either of two locations: (1) in the duct between the combustion chamber and quench zone, or (2) in the stack (Figure 5-34). Both locations have their advantages and disadvantages. In the combustion chamber outlet duct, a sufficiently long length of duct may not be available for flow pattern development. Access to this location can also be a problem when the incinerator is vertically oriented and because of the necessity to breech the duct at a high temperature point. High temperatures at this location may require special materials of construction (e.g., inconel) for measurement elements.

The advantages of flow rate measurement in the stack are relief of the problems associated with high temperature gas flow measurement, increased accessibility to the gas flow, and increased likelihood of having a proper section of duct for the flow measurement. One minor disadvantage associated with this position is the increased possibility that ambient air leaks into the system upstream of the draft fan could bias the flow measurement. This is not a common occurrence, however, and good facility management practice will normally detect such leaks quickly.

Of the instruments available to measure gas flow in closed conduits, pressure or velocity head meters are among the oldest and most common. The principal shortcomings are the need for elements to be inserted directly into the flow paths (in contact with th gas stream), making them susceptible to corrosion, erosion, and fouling; the requirement for seals; the likelihood that the conduit may have to be opened for inspection or service; and permanent pressure losses caused by restrictions placed in the channels.

Head-type flowmeters incorporate primary elements, which interact directly with the streams to induce velocity changes, and secondary elements, which sense the resulting pressure perturbations. The flow rate of interest is a function of the differential pressures which can be detected.

5.6.3.1 Orifice Plates--
Orifice plates, the predominant primary flow elements, can yield accuracy and repeatability of ±0.25 to 2% full scale at Reynolds numbers from 8,000 to 500,000 [26]. Units are offered in a variety of designs, with flow area shapes which can be:

(1) Concentric
(2) Eccentric
(3) Segmental,

and profile cross sections which can be:

(a) Square-edged
(b) Sharp-edged
(c) Quadrant-edged
(d) Double bevel
(e) Conical inlet.

Principal advantages include low cost, interchangeability, and installation with minimal modification of piping systems. The greatest disadvantages are high unrecoverable pressure loss, requirement for skill in installation and making pressure connections, need for long runs of unobstructed piping or use of straightening vanes upstream and downstream of the primary element to achieve accuracy, and sensitivity of measurement reliability to orifice geometry and surface conditions which can vary as a result of normal use or handling [26].

Orifice plates can be specified in corrosion-resistant materials appropriate for many operating conditions. For fluids above 600°F, plate materials should be specified that have thermal expansion coefficients matched with those of the mounting flanges, and effort should be made to moderate the rate of temperature change on the complete primary assembly to avoid thermal stresses [26].

The most common orifices have sharp, square, or rounded upstream edges. Circular concentric designs are particularly popular since accuracy is highly predictable and extensive performance data are available for broad ranges of flow rates, duct sizes, pressure differentials, and other application factors. Eccentric and segmental orifice designs may be considered when the measured fluid contains suspended materials since these may lead to accumulations behind concentric plates and cause erratic or false readings [26].

5.6.3.2 Venturi Tubes--

Venturi tube configurations can be standard, eccentric, or rectangular. In standard designs, cylindrical barrel sections having inner diameters close to those of the main pipes connect to the throat sections through cones of fixed angular convergence; the throats terminate in diverging exit cones which again match the inner pipe diameters. Eccentric venturi elements are available to handle flows with mixed phases, and rectangular units can be specified for use in noncircular ducts [26].

Venturis handle 25% to 50% more flow than orifices for comparable line size and head loss. The flow range for satisfactory measurement is usually considered to extend upward from Reynolds numbers of about 200,000. Advantages, in addition to capacity, include high pressure recovery, good accuracy with beta ratios greater than 0.75, integral pressure connections, minimal requirements for straight runs of upstream piping, and suitability for dirty applications because the streamlined inner surfaces resist erosion and particle accumulation. Purchase cost is high compared with most other primary elements, but the greater pressure recovery can result in significant energy savings in large ducts. A more significant problem is that large sizes make the tubes awkward to install [26].

5.6.3.3 Pitot Tubes--

Pitot tubes are the simplest velocity head sensors. Models can be specified for a variety of difficult fluid services, including high temperature, high pressure, and corrosive, dirty gases. Moreover, the sensors are formed as probes, which often are designed to be inserted in conduits without system shutdown [26].

Numerous special as well as standard configurations are available; for instance, models can be ordered to measure velocity direction as well as magnitude. Limitations include tendency to plug when fluids contain suspended solid particles unless provision is made for purging or flushing, narrow velocity ranges with standard secondary elements, and sensitivity to local distrubances in the flow pattern [26].

Another fundamental problem is that measurement indicates velocity at one point in the stream, rather than providing integrated volumetric flows. The probes must be traversed across the pipes or the velocity profiles known in advance to calculate average flow. Moreover, to avoid uncertainty about local perturbations, at least 8 diameters of straight smooth pipe are recommended upstream of typical devices [26].

5.6.4 Solid Waste Retention Time and Mixing Characteristics Information

Retention time for nonvolatile or solid wastes in an incinerator is different from that for volatiles. When solid wastes are being incinerated using incinerators which have mechanical means for agitating and moving solids through the combustion zone such as is possible with rotary kilns and multiple hearth incinerators, residence time of nonvolatiles will become a function of these variables. Mixing will also become a variable when rabble arms or other mechanical devices are used to tumble or otherwise break up chunks of solid material. Residue analysis is typically performed to ascertain the condition of the ash produced at these conditions. If analysis shows that insufficient agitation or residence time is being achieved in exposing the solids to combustion zone conditions, a change of those conditions is normally requested to eliminate the problem.

5.7 AIR POLLUTION CONTROL DEVICE INSPECTION AND MONITORING

5.7.1 Wet Scrubbers

Five parameters are routinely checked on wet scrubbers to monitor their operational effectiveness. These are discussed below. Gas and liquid flow rates are discussed together in Section 5.7.1.2

5.7.1.1 Temperature--

Deviations from the design temperature can have serious effects on the removal efficiency of a wet scrubber, particularly when the scrubber is being used to remove gaseous components. Since incineration inherently produces high temperature gas to be scrubbed, pre-cooling of the gas stream is necessary. Units used for this are commonly called quench towers, and they normally bring the gas temperature down to around 150°F prior to entry into the scrubber. This scrubber inlet temperature is continuously monitored to assure that

proper scrubbing conditions are maintained in accordance with the design inlet temperature value or range. Deviations can cause several effects, including rapid loss of scrubbing liquid, compromise of absorption efficiency, undue corrosion, and structural damage to the unit. One or more of these occurrences can increase emissions from the unit. Figure 5-34 shows the approximate position for temperature measurement. Emergency shut down features regarding this temperature measurement are discussed in Chapter 4.

5.7.1.2 Liquid and Gas Flows--
A wet scrubber must provide good gas-liquid turbulence and optimum contacting surfaces for proper absorption of contaminant gases or removal of particles [27]. This provision is typically specified by the vendor and normally expressed as the liquid-to-gas ratio (e.g., 5 gpm/1,000 cfm [L/G]). A certain L/G will be necessary to achieve design removal efficiency. The vendor also supplies the sensitivity of the L/G ratio to removal efficiency because each design has a somewhat different sensitivity to the L/G ratio. With this data in hand, a range of acceptable L/G ratios can be established, consistent with removal efficiency requirements. This range serves as the parametric limits for acceptable L/G ratio operation. System gas flow will have been measured as part of the incinerator operating requirement covered previously. Therefore, scrubber liquid flow rate measurement will provide the remaining necessary parameter measurement to define the L/G ratio. This parameter is monitored often and remedial actions taken by the operator, should the ratio exceed the parametric limits. Operator action will normally be a minor adjustment of the scrubber liquid flow rate.

A measurement of the moisture content of the gas leaving the scrubber is made in cases where some other device is in the system which can contribute additional moisture to the total gas flow such as a mist eliminator. This also covers the situation where the gas flow measurement may be made upstream of the quench zone in the hot gas area. In the case of the hot zone measurement, the sum of hot zone gas flow plus moisture content corrected to scrubber pressure and temperature conditions represent scrubber gas flow. Obviously, a direct measurement of the gas flow exiting the scrubber may also be used, but this will necessitate another measurement system set-up.

Measurement of the liquid flow rate is accomplished by using any of several types of flowmeters, including venturi, orifice, flow tube, pitot tube, magnetic, or acoustic varieties. Device acceptability considerations are summarized in Table 5-7. Figure 5-34 shows the appropriate measurement location.

5.7.1.3 pH--
Another important parameter in wet scrubber operation is pH. Materials of construction are selected in part based upon the degree of acidity or alkalinity provided by the scrubbing liquid during operation. Deviation from the design pH condition or range may result in deterioration of the scrubber structure in contact with the liquid. Furthermore, maintenance of the pH design condition is important to scrubber liquid absorption efficiency when removing gaseous contaminants.

The liquid composition and its attendant pH will be determined during the design phase. Absorption efficiency can change drastically as a function of

TABLE 5-7. DEVICES FOR LIQUID FLOW MEASUREMENT

Flow measurement device	Advantages	Disadvantages	Flow range, gpm (applicable pipe diameter)
Venturi meter	Low permanent pressure drop. Applicable to streams with appreciable solids content. Accurate.	Flow disrupted and plumbing modifications required for installation. Expensive.	0-750 (1-18 in.)
Orifice meter	Inexpensive.	Flow disrupted and plumbing modifications required for installation. Large permanent pressure drop. Solids may deposit behind device. Moderately accurate.	0-750 (0.5-30 in.)
Flow tube	Applicable to streams with appreciable solids content.	Flow disrupted and plumbing modifications required for installation. Intermediate permanent pressure drop. Moderately expensive. Moderately accurate.	0-750 (1-18 in.)
Pitot tube	Low permanent pressure drop. Inexpensive method for pipes of large diameter.	Flow disrupted and plumbing modifications required for installation. Solids may cause plugging. High flow velocities may cause instability. Moderately accurate.	250-50,000
Magnetic meter	Minimum permanent pressure drop. Applicable to streams with appreciable solids content. Accurate.	Flow disrupted and plumbing modifications required for installation. Expensive. Electrodes may be fouled by wastewaters containing oil and grease. Susceptible to electromagnetic interference from nearby equipment.	250-20,000 (0.1-100 in.)
Acoustic meter	Installation without flow disruption. Relatively accurate. No head loss or pressure drop. Applicable to streams with appreciable solids content. Portable.	Expensive. Moderately accurate.	250-20,000 (pipes of all diameters)

pH, thereby altering the scrubber removal efficiency, so an acceptable pH variation range is designed for the equipment. The pH is monitored continuously and either manual (operator) or automatic adjustment made to keep the pH within proper operating specifications. A number of commercially available pH monitoring systems can adequately serve this purpose. These systems normally include a direct readout device which can be conveniently located on a control panel for continuous monitoring accessibility. Figure 5-39, Section 5.8, shows the measurement location and arrangement for scrubber liquid pH.

5.7.1.4 Pressure Drop--
Pressure drop is an important indicator parameter in monitoring the operational condition of a wet scrubber. It is sensitive to changes in the gas flow rate, liquid flow rate, and clogging phenomena in the system. During the design phase, a proper pressure drop value or range to maintain design removal efficiency is specified. Monitoring this parameter provides a continuous, additional check on the normal operation of the scrubber. A change in the pressure drop is an indication that other measured parameters in the system need to be observed immediately to find the cause of the disturbance and corrective action should be taken. It is also an indicator which covers the time span between other routine parameter checks. If, after checking the pH, temperature, and gas and liquid flow rates, all appears in order, then the pressure drop measuring system is checked for correct operation and a visual inspection of the scrubber conducted to identify possible clogging problems. A check of the control efficiency is also routinely made to see if removal efficiency is being maintained.

Many kinds of pressure measurement devices are commercially available to measure pressure drop across a device; however, a differential pressure gage calibrated in inches of water is usually recommended for this purpose. The readout device is located in a convenient place for the operator to observe at any time. Figure 5-34 shows the location of the pressure taps relative to the device.

In selecting a pressure measuring device, the following items are considered:

- Pressure range
- Temperature sensitivity
- Corrosivity of the fluid
- Durability
- Frequency response

A guide to pressure sensing device selection is summarized in Table 5-8.

5.7.1.5 Residue Generation--
Generation of residue from wet scrubbers results from operational requirements of the scrubber liquid in the specific system used. Vaporization losses in the contacting area create the need for make-up liquid to be provided, and changes in liquid pH create the need for adjustment. Collected material (such as solid particles) also creates abrasion, contamination, and corrosion problems in the scrubbing liquid and/or transport system. In addition, when hazardous materials are collected, a need for further treatment may be created prior to disposal. Sometimes a designer will choose to accommodate these

TABLE 5-8. A GUIDE TO PRESSURE SENSING ELEMENT SELECTION [28]

Selection criteria	Common sensors			Transducers, strain gauges	
	Bourdon	Diaphragm	Bellows	Unbonded	Bonded foil
Pressure range	12 psi to 100 K psi	5 psi to 15 psi	0.5 to 30 psi	0.5 psi through 10 K psi	5 psi through 10 K psi
Temperature range	-40°F to +375°F	-40°F to +375°F	-40°F to +375°F	-320°F to 600°F (0.005%/°F)[a]	-65°F to +250°F (0.01%/°F)[a]
Advantages	Low cost; field replaceable; variety of materials for media and range.	Variety of materials for media and range; field replaceable; large force.	Compact, accurate, field replaceable.	Accepts unidirectional and bi-directional pressure measurements; ac or dc excitation.	Temperature effects small and linear; ac or dc excitation; rugged construction.
Disadvantages	Slow response; large sensor volume sensitive to shock and vibration.	Limited capacity; position sensitive in low ranges.	Limited material; may be position sensitive.	Low signal level (4 mV/V).	Low signal level (3 mV/V) limited temperature range.

(continued)

[a]Percent/°F over limited compensated range

TABLE 5-8 (continued)

Selection criteria	Transducers				
	Thin film	Diffused semiconductor	Bonded in semiconductor	Reluctive	Capacitive
Pressure range	15 psi through 5 K psi	1 psi through 10 K psi	5 psi through 10 K psi	0.4 psi through 10 K psi	0.01 through 200 psi
Temperature range	-320°F to +525°F (0.005%/°F)[a]	-65°F to +30,000°F (0.005%/°F)[a]	-65°F to +30,000°F (0.01%/°F)[a]	-320°F to +600°F (0.02%/°F)[a]	0°F to 165°F Requires temperature control.
Advantages	Excellent thermal zero and sensitivity shift; ac or dc excitation.	Small size, high natural frequency; steady and dynamic reliability, repeatability.	Small size, high natural frequency; steady and dynamic; excellent repeatability.	High output (40 mV/V excitation); rugged construction; over pressure capability.	Excellent for low pressure, excellent frequency response; output countable without A/D converter.
Disadvantages	Low natural frequency; low signal level, 3 mV/V.	Susceptible to handling problems; more temperature sensitive than most transducers; electrical output only.	Susceptible to handling problems; more temperature sensitive than most transducers.	Sensor requires ac excitation; susceptible to stray magnetic fields; ac carrier systems require balanced line for data transmission.	Requires short leads from sensor; high impedance output; temperature sensitive; needs extra electronics to produce useable output.

[a] Percent/°F over limited compensated range.

(continued)

TABLE 5-8 (continued)

Selection criteria	Transducers			
	Potentiometer	Linear variable displacement transformer	Force balance	Piezoelectric
Pressure range	5 psi through 10 K psi	30 to 10 K psi	1 psi through 50 K psi	0.1 psi throuh 10 K psi
Temperature range	-65°F to +300°F nonlinear 0.01%/°F	0°F to 165°F	40°F to 165°F 0.01%/°F	-450°F to 400°F 0.01%/°F
Advantages	Low cost; small size; high output without amplification.	Available in rotary form; not affected by mechanical overload.	High accuracy; high output; stable; wide ranges.	High frequency response; self-generating signal; small size; rugged construction.
Disadvantages	Tendency to short life due to mechanical wear; noise increases with wear.	Some problem maintaining linear movement of core proportional to pressure change; will develop mechanical wear.	Large size; shock and vibration sensitivie; low frequency response.	Temperature sensitive; requires amplifier and special cabling between device and amplifier; slow recovery to shock and overpressure.

problems in an integrated system design approach. Monitoring requirements relative to generation of residue from a wet scrubber are those required for observation of waste stream treatment systems and are covered in Section 5.8. Control of pH is also discussed.

5.7.2 Fabric Filters

Fabric filters basically consist of a porous layer of flexible, textile material through which a contaminated gas is passed to separate entrained material from the gas stream [29]. As collected material accumulates, resistance to the gas flow increases. The collected material is removed periodically by vigorously cleaning the filter to maintain proper pressure drop across the system.

Certain fabric filter parameters are monitored on a regular basis to evaluate operational effectiveness. These are detailed below.

5.7.2.1 Temperature--
A limiting factor in filtering hot gases with a fabric filter is the temperature resistance of the fibrous materials from which the filter cloth is made. Therefore, the manufacturers temperature specifications regarding appropriate filter material are important for efficient operation. Continuous recording of the temperature of the gas coming into contact with the filter media is made to assure that extended excursions above the recommended value are not occurring. Appropriate corrections are then made immediately, either automatically or by the operator, to maintain inlet temperature within design criteria. This helps minimize the occurrence of extraordinary material breakdown with resultant increased emissions. It also aids in keeping maintenance of the filter in good order and extending the life of the filter material. Measurement technique is similar to that depicted in Section 5.7.1. Figure 5-35 shows the appropriate measurement location.

5.7.2.2 Gas Flow and Pressure Drop--
Fabric filter collectors are commercially available to handle total gas flows from 100 cfm to greater than a million cfm. The quantity of gas processed and the contaminant concentration in conjunction with specific flow resistance properties of the particulate deposit on the fabric determine the amount of filtration area required for a selected value of operating pressure drop. A design pressure drop is generally chosen around 3 or 4 inches of water for economic reasons, but some units are designed to operate higher than 10 inches of water pressure drop. Variation in the pressure drop over a specified range is normal in fabric filter operation. The operational cycle consists of a gradual buildup of material on the surface of the filter which is periodically cleaned off. The development of this deposition increases the pressure drop with time. This cycle usually remains within specified limits. Continuous recording of the operating pressure drop is maintained by the operator. The pressure drop is maintained within the manufacturer's specified range so that undue disturbance of the design filtration efficiency does not occur. Chapter 4 provides further information regarding fabric filters. The pressure drop measurement device is essentially the same as described in Section 5.7.1.4. Measurement location is shown in Figure 5-35.
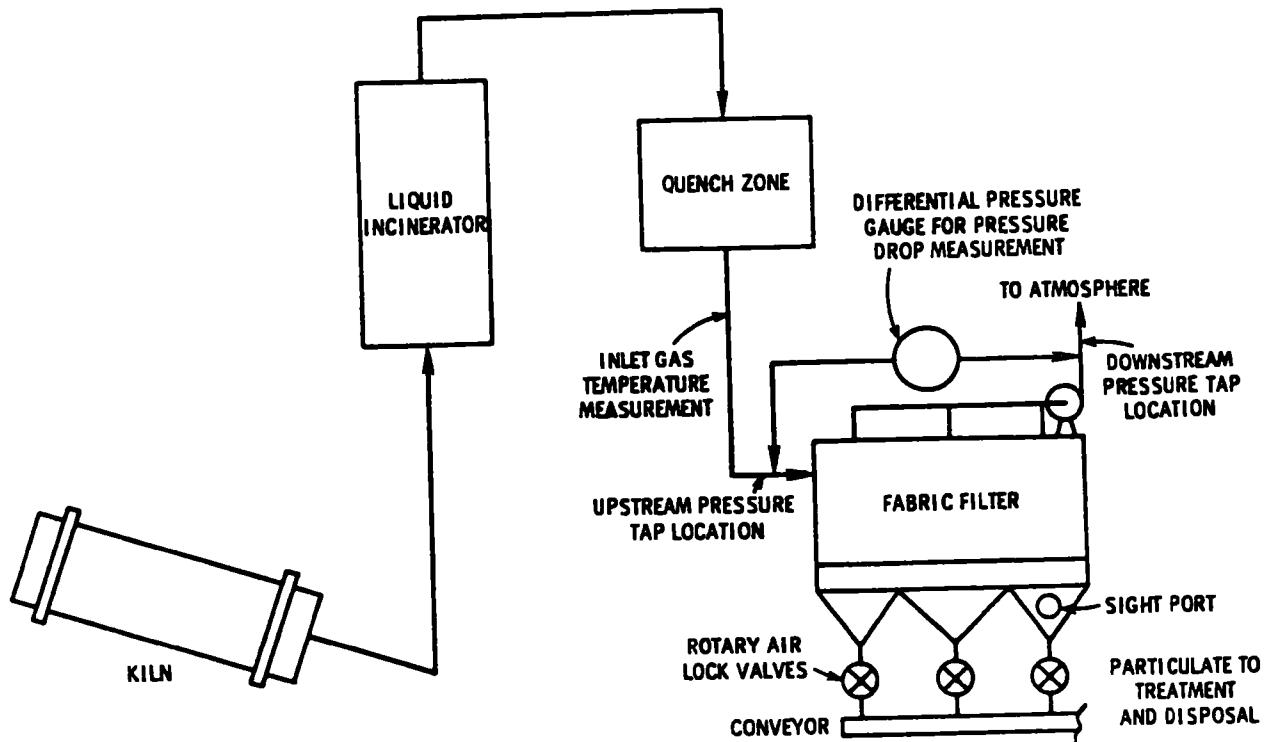
Figure 5-35. Recommended measurement and inspection locations.

5.7.2.3 Residue Generation--

Accumulated particulate matter is removed and transported to a central point for reprocessing or disposal depending on the hazardous nature of the collected material. Means of preventing gas leakage at the hopper discharge is an important design factor. This is normally accomplished through the use of double flap valves or rotary air-lock valves, although the rotary air lock valve will give the most positive seal.

A means of preventing bridging in the hoppers is also important. Common types are mechanical, spring loaded rappers, electric vibrators, and compressed air vibrators. Helicoid screw conveyors are commonly employed for horizontal transport of the collected material to a central point.

Residue analysis is needed to ascertain the hazardous nature of the collected material and to select appropriate disposal options. The type of such analyses is covered in Chapter 3.

5.7.3 Electrostatic Precipitators

Precipitators are theoretically complex control devices which are almost always specifically designed for a given application. Many technical considerations are evaluated initially to aid the applicability determination [30]. In each case, however, a set of operating conditions and checkpoints are defined by the vendor as proper and necessary to maintain the design removal efficiency. Compliance with these and other conditions pertinent to

maintaining the quality of the environment are evaluated; the following information serves as a checklist for such items.

5.7.3.1 Rapping Cycle Practice--

Precipitators use a "rapping" or force impact sequence to remove buildup of collected material on the internal surfaces of the equipment. This causes re-entrainment of collected material in the exhaust gas stream which affects precipitator removal efficiency. Three variables are involved; the rapping interval, the rapping intensity, and the duration of the rapping cycle.

(1) Rapping interval - It is desirable to know the time interval of rapping for each electrode in the precipitator field, because the upstream fields are normally rapped more frequently than the downstream fields as a result of the relatively high material buildup in the initial stages.

(2) Rapping intensity - How hard an electrode is rapped will affect the amount of material removed each rap.

(3) Cycle duration - How long a time the rap covers affects the degree of "cleanliness" achieved.

The intervals for these three variables are designed to be appropriate for the application. This choice is normally based on the experience of the company with their product. Common practice ranges from very frequent rapping (every few minutes) to intervals as long as an hour. The intensity may range from low to high with frequent intervals, but is normally high at longer intervals. The ability to change the values is normally a part of the precipitator controls. A check of the proper settings is made at least once a day by the operator and records kept for examination by the EPA upon request. A typical rapping mechanism is shown in Figure 5-36.

5.7.3.2 Temperature, Resistivity, and Gas Moisture Effects--

The resistivity of the material collected can have an influence on the collection efficiency. If the resistivity is greater than about 5×10^{10} ohm-cm, the electrical field developed in the collected particle layer can exceed the breakdown field strength. Excessive spark rates and back corona can occur which will cause operation at lower than normal current densities with resulting degraded performance. If the particle resistivity is less than about 10^7 ohm-cm, the electrical forces holding the material to the collection plates may be low. Excessive re-entrainment can occur yielding lower performance.

A resistivity range showing the allowable span for maintenance of removal efficiency is normally supplied with an ESP along with a measurement of the resistivity of the material collected. As long as the feed material does not change, no further check on the resistivity is usually necessary, unless removal efficiency changes for no apparent cause.

Increasing moisture content will also lower the resistivity. A change in moisture content will normally only occur with a change in the feed material moisture or a change in steam injection conditions if such a technique is used to increase hydrogen ion availability in the combustion zone.
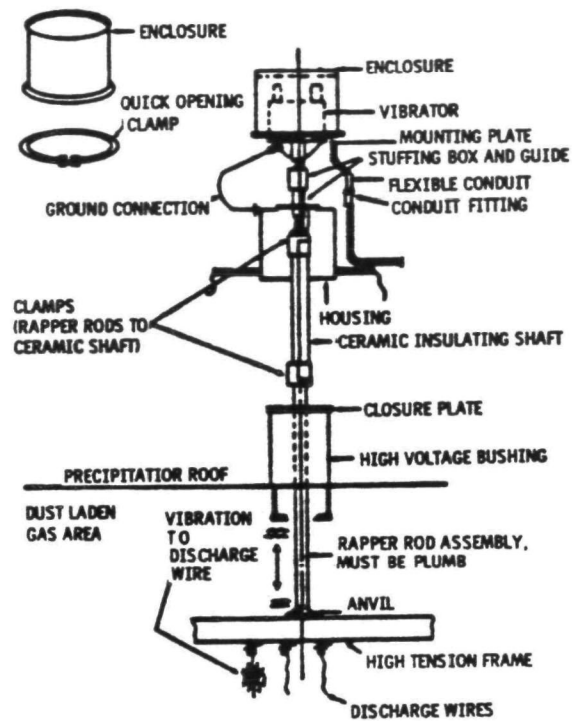
5-89

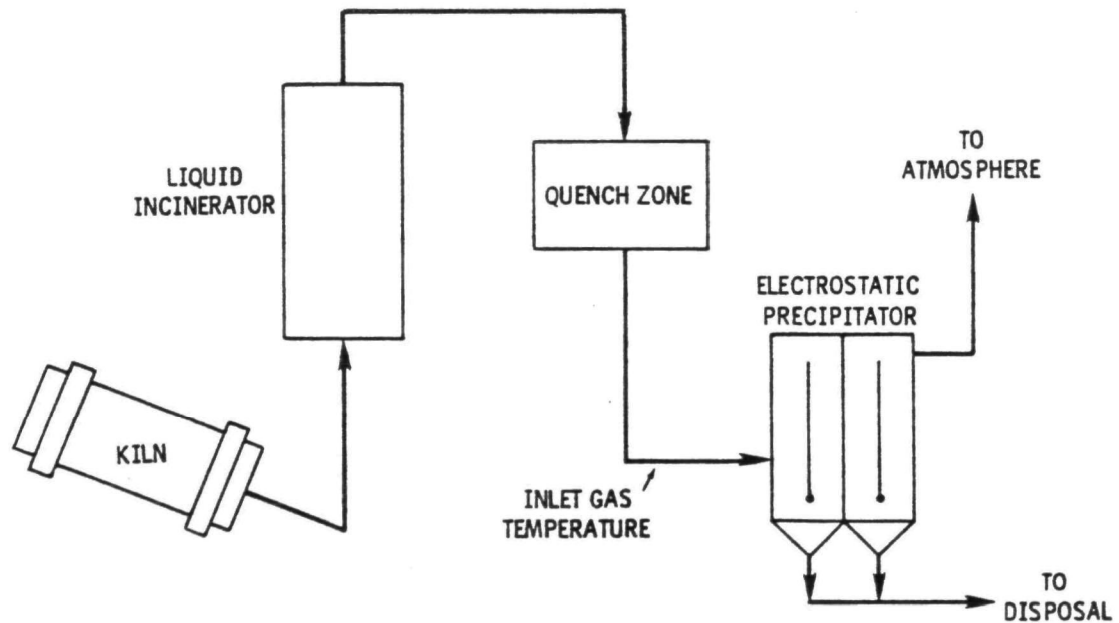Figure 5-36. Typical vibratory rapper.

Figure 5-37. Recommended measurement location.

Temperature affects precipitator removal efficiency although not as much as it affects baghouses and wet scrubbers. Temperature considerations are normally evaluated during the design phase of the precipitator by the vendor.

Specifications are provided by the owner/operator showing the allowable temperature range for design removal efficiency. Continuous recording of the incoming gas temperature is made by the owner/operator to assure that extended excursions above or below the recommended range are not occurring. Appropriate corrections are then made to maintain inlet temperature within design criteria. The measurement technique must be similar to that discussed in Section 5.7.1. Figure 5-37 shows the appropriate measurement location.
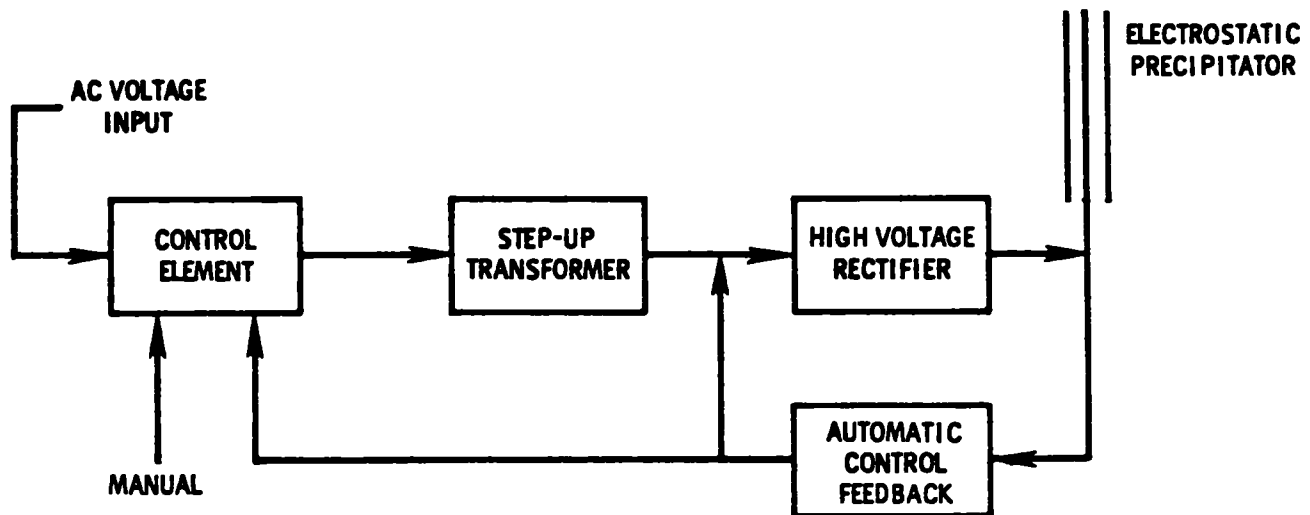
Figure 5-38. Power supply system for modern precipitators.

5.7.3.3 Applied Voltage (Power Supply Control)--
The overall objective of precipitator design is to combine the component parts into an effective arrangement that results in optimum collection efficiency. A very important aspect toward this objective is the design of the precipitator power supply.

The power supply normally consists of four components as shown in Figure 5-38; a step-up transformer, a high voltage rectifier, a control element, and a sensor for the control system. A step-up transformer is required because the operating voltages (applied voltage) range from about 20 to 100 KV. This system is used to maintain the applied voltage at an optimum value even when the material characteristics and concentration exhibit temporal fluctuations.

Once normal operating conditions have been established, continuous monitoring of the power supply system is typically maintained. The necessary indicators (meters) for this are normally provided as part of the precipitator control panel. Deviations will likely be caused by excessive buildup of collected material in the precipitator or breakdown of the electrical supply circuitry. Investigation should begin immediately to locate the cause, and correction made, including shut off of feed material and/or shut down for repair if removal efficiency drops below specifications.

5.7.3.4 Gas Flow--

Changes in the gas flow rate can affect removal efficiency. This becomes more critical as the particles get smaller. The precipitator is designed so that the combination of the forces applied on the particles and the time that the forces remain on the particle (dwell time) result in the movement of the particles to a collection surface. The smaller the particle, the longer it takes under fixed conditions to do this.

If the gas flow rate increases beyond design capacity, this combination becomes compromised and a degradation of removal efficiency will occur.

The gas flow measurement requirement discussed in Section 5.7.3 is appropriate for checking the precipitator flow parameter also. Sustained increase in the gas flow is usually checked immediately for effect on the design removal efficiency, and correction made to remain within design conditions. This may require reduction in input feed material flow or some other modification(s).

5.7.3.5 Residue Generation Rate and Dust Removal Capacity--

It is important to determine that the dust removal system remains working properly according to specifications. Hoppers are used to collect material removed from the collecting surfaces by the rapping sequence. If the residue generation rate exceeds the material removal capacity, re-entrainment of collected material will occur, greatly reducing precipitator efficiency. Historically, automatic removal of collected material is one of the major causes of precipitator failure, and daily inspection for proper operation is typically required.

5.7.3.6 Internal System Pressure--

If the precipitator system is operated with internal pressures less than ambi-ent, leakage of air through the hopper can also cause a re-entrainment of mate-rial from the hoppers. A design check to make sure the hopper area is properly sealed is made to prevent such occurrence. Section 5.7.2.3 discusses appropriate seal techniques. Further details regarding electrostatic precipitators is found in Chapter 4.

5.7.4 Mist Eliminators

Mist eliminators are extensively employed to reduce emissions of entrained liquid droplets from wet scrubbers. The most commonly used types include cyclone collectors, simple inertial separators such as baffles, wire mesh mist eliminators, and fiber bed elminators. In use, the latter three devices work by the same principle. Rising mist droplets strike the mist elminator, coalesce due to inertial impaction and direct interception, and form larger droplets which fall back into the scrubber.

Cyclones differ from the other types of mist eliminators because centrifugal force is used to remove the droplets. The particulates, because of their inertia, tend to move toward the outside wall from which they are led to a receiver [20].

The choice of mist eliminator equipment is dependent on droplet size, gas flow pressure drop, and cost considerations. Cyclone collectors are used to remove

larger droplets (10 to 100 μm range), and are used commonly in conjunction with venturi scrubbers. Simple inertial mist eliminators (baffle, louvre, and vane-type among others) are effective with droplets about 10 μm in size. Fiber bed mist eliminators have the highest efficiency of any of the types of eliminators for trapping very fine droplets (as small as 0.5 μm).

Although the different types of mist eliminators vary in design, they have common parameters which must be monitored to evaluate operational effectiveness. These are detailed below.

5.7.4.1 Temperature--

Excessive temperatures can adversely effect the performance of a mist eliminator. Higher temperatures could result in a heavier loading and increased corrosion. Since the mist eliminator is located downstream from the wet scrubber, monitoring the temperature of the scrubber is sufficient to ensure the mist eliminator is operating at a suitable temperature.

5.7.4.2 Gas Flow and Pressure Drop--

For maximum efficiency, flow of gases through the mist eliminator should be high enough to be practical while allowing a reasonable retention time. Re-entrainment of the liquid droplets can result if the gas flow is too high. The optimum gas flow varies according to the particulate mist eliminator used, and is normally supplied by the manufacturer. Pressure drop may vary from 2 to 12 in. of water gage, in accordance with manufacturers' specifications.

Continuous recording of the operating pressure drop is typically maintained by the owner/operator and such records made available for inspection. A change in the pressure drop would indicate a change in the gas flow rate or, more importantly, the accumulation of solids in the equipment, decreasing its efficiency.

5.7.4.3 pH Level--

To prevent excessive corrosion, the mist eliminator is normally constructed of material that is resistant to the pH level of the mist. pH is monitored in the wet scrubber to ensure the mist eliminator is operating within the manufacturer's recommended pH range.

5.7.4.4 Maintenance--

Proper maintenance of mist elimination equipment is essential in order to maintain optimal efficiency, for collection of solid material in the equipment can decrease efficiency. The equipment can be cleaned by backwashing or by automatic spray devices. Often, daily inspection is required to assure that the backwash system is operating properly.

5.8 SCRUBBER WASTE STREAM TREATMENT INSPECTION AND MONITORING

5.8.1 Flow Measurement and Monitoring

In any treatment system unit operation, the measurement and/or control of flow is a critical parameter. In this case, flow is a factor in determining the rate of caustic solution addition in the neutralization system. Flow measuring and recording devices are described in detail in Section 5.7.1.2.

5.8.2 Flow Control

Automatic monitoring systems are employed to provide advanced warning when the water level in the neutralization system has increased above a set operating limit. This enables operators to institute immediate process alterations to allow the neutralization system to equilibrate back to normal operations.

5.8.3 pH Monitoring

Sensors for automatic monitoring, recording, and control of pH are especially sensitive to process interferences. It is necessary, therefore, that care is taken in the selection of automatic equipment in order to ensure that it will function satisfactorily in the treatment scheme.

Automatic monitoring of pH has the following advantages:

(1) pH is recorded on a continuous basis, producing a clear picture of variation with time.

(2) Time lag between sampling and analysis is much shorter than in manual sampling. Problems resulting from the storage of sampling equipment are also eliminated.

(3) The rate of neutralizing chemical addition can be continuously controlled.

(4) Automatic monitoring can be combined with an alarm system to provide warning if the neutralized effluent is of insufficient quality. When this occurs, a by-pass valve could be opened to direct the effluent to a storage basin for gradual addition to the treatment system once normal operations have been resumed.

Automatic monitoring is not without disadvantages, however. Among them are:

(1) The sensor may not be capable of registering unusual circumstances due to probe location.

(2) The wastewater characteristics, at least in general, must be known in advance of monitoring equipment selection.

(3) The initial cost of automatic equipment is relatively high.

Problems which can be anticipated and need to be addressed in system design and operation are:

(1) Loss of calibration. Regular maintenance is necessary to prevent errors.

(2) Bacterial growth may inhibit sensor operation. Regular cleaning is necessary unless self-cleaning sensors are used.

(3) Mechanical damage may occur if the probe is unprotected by a screen, similar device, or design.

(4) Miscellaneous problems resulting from power failures, mishandling of equipment, pump difficulties, etc.

(5) Interferences should be analyzed and addressed before equipment selection and installation.

5.8.4 pH Control Systems

A pH control system consists of a pH electrode probe, located in the flow scheme, connected to a controller which reports to a recorder. The controller regulates the rate of neutralization chemical addition.

In the monitoring/control system, several types of valves may be used, depending on the consistency of the influent quality and the treatment chemicals used. The types of controllers likely to be employed are on-off, proportional, resetting derivative, and flow-proportional.

5.8.4.1 On-Off Controller--
The on-off controller is the least expensive of the above devices. If the pH exceeds, in either direction, a certain limiting value, the valve opens and neutralizing agent is added until an established corrected value is achieved. This system has limited application here due to the potential for large chemical overdose.

5.8.4.2 Proportional Controller--
Proportional controllers are more advanced than on-off controllers and are used where a more constant effluent quality is desired. In its simplest application, the proportional controller regulates the amount of neutralizing solution in proportion to a deviation from a set point as a means of controlling pH within an acceptable range.

5.8.4.3 Resetting Derivative Controller--
A resetting derivative controller regulates the speed with which the valve opens to add neutralizing agent. The valve speed is based on the rate of derivation from a set point. This system does not typically operate well with high suspended solids effluent, however.

5.8.4.4 Flow Proportional Controller--
If the influent water quality is constant, but flow varies, the neutralization control valve may be connected to a flow meter rather than the pH probe. Neutralizing agent will be added proportional to the flow.

A schematic of the general elements in a pH control system using lime is given in Figure 5-39.

5.8.5 Scrubber Solution pH Control

The particulate removal efficiency of a venturi scrubber and the acid gas scrubbing efficiency of a packed tower is affected by maintenance of the pH of the incoming scrubbing solution.
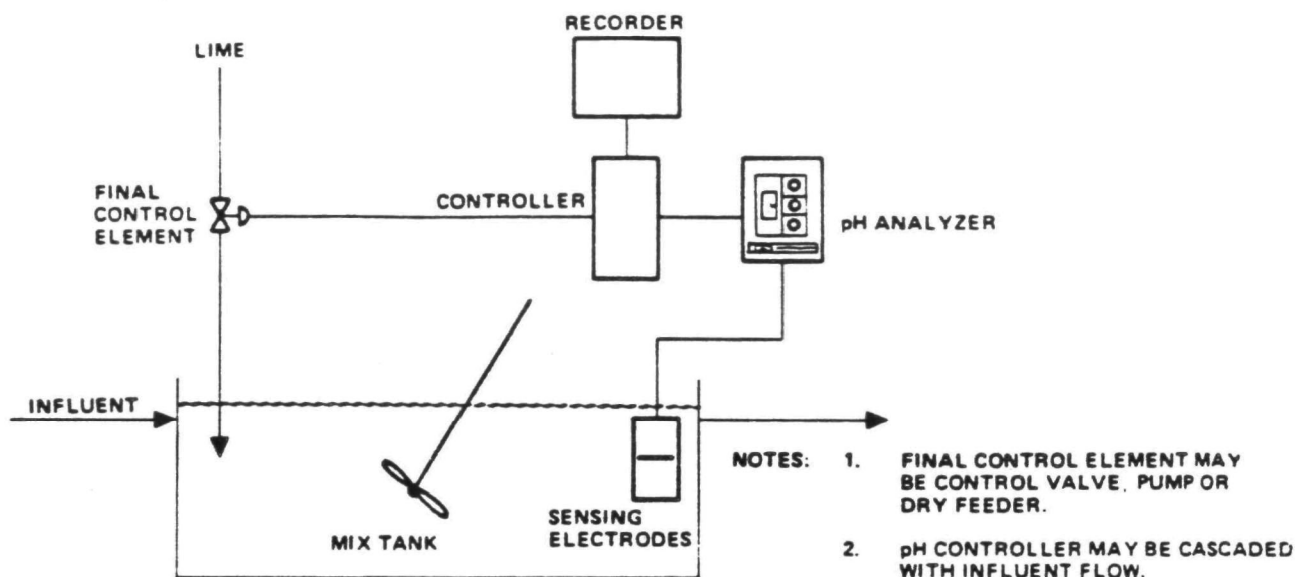
Figure 5-39. Elements of a typical pH control system.

If a recirculating mode is utilized, the incoming stream must be neutralized after contact with the gas. Neutralization is necessary to prevent corrosion of metal surfaces, construction materials, and tower packing.

The process of neutralization is the interaction of an acid with a base. The typical properties exhibited by an acid in solution are due to the concentration of the hydrogen ion, (H^+). Alkaline (basic) properties are the result of the concentration of hydroxyl ion (OH^-). In an aqueous solution, acidity and alkalinity are defined with respect to pH, where $pH = -\log [H^+]$, or as $pH = 14 + \log [OH^-]$. Neutralization is typically the adjustment of pH from one extreme to a range of pH 6.0 to 8.5.

The scrubber and absorber solutions will, after contact with acid gases, be acidic in nature, (pH <7). Neutralization is accomplished by the addition of an alkaline material, such as caustic soda (NaOH). An example of the neutralization process is the reaction between hydrochloric acid and sodium hydroxide:

$$HCl + NaOH \rightarrow H_2O + NaCl$$

The product, sodium chloride in aqueous solution, is neutral with pH = 7.0.

Neutralization is usually accomplished by contacting the incoming feed with concentrated caustic or acid solution in a well mixed chamber.

Lagoons, concrete basins, chemically resistant tanks, and in-line static mixers are all used for this purpose.

Neutralized water can be piped to storage ponds for subsequent process reuse, solar evaporation, or further treatment, if necessary for NPDES discharge.

A simple schematic of a two-step neutralization system is given in Figure 5-40.
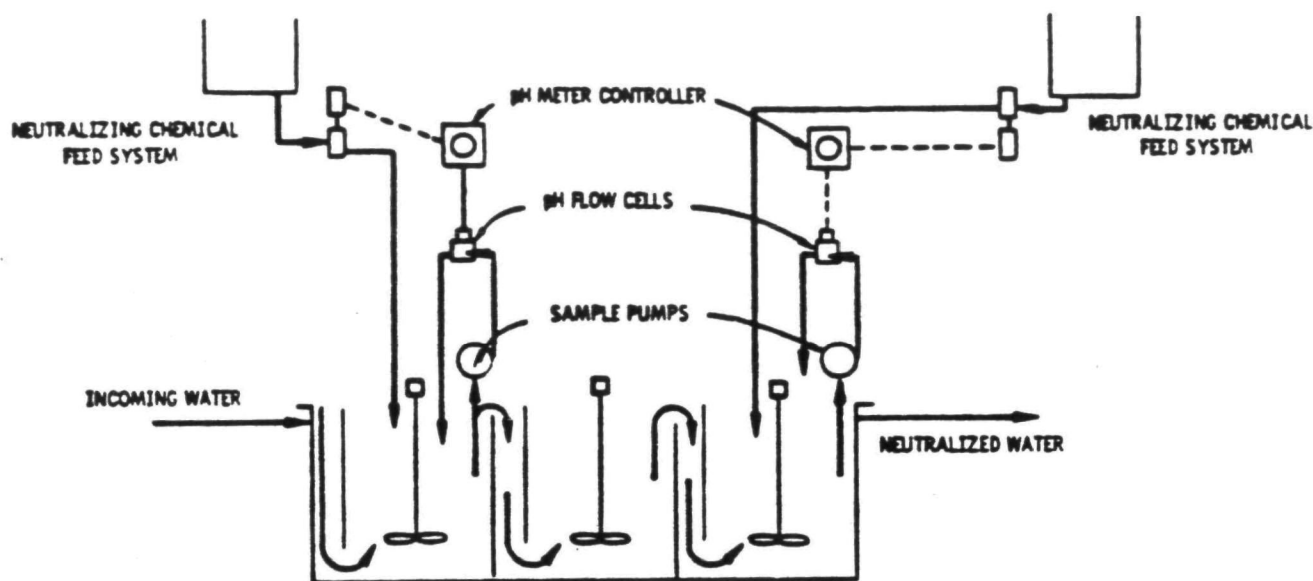
Figure 5-40. Two-step neutralization flow schematic.

5.9 CONTINUOUS MONITORING INSTRUMENTATION FOR GASEOUS COMPONENTS

Continuous monitoring of at least O_2, CO, and CO_2 gases in the exhaust stream of hazardous waste incineration are proposed. A number of continuous monitoring systems are available for this general purpose. These monitors are automated, and are capable of unattended operation for days or weeks. While such instruments have been successfully applied to measuring CO, CO_2, and O_2 in combustion gases, their accuracy remains somewhat controversial within both the technical community and users.

The following text provides a summary of aspects pertinent to the evaluation. Should greater detail be desired, the permit writer is encouraged to consult the EPA Handbook of Continuous Air Pollution Source Monitoring Systems, EPA-625/6-79-005, from which most of the following information is derived [31].

The basic elements of a pollutant monitoring system are shown in Figure 5-41.

5.9.1 Available Systems

Proposed continuous monitoring systems will likely fall into one or more of the following types:

· Nondispersive infrared analyzers (NDIR)
· Polarographic analyzers
· Paramagnetic analyzers
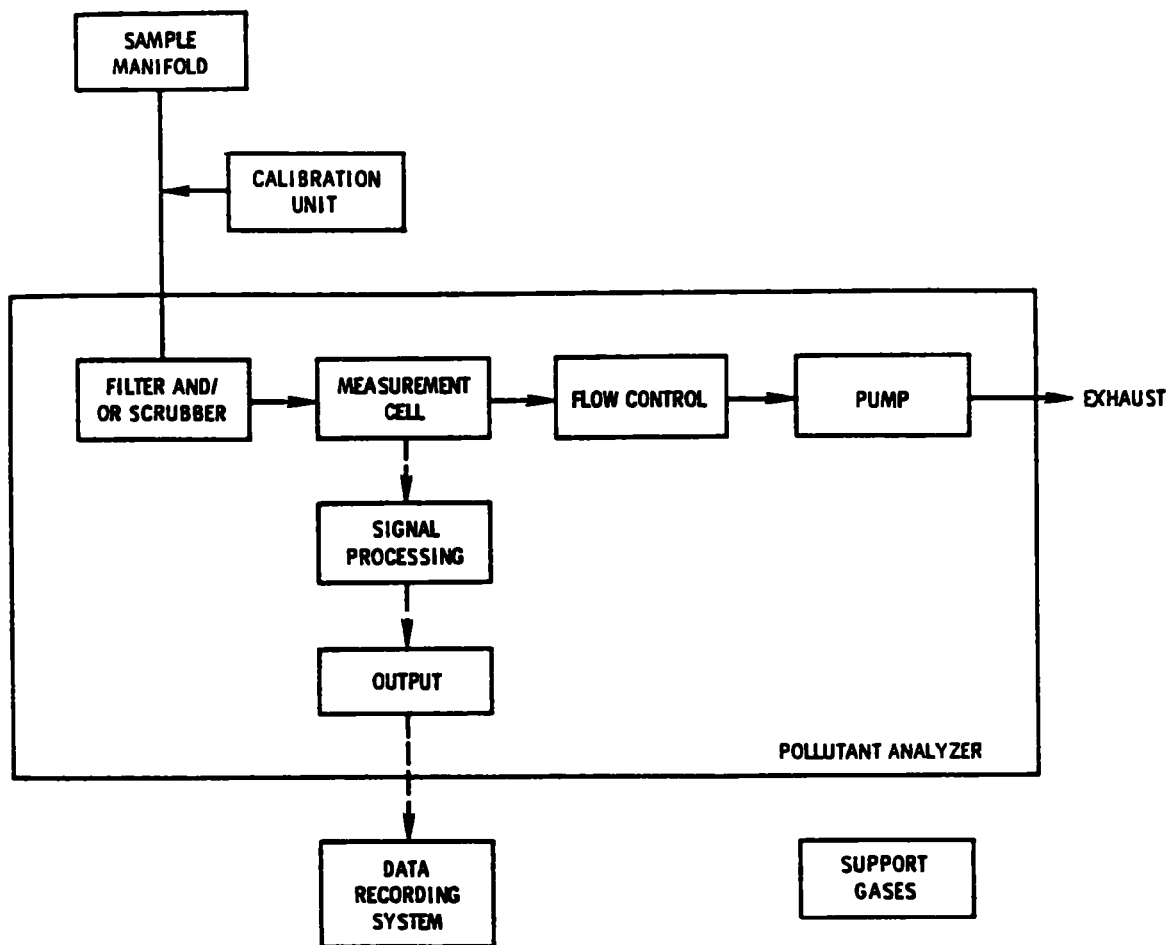
Figure 5-41. Elements of pollutant monitoring system.

- Nondispersive ultraviolet analyzers (NDUV)
- Electrocatalytic analyzers

Table 5-9 summarizes what component each type of analyzer is capable of measuring.

In addition to being categorized according to detection type, a broader classification of monitoring systems exists which distinguishes between extraction and in-stack or in-situ type systems. All five of these instruments with the exception of the polarographic monitor, are available in both extractive and in situ types.

Discussions of the components, advantages and disadvantages, and limitations of both extractive and in-situ versions follow. The general principles of operation discussed for the analyzers themselves may be applied to either version, as the differences in the detector mechanics are subtle.

TABLE 5-9. ANALYZERS CAPABLE OF MEASURING
GASEOUS COMPONENTS

Detection device	Component		
	O_2	CO_2	CO
NDIR		X	X[a]
NDUV		X	X
Paramagnetic	X		
Polarographic	X	X	X
Electrocatalytic	X		

[a]GFC method used for CO detection
(covered in text).

5.9.1.1 Extractive Systems--

The ability of an extractive, or remote monitoring system, to provide reliable
data depends upon a properly designed sampling interface. The total
extractive system must perform several functions:

- Remove a representative gas sample from the source on a continuous basis.
- Maintain the integrity of the sample during transport to the analyzer
  (within specified limits).
- Condition the sample to make it compatible with the monitor analytical
  method.
- Allow a means for a reliable calibration of the system at the sampling
  interface.

The design of the sampling interface, including the components used in its
construction, will depend on the characteristics of both the source gas stream
and the monitoring instrument.

The design of a sampling interface requires that the system deliver a condi-
tioned, continuous gas sample to the gas analyzer. A number of different
interface designs may be able to perform this task at a given source. The
actual system designed for a specific source generally incorporates a variety
of trade-offs based on source/analyzer requirements and financial restraints.
A system typically will include the following components:

- In-stack sampling probe
- Coarse in-stack filter
- Gas transport tubing
- Sampling pump
- Moisture removal system
- Fine filter
- Analyzer
- Calibration system
- Data recorder

Sampling Probe--Representative gas sampling requires samples that will demonstrate the total pollutant gas emissions from a source. The temperature and velocity traverse across the duct may indicate a necessity for a multipoint probe to extract samples from numerous points across the entire duct. Several research studies have shown that, although gas concentration cannot be assumed to correspond directly to temperature and velocity gradients in a duct, these measurements are excellent indications for positioning gas sampling probes. This research has shown that a representative gas sample may be extracted from a grid of equal areas laid out in the duct. A temperature and velocity traverse is then performed in each row of the grid. The multipoint gas sampling probe is then positioned across the row that indicated temperature and velocity readings closest to the average reading in the duct.

Gas sampling requires that particulate matter, which can harm the analyzer and shorten the operating life of the sample pump, be removed from the gas stream. Directing the probe inlet countercurrent to the gas flow helps prevent many large particulates from entering the system. Particulates that enter the probe can be removed by coarse and fine filters.

Coarse Filters--The coarse filter is usually located at the probe tip in the stack, where it then can prevent particulate matter from plugging the sampling probe and will not require heat tracing to prevent moisture condensation. There are two general types of coarse in-stack filters: external or internal.

The external coarse filter is a porous cylinder, typically constructed of sintered 316 stainless steel, though it may also be glass, ceramic, or quartz. It is essential that the porous cylinder be protected by a baffle to prevent excessive particulate buildup on the leading edges. These porous cylinders have an expected utility of approximately 2 to 3 months before they become clogged with particulate, depending on the sampling rate. Although they can be regenerated by back flushing, they eventually need replacing. The nominal cost ($\sim$$25) suggests that it may be easier to replace the filter on a routine basis than to install costly automatic backflushing equipment.

Filter material is available from a number of manufacturers. Glass wool filters have been used in some experiments; however, they have a higher pressure drop than the Alundum thimble.

Fine Filters--The majority of extractive stack gas analyzers require almost complete removal of all particles larger than 1 micron from the gas stream. This is best accomplished by including a fine filter near the analyzer inlet. Fine filters are divided into two broad categories: surface filters and depth filters.

Surface filters remove particulates from the gas stream using a porous matrix. The pores prevent penetration of particulates through the filter, collecting them on the surface of the filter element. Surface filters can remove particulates smaller than the actual filter pore size with particulate cake buildup and electrostatic forces acting to trap smaller particles. These filters perform well on dry, solid particulates without excessive pressure drop. A surface filter will foul quickly if it becomes wet or if the particulate is gummy.

Depth filters collect particulates within the bulk of the filter material. A depth filter may consist of loosely packed fibers or relatively large diameter granules. These filters perform well for gummy solids or moist gas streams and dry solids. In the case of malfunction, their flexibility can protect the analyzer from damage. Glass wool packed to a density of 0.1 gm/cm^3 and a bed depth of at least 2 inches can act as an inexpensive depth filter for normal gas flowrates. These filters must be carefully packed to avoid channeling.

Gas Transport Tubing--The gas tubing or sample lines transport the extracted gas sample from the stack through the interface system and into the analyzer. When evaluating sampling lines, it is important to consider:

- Tube interior-exterior diameter
- Corrosion resistance
- Heat resistance (for lines near high temperature areas or heat tracing)
- Chemical resistance to gases being sampled
- Cost

The gas tubing is sized to ensure an adequate gas flowrate with a reasonable pressure drop and good system response time. A flowrate of 2 standard liters per minute (enough to supply two gas analyzers) through a 6.35-mm OD (1/4 in.) tubing exhibits a pressure drop between 1 and 3 mm Hg per 30.48-m length. This pressure drop is quite acceptable for most sampling pumps. The response time (t) for a sampling line volume (V) can be calculated at a flowrate (F) in the equation:

$$t = \frac{V}{F} \text{ (assuming no axial dispersion or wall effects)}$$

At a flowrate of 1 standard liter minute, the response time for a 30.48-m tube section at 25°C and pressure drop of 152 mm Hg is only 30 seconds. These data indicate that 6.35-mm OD tubing is acceptable for sampling lines [31].

Teflon® and stainless steel exhibit excellent corrosion and heat resistance in addition to being chemically inert to stack gases and acid mist. The corrosion resistance of stainless steel is enhanced by keeping gases above the dew point. These materials are commercially available in heat traced form. Teflon® is normally recommended for out-of-stack heat traced lines; stainless steel is a good material for in-stack lines. Polypropylene and polyethylene lines exhibit good chemical resistance (except to nitric acid). Plastic lines are a good, economical choice for sampling lines that carry dry gas and are maintained above the freezing point without heat tracing. A reliable, effective, and economical sampling line system probably would incorporate stainless steel, Teflon®, and plastic.

Sampling Pump--A diaphragm or bellows pump upstream of the analyzer is superior to other pump types for gas handling. The primary advantages offered are:

- No shaft seal required.
- No internal lubrication required.

- Pumps are relatively inexpensive.
- Adequate suction and discharge pressures are developed at flowrates well above those needed for gas sampling systems.

Some sampling interface systems may place the pump downstream of the analyzer, pulling the sample through the system. This could allow the use of an aspirator pump without moving parts. Pressure drop at the analyzer would be higher, but for some analyzers with built-in pressure regulators, this may be preferable arrangement. Downstream pumps increase the potential for air leaking in and, in the case of aspirator pumps, require a source of large quantities of compressed air, steam, or water.

Moisture Removal--Stack gases may contain significant quantities of water vapor. A limited number of analyzers are not affected by the presence of water vapor in the sample (e.g., a differential absorption ultraviolet instrument). These analyzers do, however, require that gases be kept above the dew point to protect against condensation and corrosion within the analyzer. Other analytical methods that are affected by water vapor require moisture removal. Generally, the gas is dried to a low constant level of moisture content for both stack gases and calibration gases. Refrigerated condenser traps or permeation dryers are commonly used for moisture removal.

Sampling Interface Monitor Calibration--The entire sampling interface and monitor must be calibrated as a unit. The calibration gases enter the continuous gas monitoring system as near as possible to the same entrance point for the stack gas. This is essential to check the entire system. The analyzer is then calibrated at the same gas flowrate, pressure, temperature, and operating procedure used in monitoring the stack gas. Flooding the coarse filter with calibration gas at the probe inlet or using a check valve that allows calibration gas injection directly behind the coarse filter are the best methods for accomplishing this calibration. Calibration in this manner assures that any leaks, blockage, or sorption of gases taking place in the system will be discovered. The importance of this method cannot be overemphasized. Automatic gas injection systems are easily constructed with electric solenoid valves.

The calibration gases are typically checked with triplicate runs of the reference method procedure for that gas. All runs of the reference method must agree with the average for the three runs within 20% or they must be repeated. The gas analysis is repeated every six months. Although many manufacturers certify a longer shelf life, experience has shown that manufacturer calibration gas certification is subject to error.

EPA is currently studying the option of using National Bureau of Standards (NBS) calibration gases or gases traceable to NBS standards, instead of requiring reference method analyses. NBS gases are relatively accurate and stable but are more expensive than commercial gases.

Controlling the Sampling Interface/Monitor System--The best system does not require elaborate control mechanisms. The necessary controls are easily installed and maintained by owner/operator personnel. The suggested controls include the following:

- Temperature control at the cold end of the heated sample line. This is to ensure that the gases are above freezing to protect the lines from fracture or blocking. Temperature is also controlled at the refrigerated condenser to maintain moisture removal efficiency.

- Pressure control is needed at the pump discharge to protect the pump. The pressure drop across the fine filter is monitored to protect the analyzer and to ensure proper system function (most analyzers are sensitive to pressure changes).

- Gas flowrate control is installed to make certain the analyzer receives the correct gas flow. This is not critical, since most analyzers are relatively insensitive to minor flowrate change.

- Calibration gas valving automatically injects calibration gases once every 24 hr. This can be accomplished with a simple electric solenoid valve. The calibration gases should flow through the sampling system at the same condition of temperature, pressure, and flow as does the stack gas.

5.9.1.2 In-Situ Monitoring Systems--

The problems and expense associated with extractive monitoring systems have led to the development of instrumentation that can directly measure source-level gas concentrations in the stack. The so-called in-situ systems do not modify the flue gas composition and are designed to detect gas concentrations in the presence of particulate matter. Since particulate matter causes a reduction in light transmission, in-situ monitors utilize advanced electro-optical techniques to eliminate this effect when detecting gases.

Cross-stack in-situ monitors measure a pollutant level across the complete diameter or a major portion of the diameter of a stack or duct. Stratification effects are lessened by the use of cross-stack instruments, since an average reading is taken over a relatively long sample path. There are two types of cross-stack monitors: single pass and double pass.

- Single-pass systems locate the light transmitter and the detector on opposite ends of the optical sample path. Since the light beam travels through the flue gas only once, these systems are termed single pass.

- Double-pass systems locate the light transmitter and the detector on one end of the optical sample path. To do this, the light beam must fold back on itself by the use of retroreflector. The light beam will traverse the sample path twice in going from the instrument housing to the retroreflector and back to the instrument. Double-pass systems are easier to service than single-pass systems, since all of the active components are in one location.

In-stack in-situ systems monitor emission levels by using a probe that measures over a limited sample pathlength. All of the commercial, optical in-stack monitors are double-pass systems.

In principle, currently marketed cross-stack gas analyzers present many advantages over extractive monitoring systems. A cross-stack system may allow greater flexibility in site selection, since an average sample reading is taken over a relatively long path. It should be noted, however, that gas stratification in a duct or stack is a two-dimensional phenomenon, not one-dimensional. A cross-stack monitor can linearly average concentrations over its measuring path, but does not properly weigh the contributions of stratified areas to the measurement. For severe cases of stratification, the problem of obtaining representative concentration values may be comparable to the problems encountered by point monitors.

One of the principal marketing features of cross-stack analyzers is that a single instrument can monitor a number of gases and even opacity. The cost of such a monitor can be comparable to the purchase price of three or four separate instruments combined in an extractive system.

There are, however, a number of disadvantages associated with the cross-stack monitors. An in-situ cross-stack monitor can monitor only one flue or stack at a time. Costs might be prohibitive if a number of stacks must be monitored. In such a case, multiple probes and sampling lines leading into a single extractive system might be the better choice. Problems with optical misalignment, vibration affecting the optical systems, and the failure of electronic components also can occur. It is common among vendors of these instruments to offer service packages whereby the systems are periodically checked by a company serviceman. A service package generally will ensure that a system will continue to function, but the cost involved may bring the operating expenses to a level comparable to that of an extractive system.

5.9.2 Analyzers

5.9.2.1 NDIR Analyzers--

Nondispersive infrared (NDIR) analyzers have been developed to monitor SO_2, NO_x, CO, CO_2, and other gases that absorb in the infrared, including hydrocarbons. NIDR instruments utilize a broad band of light that is centered at an absorption peak of the pollutant molecule.

This broad band is usually selected from all the light frequencies emitted by the infrared source by using a bandpass filter. Table 5-10 gives the band centers for several of the gases found in source emissions.

In a typical NDIR analyzer, infrared light from a lamp or glower passes through two gas cells--a reference cell and a sample cell. The reference cell generally contains dry nitrogen gas, which does not absorb light at the wavelength used in the instrument. As the light passes through the sample cell, pollutant molecules will absorb some of the infrared light. As a result, when the light emerges from the end of the sample cell, it will have less energy than when it entered. It also will have less energy than the light emerging from the reference cell. The energy difference is then sensed by some type of detector, such as a thermistor, a thermocouple, or microphone arrangement.

TABLE 5-10. INFRARED BAND CENTERS OF SOME COMMON GASES

Gas	Location of band centers, μm	Wave number, cm^{-1}
NO	5.0 - 5.5	1,800 - 2,000
NO_2	5.5 - 20	500 - 1,800
SO_2	8 - 14	700 - 1,250
H_2O	3.1	1,000 - 1,400
	5.0 - 5.5	1,800 - 2,000
	7.1 - 10	3,200
CO	2.3	2,200
	4.6	4,300
CO_2	2.7	850 - 1,250
	5.2	1,900
	8 - 12	3,700
NH_3	10.5	950
CH_4	3.3	1,300
	7.7	3,000
Aldehydes	3.4 - 3.9	2,550 - 2,950

The advantages of the NDIR-type analyzers are their relatively low cost and the ability to apply the method to many types of gases. Generally, a separate instrument is required for each gas, although several instruments have inter-changeable cells and filters to provide more versatility. Problems associated with the method are those that arise from interferring species, the degrada-tion of the optical system caused by corrosive atmospheres, and in some cases, limited sensitivity. The microphone type detectors are sensitive to vibration and often require both electronic and mechanical damping, for example, by placing the instrument on a foam insulation pad.

5.9.2.2 Nondispersive Ultraviolet Analyzers (NDUV)--
Several available nondispersive systems use light in the ultraviolet and visible regions of the spectrum rather than in the infrared. Essentially, the analyzers measure the degree of absorption at a wavelength in the absorption band of the molecule of interest. This is similar to the NDIR method, but the major different is that a reference cell is not used. Instead, a reference wavelength, in a region where the pollutant has minimal absorption, is utilized.

This method of analysis is often differential absorption, since measurements are performed at two different frequencies. This method is not limited to extractive monitoring systems, but it also is used in both in-situ analyzers and remote sensors. As with all extractive monitoring systems, particulate matter is removed before entering the analyzer. It is not necessary, however, to remove water vapor in some of these systems. A heated sample line and heated cell prevent condensation in the analyzer. Since water does not absorb light in this region of the ultraviolet spectrum, no interference occurs.

5.9.2.3 Polarographic Analyzers--

Polarographic analyzers have been called voltammetric analyzers or electro-chemical transducers. With the proper choice of electrodes and electrolytes, instruments have been developed utilizing the principles of polarography to monitor SO_2, NO_2, CO, O_2, H_2S, and other gases.

The transducer in these instruments is generally a self-contained electro-chemical cell in which a chemical reaction takes place involving the pollutant molecule. Two basic techniques are used in the transducer: (1) the utiliza-tion of a selective semipermeable membrane that allows the pollutant molecule to diffuse to an electrolytic solution, and (2) the measurement of the current change produced at an electrode by the oxidation or reduction of the dissolved gas at the electrode.

The electrolyte of the cell generally will be used up in 3 to 6 months of continuous use. The cells can be sent back to the company and recharged, or new ones can be purchased. It is extremely important that the sample gas be conditioned before entering these analyzers. The stack gas will come to ambient temperature, and the particulate matter and water vapor are removed to avoid fouling the cell membrane.

5.9.2.4 Electrocatalytic Oxygen Analyzers--

A new method for the determination of oxygen has developed over the past several years as an outgrowth of fuel-cell technology. These so-called fuel-cell oxygen analyzers are not actually fuel cells, but simple electrolytic concentration cells that use a special solid catalytic electrolyte to aid the flow of electrons. These analyzers are available in both extractive and in-situ (in-stack) configurations. This versatility of design is making them popular for monitoring diluent oxygen concentrations in combustion sources.

In basic electrochemistry, one of the common phenomena studied is the flow of electrons that can result when two solutions of different concentrations are connected together. The electron flow results from the fact that the chemical potential is different on each side and that equilibrium needs to be reached. There are two half-reactions that take place in this example.

The instruments designed to continuously monitor oxygen concentrations utilize different concentrations of oxygen gas expressed in terms of partial pres-sures. A special porous material, zirconium oxide, serves both as an electrolyte and as a high temperature catalyst to produce oxygen ions.

If the temperature is well stabilized and the partial pressure of the oxygen on the reference side is known, the percentage of oxygen in the sample can be easily obtained.

One problem with the method is that carbon monoxide, hydrocarbons, and other combustible materials will burn at the operating temperature of the device. This will result in a lowering oxygen concentration in the sample cell, which, however, would be insignificant for concentrations of the combustible materials on the ppm level.

5.9.2.5 Paramagnetic Oxygen Analyzers--

Molecules will behave in different ways when placed in a magnetic field. This magnetic behavior will be either diamagnetic or paramagnetic. Most materials are diamagnetic and when placed in a magnetic field will be repelled by it. A few materials are paramagnetic; they are attracted by a magnetic field. Paramagnetism arises when a molecule has one or more electrons spinning in the same direction. Most materials will have paired electrons; the same number of electrons spinning counterclockwise as spinning clockwise. Oxygen, however, has two unpaired electrons that spin in the same direction. These two electrons give the oxygen molecule a permanent magnetic moment. When an oxygen molecule is placed near a magnetic field, the molecule is drawn to the field and the magnetic moments of the electrons become aligned with it. This striking phenomenon was first discovered by Faraday and forms the basis of the paramagnetic method for measuring oxygen concentrations.

There are two methods of applying the paramagnetic properties of oxygen in the commercial analyzers. These are the magnetic wind or thermomagnetic methods and the magnetodynamic methods:

- Magnetic Wind Instruments (Thermomagnetic)--The magnetic wind instruments are based on the principle that paramagnetic attraction of the oxygen molecule decreases as the temperature increases.

  Several problems can arise in the thermomagnetic method. The cross-tube filament temperature can be affected by changes in the thermal conductivity of the carrier gas. The gas composition should be relatively stable if consistent results are desired. Also, unburned hydrocarbons or other combustible materials may react on the heated filaments and change their resistance.

- Magneto-dynamic Instruments--The magneto-dynamic method utilizes the paramagnetic property of the oxygen molecule by suspending a specially constructed torsion balance in a magnetic field. When a sample containing oxygen is added, the magnet attracts the oxygen and the balance swings to realign itself with the new field. Light reflected from a small mirror then can be used to indicate that degree of swing and hence, the oxygen concentration.

Water and particulate matter have to be removed before the sample enters this monitoring systems. It should be noted that NO and NO_2 are also paramagnetic and may cause some interference in the monitoring method if high concentrations are present.

Tables 5-11, 5-12, and 5-13 summarize information on extractives and in-situ monitoring instrumentations, including range capabilities, approximate cost, and ability to measure specific effluent gas components.

TABLE 5-11. EXTRACTIVE MONITOR SUMMARY[a]

Instrument vendor	Gases measured						Measurement range	Approximate cost in thousands of dollars
	SO_2	NO	NO_2	CO_2	CO	O_2		
Nondispersive infrared instruments								
Beckman	X	X		X	X		Various ranges in ppm or %	3 - 5.4
Bendix	X	X		X	X		0.5 ppm - 50%	3 - 4
Esterline Angus	X	X		X	X		2 ppm - 100%	5
Horiba	X	X	X	X	X		10 - 2,000 ppm	3 - 5
Infrared Ind.	X	X		X	X		200 ppm - 10%	1 - 2
Leeds and Northrop	X			X			0 - 1,000 ppm	5.5
MSA	X	X		X	X		0 - 2,000 ppm	3 - 4
Teledyne				X	X		0 - 1,000 ppm	11 - 13
Extract differential absorption instruments								
CEA	X	X		X			2 - 50,000 ppm	3 - 6
DuPont	X	X	X				1 ppm - 100%	13 - 23
Esterline Angus	X		X					
Teledyne	X						2 ppm - 100%	12 - 14
Western	X	X	X	X			75 - 5,000 ppm	12 - 22
Polarographic instruments								
Beckman						X	0 - 25%	1 - 1.5
IBC/Berkeley	X	X	X				0 - 1,000 ppm	2 - 5.5
Dynasciences	X	X	X		X	X	0.01 - 200,000 ppm	2 - 8
Interscan Corp.	X		X		X			1
Teledyne						X	0 - 25%	1.5
Theta Sensors (MRI)	X		X			X	1 - 20,000 ppm	1 - 4
Western Precipitator (Joy)	X		X	X	X	X	0 - 1,000 ppm	1.5
Electrocatalytic instruments								
CEA						X	0 - 25%	
Dynatron						X	0 - 25%	
Lear Siegler						X	0 - 25%	4.5 - 5.8
MSA						X	0.1 - 20.8%	2
Teledyne						X	0 - 25%	1.5
Thermox						X	0 - 25%	2
Paramagnetic instruments								
Beckman						X	0 - 25%	
MSA						X	0 - 25%	3
CEA						X		
SCOTT						X	0 - 100%	1 - 1.5
Ledds and Northrop						X		
Taylor-Servomex						X	0 - 100%	1 - 1.5

[a]This is a representative listing of known vendors. It is not intended to be a complete listing of all suppliers of such equipment.

TABLE 5-12.   IN-SITU MONITOR SUMMARY[a]

Vendor	Gases measured					Method			Measurement range	Approximate cost in thousands of dollars
	SO$_2$	NO	CO$_2$	CO	O$_2$	Opacity	In-stack	Cross-stack		
CEA					X		X			
Contraves Goerz	X	X	X	X				X		30
Dynatron					X		X		0 - 25%	
Environmental Data Corp.	X	X	X	X		X		X	0 - 5,000 ppm	20 - 40
Lear Siegler	X	X			X		X		0 - 500; 0 - 1,000; 0 - 1,500 ppm	4.5 - 17
Westinghouse					X		X			

[a]This is a representative listing of known vendors. It is not intended to be a complete listing of all suppliers of such equipment.

TABLE 5-13.   OXYGEN ANALYZER SUMMARY[a]

Vendor	Analysis method			Sampling type	
	Paramagnetic	Polarographic	Electro-catalytic	In-Situ	Extractive
Astro			X	X	X
Beckman		X			X
Cleveland Controls	X		X	X	X
Corning			X	X	
Dynasciences		X			X
Dynatron			X	X	
Esterline Angus	X				X
Gas Tech		X			X
Hays-Republic			X	X	X
Joy		X			X
Lear Siegler			X	X	
Leeds and Northrop	X				X
Lynn		X			X
MSA	X		X		X
Scott	X				X
Taylor-Servomex	X				X
Teledyne		X			X
Thermox			X		X
Theta Sensors		X			X
Westinghouse			X	X	

[a]This is a representative listing of known vendors. It is not intended to be a complete listing of all suppliers of such equipment.

5.10 PLANT CONDITION MONITORING SYSTEMS

The presence of defects in machinery and mechanical structures can lead to catastrophic failure. Plant facilities which are super-designed for safety and minimal downtime (e.g., nuclear power plants and oil refineries) utilize large fixed-base condition monitoring systems for lowered repair costs, lower production losses, and decreased accident and fire risks.

Defects present are characterized by corresponding abnormalities and changes in acoustic and vibratory emission patterns. By the use of sensors small defects in bearings and gears, growing cracks in shafts and weld joints, loose parts, and operating deficiencies such as pump cavitation can be detected early enough to either allow correction of the problem or provide time for predictive maintenance planning. These plant-wide incipient failure detection (IFD) systems can sequentially examine more than 800 channels and quantize their vibratory or acoustic energy levels. The signal is compared with the previously obtained energy level retrieved from the memory bank of a dedicated minicomputer. Significant deviations are programmed to cause an alarm annunciation [32].

5.10.1 Machine Vibratory Signature Analysis

Traditional machinery vibration signature analysis (MVSA) is a method of determining the mechanical condition of an operating machine by monitoring and analyzing frequency characteristics produced by internal elements using narrow band spectrum analysis techniques.

Vibration signature analysis makes use of the fact that vibration produced by a machine contains a great number of discrete frequencies, some of which can be tied directly to the operating dynamics of particular elements within the machine. When the amplitude of a specific frequency or pattern of frequencies changes, it represents a change within the machine and possibly a deteriorating condition.

5.10.2 High Frequency Acoustic Emission Analysis

The basic premise of high frequency acoustic IFD monitoring is that the presence of defects in machinery and mechanical structures is characterized by corresponding abnormalities and changes in the acoustic signature and that machinery vibration is inevitably accompanied or even preceded by metal deformation. Metal deformation generates "acoustic emissions," i.e., noise resulting from the propagation of intergranular dislocations in material subjected to stress.

For early identification of failure these defects must be detected when they first develop and are quite small. However, the amount of detectable energy released from a small defect is usually negligible in comparison to normal machinery operating noise. Fortunately, operating noise tends to be concentrated in the low frequency range of vibration while defect-originated energy extends to much higher frequencies. It is this frequency separation that accounts for the success of IFD technology.

High frequency acoustic techniques have been shown to be more effective in detecting mechanical failures at a very early stage then the popularly used low frequency vibration and sound techniques. Furthermore, high frequency acoustics have very often picked up fluid flow deviations such as pump cavitation and mechanical seal leakage.

5.11 SCRUBBER/QUENCH WATER AND ASH HANDLING

5.11.1 Description of Potential Incinerator Wastes

Operation of a hazardous waste incinerator typically produces a number of secondary products, namely quench water, scrubber effluent, and ash. The following subsections describe each of these possible secondary wastes and provide information on their potential composition.

5.11.1.1 Quench Water--
Following the afterburner section, a quench section is usually installed to reduce the combustion gas temperature prior to entering the scrubber. Entering temperatures are approximately 1,800°F to 2,000°F and the exit temperature may be below 250°F. The inclusion of the quench section becomes necessary when nonmetallic materials are used for scrubber construction and packing. The upper temperature limit for sustained operation is about 300°F for polyester and epoxy fiberglass and 150°F for PVC [33]. The gases are commonly quenched with a water spray at a rate capable of reducing the gas temperature to a desired level. Besides lowering the flue gas temperature, this quench water functions as a scrubber by removing some particulate matter and certain gaseous pollutants from the exhaust stream.

Four basic designs are used to generate the water spray in quench towers:

(1) Air and water nozzle (2) High pressure sequenced spray nozzles (3) Orifice plate (4) Low pressure venturi or variable throat venturi

The type of device used depends upon the composition of the quench water, the composition of the exhaust gas, the type of air pollution control equipment being used, the initial investment, and maintenance considerations. Various quenching devices are illustrated in Figure 5-42.

The air and water nozzle system is the most sophisticated device and requires a fresh water feed, free from particles which might clog the spray nozzles. It also requires the least amount of water because it produces small, uniform droplets which efficiently cover an exhaust area.

High pressure sequenced spray nozzles operate on a demand basis. Initially, certain banks of spray are activated and as the gas temperature rises, additional banks come on to maintain a constant temperature. This system, like the air and water nozzle system, cannot operate on clarified recycle water due to dissolved and suspended solids; however, where fabric filters or electrostatic precipitators follow, these types of systems are necessary to prevent damage to these units from excessive heat.

HOT GAS IN

QUENCH SPRAY

THROAT
ADJUSTMENT

COLD GAS OUT

VARIABLE THROAT VENTURI

HOT GAS IN

QUENCH
SPRAY

THROAT

COLD GAS OUT

VENTURI

COLD GAS OUT

SPRAY
NOZZLES

QUENCH
SPRAY

HOT GAS IN

SPRAY TOWER

ORIFICE
PLATE

COLD GAS OUT

ORIFICE
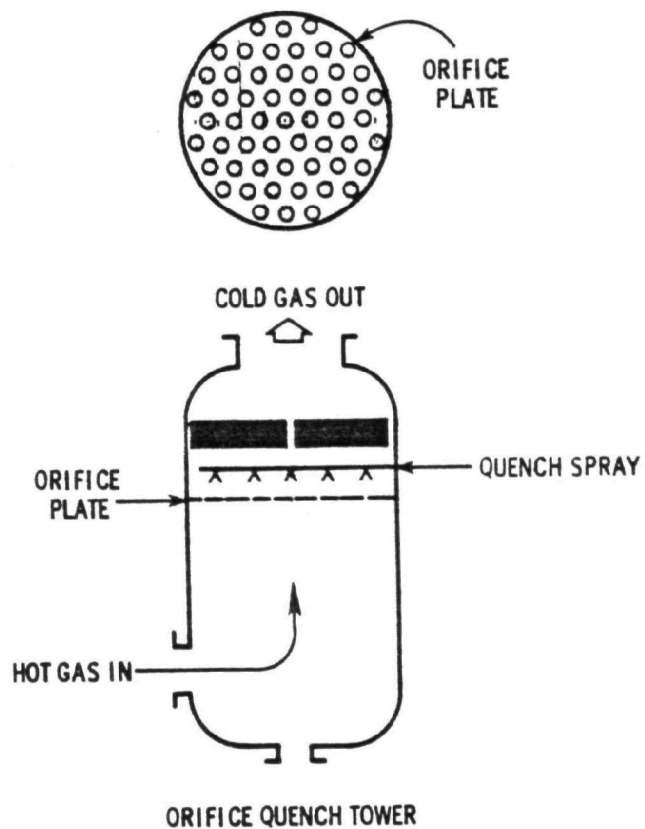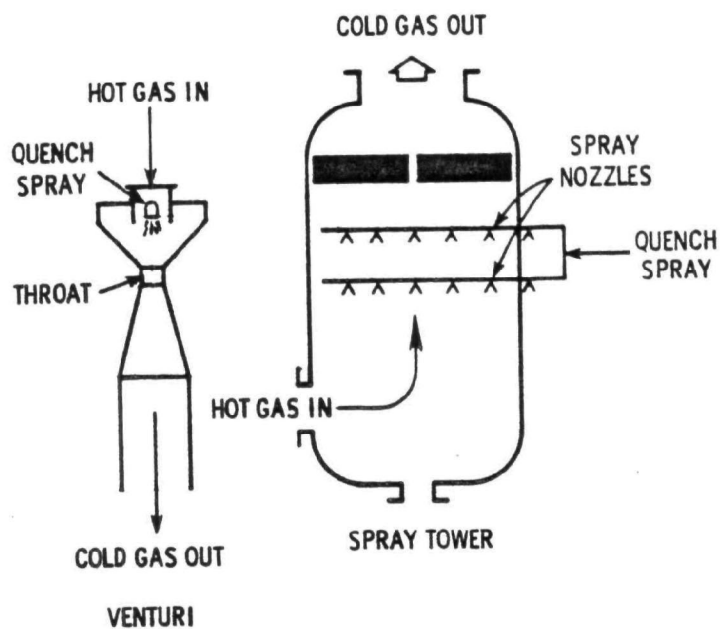PLATE

QUENCH SPRAY
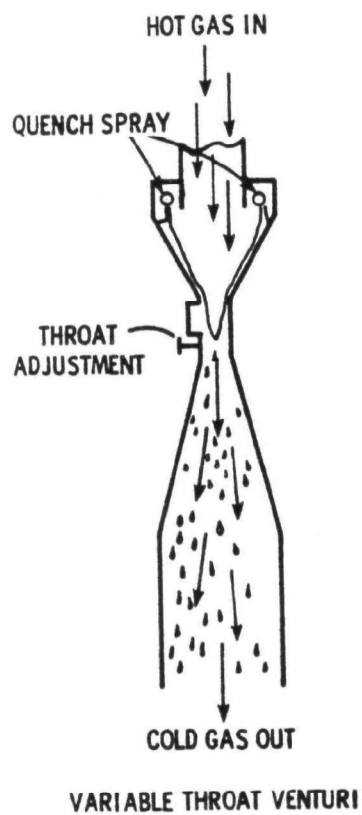
HOT GAS IN

ORIFICE QUENCH TOWER

Figure 5-42. Various quenching devices [34].

An orifice plate is an effective precleaner capable of removing particulates down to 5-10 microns [34]. It is simply a perforated plate through which water is forced. It is very effective preceding a high energy scrubber because it removes the larger particles which would create an erosion problem in the high velocity throat.

Another device which is essentially maintenance free and works well when used ahead of a scrubber is a low pressure venturi. Water nozzles, located just upstream of the venturi throat, saturate the flow and knock out the larger particles. In a variable throat venturi, gas velocities and corresponding pressure drop can be varied by adjusting throat diameter. For any particle size, the collection efficiency increases with increased energy consumption. Increased energy can be obtained by increasing gas velocities through the variable throat. Due to their larger and less restrictive water nozzle systems, both the orifice plate and low pressure venturi or variable throat venturi quenching devices may be operated using recycled quench water, after passing through a reduction and clarification process.

A generalized schematic of incinerator facilities and schematic of a rotary kiln facility with quench spray chamber and venturi scrubber are illustrated in Figures 5-43 and 5-44, respectively.

Material selection of the nozzles is very important because the cooling effect of the spray nozzle can cause condensation of the hot acidic gases along the wall of the spray nozzle, and these gases will react with the metal at or below the dewpoint of the acid. Also, the water will immediately react with the acid gas to form, for example, hydrochloric acid mist in the fine spray droplets, if an organochlorine waste is being destroyed. These are recycled and result in direct contact with the nozzle body.

The main body of the quench chamber is in contact with the highly acidic solution formed by the partial scrubbing of the combustion gases. Material selection is also important for this section. Hastelloy alloy B is a material generally recommended for the quench section, spray nozzles, and the duct work leading into the quench chamber. This material is a nickel-molybdenum alloy developed primarily for resistance to the corrosive effects of hydrochloric acid. This alloy also possesses useful high-temperature properties. In oxidizing atmospheres, the alloy may be used at temperatures up to 1,400°F. In reducing atmospheres, the alloy may be used at substantially higher temperatures.

Hastelloy alloy B is particularly well suited for equipment handling hydrochloric acid at all concentrations and temperatures including the boiling points. Hastelloy alloy B is easily fabricated, and can be forged and cold-formed by a variety of methods. Most of the common welding methods can be used to weld it, although the oxy-acetylene process is not recommended when the alloy is to be used in corrosion service.

Inconel alloy 625 and Incoloy alloy 825 are two other materials which show good resistance to hydrochloric acid and could thus be used in the quench section.
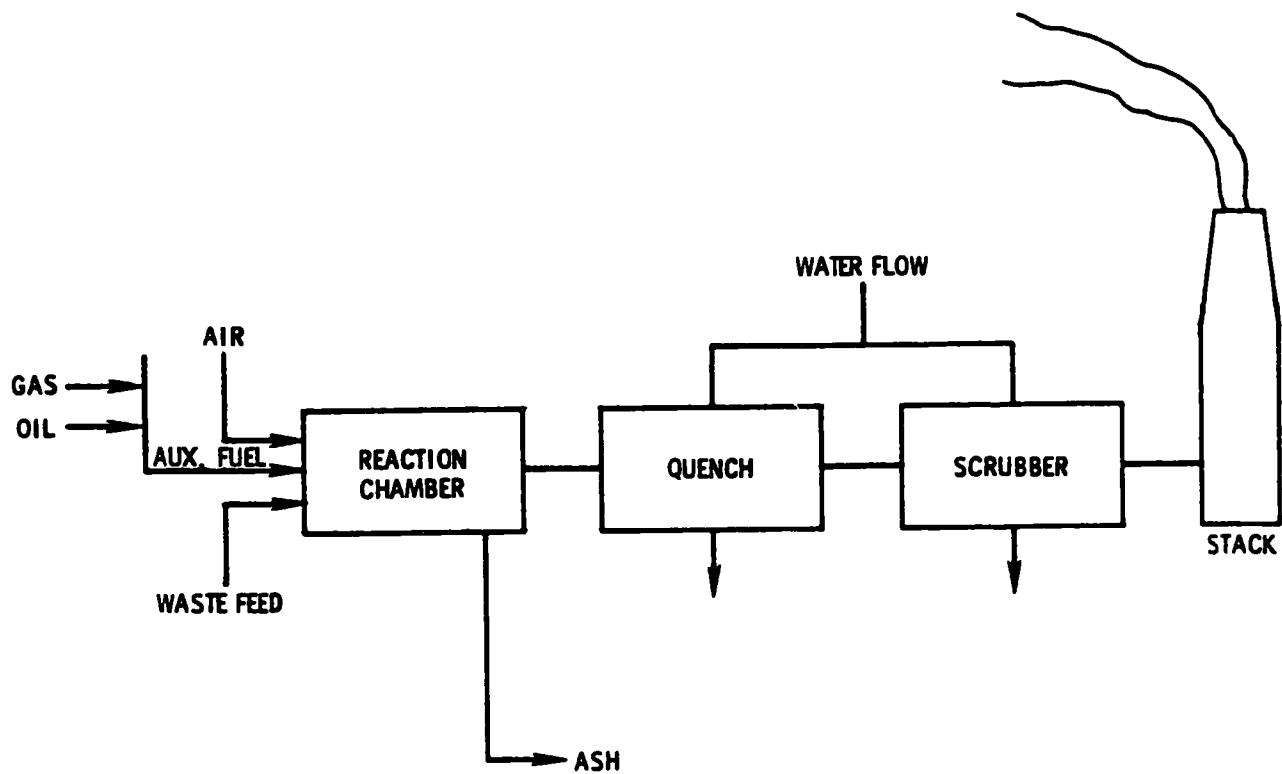
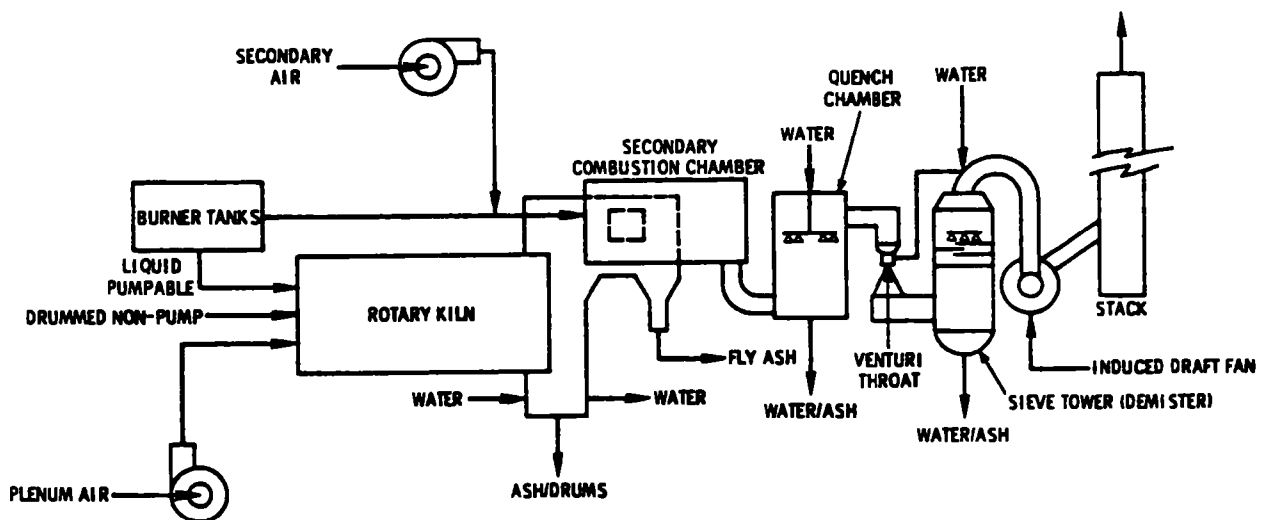Figure 5-43. Generalized schematic of incinerator facility.

Figure 5-44. Schematic of rotary kiln facility with quench
spray chamber and venturi scrubber.

The composition of the quench water depends directly on the wastes being incinerated. Table 5-14 summarizes the possible air pollutants that may be produced and captured by the quench tower and by other air pollution control devices. Because chlorinated organic compounds constitute the most common type of hazardous waste disposed of by incineration, quench waters are generally acidic and must be neutralized before discharge. Although hazardous species would not typically be present in quench water, this is typically verified before the effluent is disposed. Quench water is normally combined with the scrubber effluent for treatment and disposal.

TABLE 5-14. POTENTIAL AIR POLLUTANTS FROM HAZARDOUS WASTE INCINERATION

Hazardous waste	Air pollutants[a]	Likely removal sites		
		Quench tower	Scrubber	Baghouse or ESP
Organic materials containing:				
1. C, H, O only	Thermal NO_x[b]	-	c	-
2. Cl	HCl	X	X	-
3. Br	HBr	X	X	-
4. F	HF	X	X_d	-
5. S	SO_x	-	X_e	-
6. P	P_2O_5	-	X_c	-
7. N	NO_x	-	-	-
8. C, N	CH^- compounds	X	X	-
Materials containing some inorganic components:[f]				
1. Nontoxic minerals only, e.g., Al, Ca, Na	Particulate matter	X	X	X
2. Toxic elements including metals, eg., PB, As, Sb	Particulate matter Volatile species[g]	X -	X X^g	X X^g

[a]Based on complete destruction (i.e., oxidation) of hazardous waste.

[b]NO_x produced from atmospheric nitrogen at high temperatures (about 1,100°C) in the incinerator.

[c]NO_x is not normally controlled. Special scrubbers have been developed for NO_x control in special circumstances.

[d]Alkaline scrubbers are required for efficient SO_x control.

[e]Special high efficiency scrubbers are needed to collect phosphoric acid mist.

[f]A portion of the inorganic components may be removed as bottom ash from the incinerator.

[g]Certain elements from volatile species (e.g., As_2O_3) that condense out in the exhaust gas as the temperature falls. They can be collected in the gas phase by special scrubbers or as particulate matter at low temperatures by normal particulate control equipment.

5.11.1.2 Scrubber Effluents--

Characterization of scrubber effluents varies considerably from that of the quench water. Quench towers are primarily used to reduce the combustion gas temperatures prior to entering the scrubber, whereas scrubbers are primarily used to reduce noxious gases from the combustion gas prior to discharge to atmosphere. Commonly used scrubber types, design, material of construction, scrubber selection for specific applications, advantages, and disadvantages, etc., are covered in detail in Chapter 4.

In an incinerator burning chlorinated organic compounds, if water is the scrubbing fluid, the wastewater effluent will contain suspended particulates, dissolved HCl (i.e., hydrochloric acid), and other soluble constituents which may be present (e.g., trace quantities of organics and waste constituents that may be soluble). If alkaline scrubbing solutions are used, the HCl will undergo neutralization reactions to produce additional water and salts (either NaCl or $CaCl_2$ depending on whether NaOH or $Ca(OH)_2$ was used in the scrubbing solution). Because alkaline materials are often used in excess, residual amounts of these substances will be present. The wastewater will also contain suspended particulates and any soluble combustion products.

The venturi scrubbing process involves either a single pass of the scrubbing fluid or recirculation of the scrubbing fluid. If recirculation is used, scrubber fluid is recirculated through the venturi scrubber until the total dissolved solids (TDS) content reaches approximately 3% [35]. When this occurs, a portion of the scrubbing fluid is removed (blowdown) and new scrubbing fluid is added to make up for the fluid lost as blowdown. The blowdown from the single pass or recirculation scrubbing systems is neutralized (as needed) before delivery to on-site wastewater treatment processes, on-site storage facilities (e.g., evaporation ponds), or dispensing to the municipal sewer or a receiving water body. Single pass and recirculating scrubber systems are illustrated in Figure 5-45 and 5-46, respectively.

Alternative types of scrubber systems have been designed to recover HCl produced during organochlorine incineration. Such systems can produce commercial grade hydrochloric acid streams with concentrations ranging between 20% and 60% HCl [35]. These systems utilize aqueous solutions to absorb HCl from the combustion chamber effluent gas stream, and the resulting solution is concentrated via water extraction procedures. Residual HCl that may be left in the remaining combustion gas stream can be removed by passing this stream through an alkaline neutralization tower, or by using conventional gas scrubbing procedures.

Characteristics of Blowdown from Recirculating Scrubbers--Blowdown from recirculation systems occurs when the salinity reaches approximately 3 percent. This relates to a TDS value of 30,000 milligrams per liter [35]. The blowdown rate is variable, depending on the amount of chlorine in the liquid incinerated and on the liquid feed rate.

Characteristics of Single-Pass Scrubber Effluent--The characteristics of single-pass scrubber effluents are highly variable, depending on the chlorine content of the liquid incinerated, the liquid feed rates, the scrubber solution feed rates, and the efficiency of the scrubber, Because single-pass
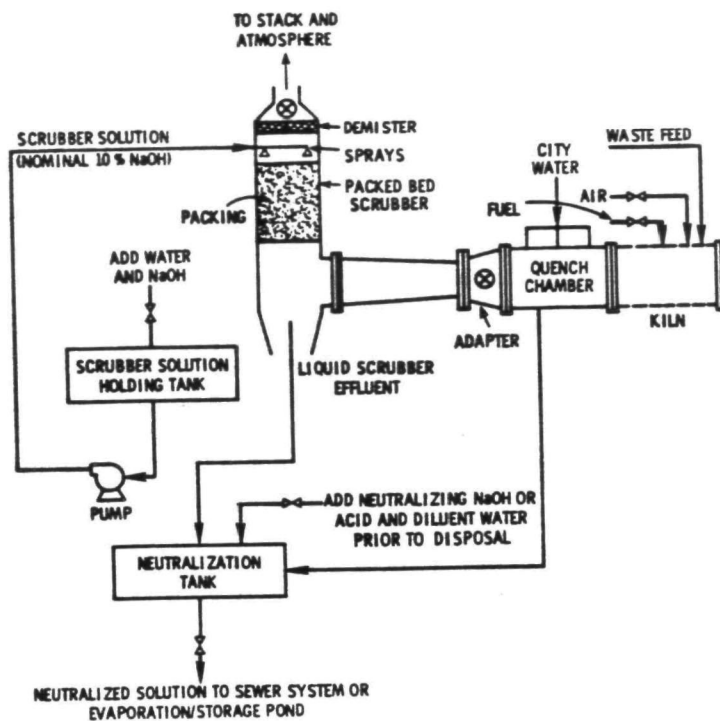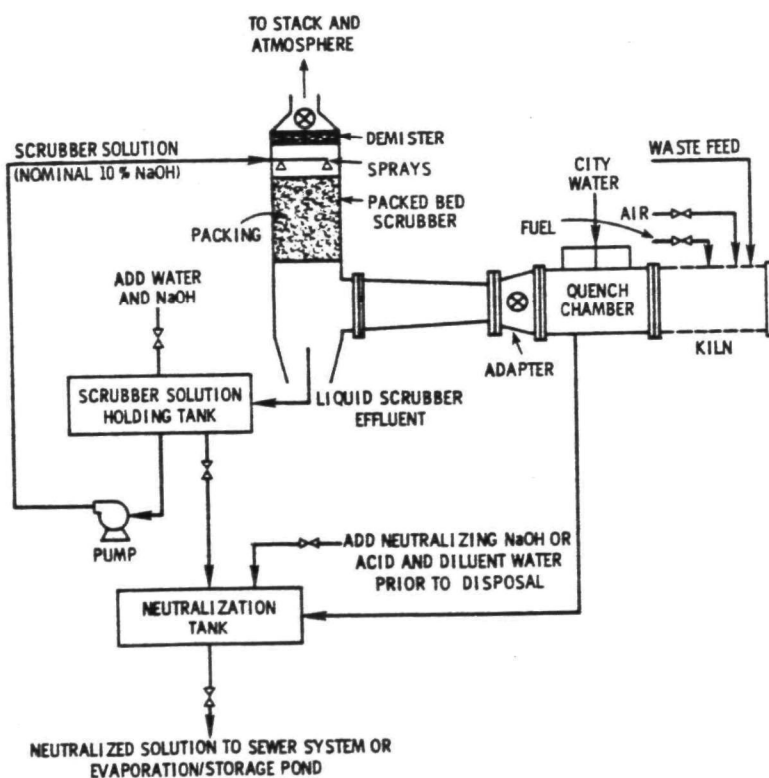
Figure 5-45.   Single-pass scrubber system [33].

Figure 5-46.   Recirculating scrubber system [33].

5-117

systems have so many variables, it is not possible to obtain a normal or average TDS concentration. However, it is possible to estimate the magnitude of TDS concentration. This has been done by using two sets of data shown in Tables 5-15 and 5-16. The data were picked because their operating parameters produced two extremes in scrubber water quality, as shown in Table 5-15. Generally, scrubber wastewaters will contain TDS concentrations less than 40,000 milligrams per liter.

TABLE 5-15. SCRUBBER WATER AND WASTE PARAMETERS FOR TWO
LAND-BASED LIQUID INJECTION INCINERATORS [35]

	Waste incinerated	
	Hexachlorocyclo-pentadiene[a]	Nitrochloro-benzene[b]
Fresh scrubber water feed rate (liters/min)	60	3,200
Caustic solution feed rate (liters/min)	23.8	8.5
Type of solution used	12% NaOH	32% $Ca(OH)_2$
Liquid waste feed rate (kg/hr)	52.8	1,893
Elemental chlorine content of the waste	77%	10%

[a]Source: Reference 31.

[b]Source: Reference 33.

TABLE 5-16. SCRUBBER WATER QUALITY [35]

	Waste incinerated	
	Hexachlorocyclo-pentadiene	Nitrochloro-benzene
Chlorides (mg/L)	11,000	1,300
Calcium (mg/L)	--	530
Sodium (mg/L)	25,670	--
Total dissolved solids (mg/L)	36,670	1,830

It can be expected that the HCl recovery processes will have much lower TDS concentrations than systems which do not recover HCl because a large proportion of the dissolved ions would be removed during recovery of the acid.

Scrubber effluents generally contain very little organic material due to high waste destruction efficiencies required.

The particular gaseous pollutant of interest may require scrubbing with a medium specific for the pollutant. Water is adequate for a gas such as HCl, but other scrubber media may be required for SO_2, NO_x, etc. In some cases, multiple stages are required to efficiently remove a combination of gaseous pollutants, with each stage specific for given pollutant. Two-stage and three-stage scrubber systems are illustrated in Figures 5-47 and 5-48, respectively. The type of technology illustrated in Figure 5-47 is not normally utilized for a hazardous waste incinerator. It is presented here for scrubber review. The three stage scrubber system illustrated in Figure 5-48 was implemented for a research project in an attempt to very carefully scrub effluent from a pesticide incineration program.
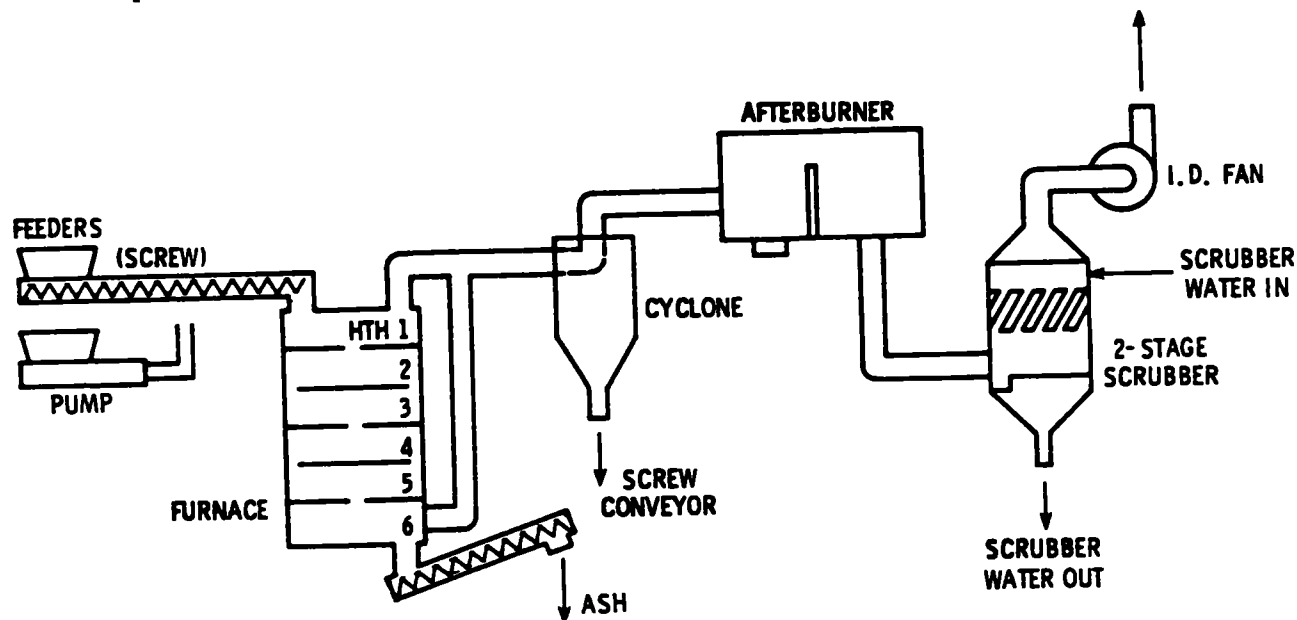

Figure 5-47. Incineration system with two-stage scrubber [36].

5.11.1.3 Ash--

Ash denotes the solid residue that remains after a material is incinerated. Ash produced during incineration is primarily inorganic and falls into two basic categories. Fly ash consists of the ash that is entrained in exhaust gases leaving the incinerator and which is usually captured in air pollution control equipment. Bottom ash refers to the ash remaining in the combustion chamber after incineration and is normally associated with inerts. The composition of the ash depends on the composition of the waste being incinerated and can therefore vary greatly. Because hazardous waste incinerators are designed for complete destruction of toxic organic compounds, the ash normally contains very little carbonaceous material. Solid materials not susceptible to oxidation (e.g., glass or ceramic) consitute the major ash species. Amount of ash produced is very small in relation to total mass of waste incinerated.

The relative proportion of fly ash to bottom ash is influenced by the waste composition and the incinerator design and operation. As expected, no bottom ash and relatively little fly ash result when liquid (except when liquids are from a complex chemical process that has inert materials in it or from a
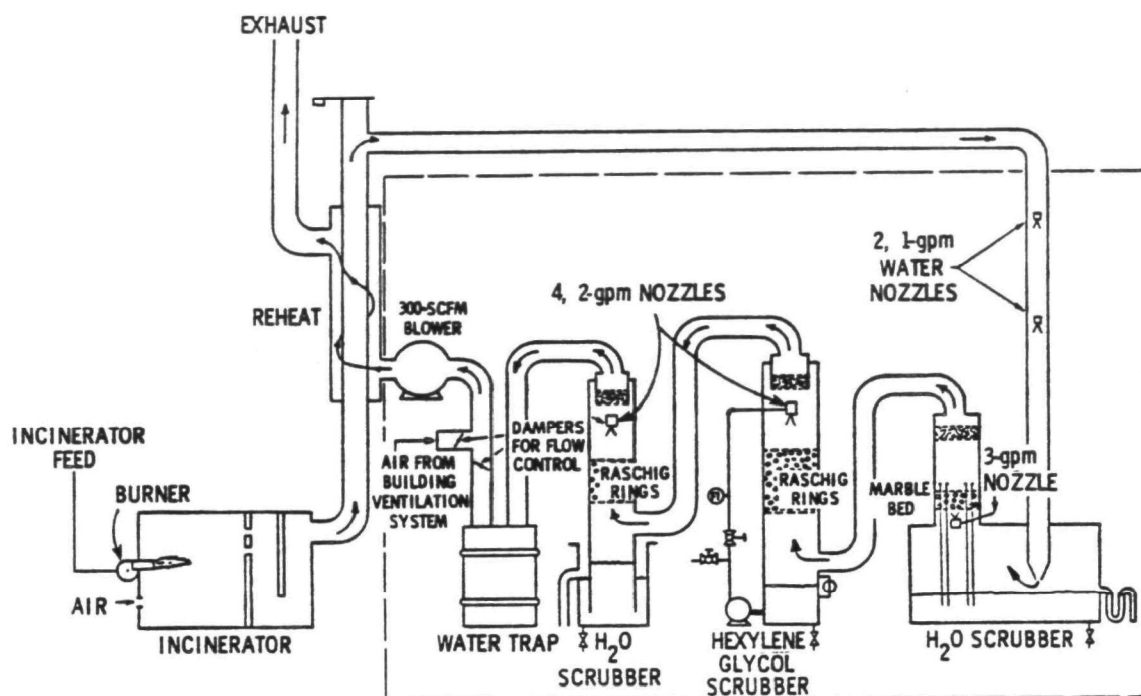
Figure 5-48. Incineration system with three-stage scrubber [37].

blending procedure that creates incompatible reactions that produce inerts) or gaseous wastes are incinerated.

5.11.2 Sampling and Analysis of Quench/Scrubber Water and Ash

Samples collected must be a representative sample of the whole water or ash. A representative sample for water can be collected by using various techniques and devices such as a coliwasa, automatic composite samplers like Isco, Manning, pond sampler, weighted bottle sampler, etc. Representative samples for ash can be collected by using devices such as a grain sampler, sampler corer, trowel or scoop, etc. Sampling devices and strategies are covered in detail in Chapter 3. Water samples are usually preserved because of any unstable species with the addition of appropriate preservatives. Where possible, samples are stored in a cool (4°C) and dark area prior to shipment to the laboratory for analysis.

The analysis of samples is directed primarily at determining the concentration of:

- Principal chemical species known to be present in the waste incinerated and believed to be hazardous. In some cases these will represent discrete chemical species such as nitrochlorobenzene and HCB. In other cases, such as those involving the incineration of tarry wastes from captan, rubber manufacturing and TDI, the analyses may have to be restricted to a general class of chemical species such as total organic chloride, total aromatic amine, etc.

5-120

- Primary decomposition products of waste such as chlorides, phosphates, sulfates, nitrates.

Solids can be analyzed via soxhlet extraction and water via liquid-liquid extraction.

5.11.3 Handling of Quench/Scrubber Wastewater

Quench water and scrubber effluents are normally combined for treatment and ultimate disposal. Depending on the scrubbing liquids used and the gaseous contaminants removed, wastewater may contain chlorides, fluorides, sulfites, sulfates, phosphates, bromides, and bromates, as well as particulate matter. Liquid waste streams containing sodium fluoride can be treated with lime or limestone slurry to yield the insoluble calcium fluoride. Sulfates, phosphates, and fluorides can be readily removed from the wastewater stream because of the low solubility of their calcium salts. Therefore, treatment normally includes clarification (to remove particulates), neutralization (to take care of any residual acid or base that may still be present), and dilution (to help control TDS levels). Particulates which are insoluble in the scrubber fluid become suspended solids in the scrubber wastewater. If the particulates dissolve in the scrubber fluid, they contribute to the wastewater's TDS level. Suspended solids in scrubber wastewater generally present little, if any, problems because their concentrations are usually less than 5 mg/L [35]. Suspended solids are usually removed by on-site settling ponds. Overflow from settling ponds can be recycled to scrubber.

Wastewater with either high or low pH levels is neutralized prior to final discharge (to a municipal sewer, or receiving stream). This is usually accomplished by adding either acid or base.

The high concentration of total dissolved solids (due to NaCl, CaCl$_2$ and in some cases the excess NaOH not used to neutralize HCl) is also reduced. This is usually accomplished by piping scrubber effluents to in-plant treatment systems or by diluting with other plant process streams and storing in a holding pond or lagoon.

In geographical locations with high evapotranspiration rates, solar evaporation could be used as a method for disposing of scrubber wastewater. For such a method to be considered environmentally acceptable, the scrubber wastewater would have to be devoid of potentially volatile materials which are hazardous. The ponds used for evaporation are periodically drained, and the accumulated sludge removed. Quench/scrubber effluents, evaporation sludge and ash treatment, and disposal options are illustrated in Figure 5-49.

For a discharge to a municipal sewer (publicly-owned treatment works - POTW), discharge must meet national general pretreatment standards and local POTW requirements, and must have approval from local POTW authority for such a discharge. By national pretreatment standards, pollutants introduced into POTW by any source of a nondomestic discharge are not to inhibit or interfere with the operation or performance of the works. The following pollutants may not be introduced into a POTW:
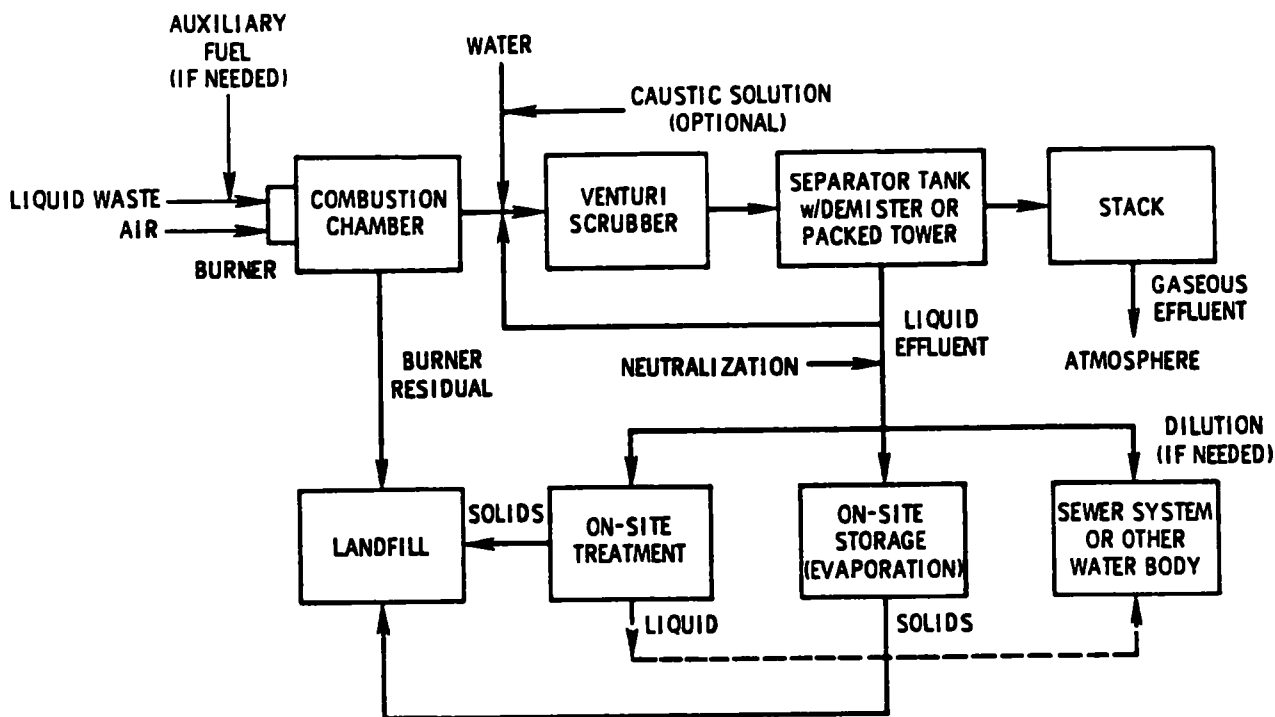
Figure 549. Incineration process with emissions
treatment and disposal options [36].

1. Pollutants which create a fire or explosion hazard in the POTW .

2. Pollutants which will cause corrosive structural damage to the
    POTW, but in no case discharges with pH lower than 5.0, unless
    the works is specifically designed to accommodate such discharges.

3. Solid or viscous pollutants in amounts which will cause obstruc-
    tion to the flow in sewers, or other interference with the opera-
    tion of the POTW .

4. Any pollutant, including oxygen demanding pollutants (BOD, etc.),
    released in a discharge of such volume or strength as to cause
    interference in the POTW.

5. Heat in amount which will inhibit biological activity in the POTW
    resulting in interference but in no case heat in such quantities
    that the temperature at the treatment works influent exceeds 40°C
    (104°F) unless the works is designed to accommodate such heat.

Compliance with Prohibited Discharge Standards was required beginning August
25, 1978, except for the heat Standard which must be compiled with within 3
years, or August 25, 1981.

For a discharge to a receiving body, an NPDES permit will be required. Such a discharge has to meet with the limitations set in the permit. Wastewater may require costly treatments to meet the limitations set in the NPDES permit.

The sludges or other sediments collected from settling ponds, evaporation ponds, or other types of lagoons may contain unburned wastes or toxic trace elements (abstracted from the combustion gases as particulates, or formed as precipitates following chemical reactions occurring in the pond). Sludges from scrubber processes are chemical sludges; these are handled and treated carefully and possibly differently from municipal sludges. In order to insure the fewest adverse effects, they sometimes can be properly disposed of in an approved hazardous waste landfill in accordance with federal guidelines mandated by RCRA.

5.11.4 Handling of Ash

Bottom ash will contain primarily inorganic and carbonaceous compounds. Less than 3% of the total weight of carbonaceous compounds will be trace compounds, including heavy metals. These solids can be disposed of in landfills approved for hazardous wastes.

5.12 FUGITIVE EMISSIONS

Fugitive emissions are those which result from occurrences such as leaks in valves and piping, entrainment from open vents or piles of material, and transfer operations [2]. Such emissions must be minimized and/or eliminated at hazardous waste incineration facilities. This section discusses monitoring and techniques which may be used to control such emissions. Table 5-17 illustrates areas having fugitive emission potential.

The most likely areas of process oriented fugitive emissions are around rotating seals on kilns, piping joints and valves, ductwork leaks on the positive pressure side of induced draft systems, ash handling system leaks, and quench water scrubber liquid handling and treatment system leaks. For illustration purposes, these areas are indicated in Figure 5-50. In the preprocess area, handling, storage, and preparation of the waste for feeding into the incinerator are critical operations to watch for fugitive emissions. Post-process operations also can pose a problem, such as those which transport and treat residue streams emanating from quenching, scrubbing, and post-treatment of residue.

5.12.1 Significance of Observed Emissions

The two primary concerns regarding inspection and monitoring of fugitive emissions are protection of the personnel around the operation itself and the health and welfare of those residing outside the fence limits of the facility. Working conditions within the facility must be in accordance with the exposure constraints defined by OSHA regulations. Such emissions outside the facility area are governed by applicable ambient air regulatory constraints.

TABLE 5-17. POSSIBLE SOURCES OF FUGITIVE EMISSIONS FROM
HAZARDOUS WASTE INCINERATOR SYSTEMS

WASTE PROCESSING AND FEED

- Waste shipping
- Waste unloading
- Waste loading to preparation/processing plant
- Waste processing

  - Crushing
  - Sizing
  - Washing
  - Drying

- Fine particulate removal or preparation for recycle
- Material transfer in waste processing plant
- Fugitives from loading/unloading storage bins
- Waste feed hopper backflow

WASTE INCINERATION AND POLLUTION CONTROL

- Waste feed
- Waste incineration/feed
- Air flow leaks in the incinerator furnace and associated systems
- Ash collection
- Stack flue gas particulate removal and disposal systems
- Ancillary equipment

  - Scrubber wastes/neutralization water
  - Dust collectors
  - Secondary combustion units (afterburners)
  - Gas/steam storage lines and transport lines
  - Water treatment units
  - Air coolers
  - Mixing chambers

- Ancillary equipment leaks

REMOVAL OR DISPOSAL METHODS

- Solids removal
- Ash transfer and storage
- Recycling systems
- Transfer lines for scrubber and cooler water
- Ash transport vehicles
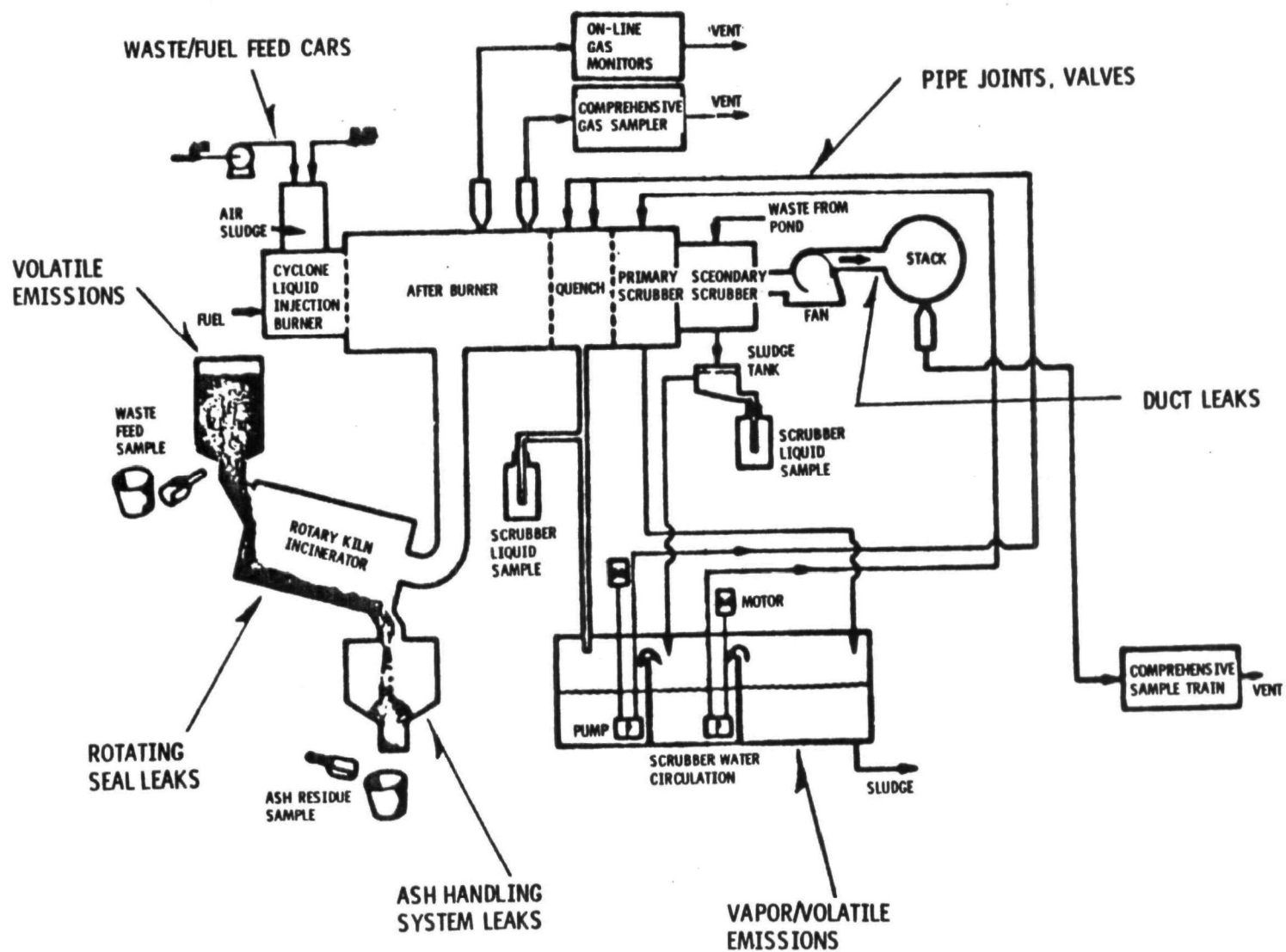- Ash transport
- Ash unloading
- Ash disposal

Figure 5-50.   Possible process leakage areas.

5.12.2 Fugitive Emission Control

Control of fugitive emissions is best accomplished through implementation of good engineering management practice. Initially, for a new facility a careful leak check is performed without hazardous components being treated in the system. Then during normal operation, visual inspection of all areas is performed to minimize the occurrence of undetected leaks. These visual inspections are then conducted regularly for any leaks, spills, odors, or other fugitive emissions. All automatic control system alarms and emergency shutdown features are also checked during the inspection to assure proper operation.

Any leak detected is recorded in a log as outlined in Section 5.12.5. Immediate repair is accomplished if feasible. If immediate repair is not feasible, as judged by the owner/operator, a sample of the leak is then taken. If analysis shows that a hazardous component is leaking at a concentration above 10 ppm, immediate temporary or permanent repair should be affected. Maintenance data is recorded on the leak detection and repair survey log. This includes a recheck to make sure the repair was effective after maintenance.

For sources of fugitive dust emissions, several control alternatives are possible. Table 5-18 illustrates the types of activities which can generate dust (primarily around storage and ash handling), and the traditional techniques or types of equipment used for air pollution control. Two decisions need to be made initially for the control of particulate matter at a facility-- the degree of control required, and whether the system will handle dust, wet or dry.

A wet-type particulate control system has limitations in that the wastewater created must be collected and treated for discharge and/or recycle. Recycle systems are preferred because of compliance with the NPDES permit program.

TABLE 5-18. CONTROL ALTERNATIVES FOR FUGITIVE DUST [38]

Type of activity	Control techniques					
	Baghouses/ scrubbers	Covers and enclosures	Spray systems	Encrusting agents	Wind breaks and physical arrangements	Paving or spray vehicle
Transfer points	X	X	X			
Conveyor belts		X	X			
Hoppers, dumpers	X	X	X			
Reclaimers			X			
Stockpiling equipment (bandwagons)			X			
Roads			X			X
Piles			X	X	X	
Bins, silos, bunkers	X	X				

5.12.3 Fugitive Emission Measurement Devices and Methodology

Source monitoring, area monitoring, and fixed-point monitoring are methods that can be used to detect fugitive emissions. Each of these is discussed below.

5.12.3.1 Area Monitoring--

To perform area monitoring, a path through the area to be monitored is predetermined so that one following the path will pass within a given distance (~3 ft) from all equipment within the area to be monitored. An instrument operator with a portable analyzer follows the predetermined path through the area and makes a complete survey around each piece of equipment. The operator must be careful that both the upwind and downwind sides of the equipment are sampled. If a concentration peak is observed, the location is recorded and a subsequent, more detailed survey made to pinpoint the exact source.

This is the same general procedure used for the regular visual inspection, but with a portable measuring instrument. An advantage of this method is that leaks can be detected quickly. Disadvantages include the possible detection of other emissions from outside the process area or improper readings due to wind gusts and wind direction variability. One outstanding disadvantage currently is that continuous portable monitoring equipment for measuring specific hazardous air pollutants are in the developmental stage and use would need to be examined carefully for appropriateness and utility.

5.12.3.2 Fixed-point Monitoring--

In the fixed-point methodology, analyzers are placed at specific points in the process area to monitor automatically for fugitive emissions. Individual samplers are placed either near specific pieces of equipment or in a grid pattern throughout the process area. If a concentration peak is observed, the operator then performs an individual component survey to detect the leak.

5.12.3.3 Source Monitoring--

In this methodology, leaks are detected by examining each individual component. Again, a portable detector is used. The instrument sample probe is moved along the component surface with care that both upwind and downwind areas are sampled. For sources such as drains, residue treatment tanks, and pressure relief valves, the probe is placed in the center and then along the periphery.

When no portable instrument is available, individual components can be en closed in a plastic bag (where practical). Any leaks accumulate in the bag and are exhausted through a sampling train designed to measure flow and prepare the sample for subsequent analysis by applicable laboratory techniques.

5.12.3.4 Current Instrumentation--

Particulate Measurements--Particulate sampling downwind of potential sources can be accomplished using high volume samplers. These devices consist of a pump and filter holder assembly encased in a weatherproof container. Ambient air is drawn across a preweighed filter membrane by a calibrated/feedback pump system. Filters are then weighed to obtain total mass particulate dust levels and analyzed for appropriate components.

Generally, a weather station is used to record wind speed, direction, temperature, atmospheric stability and barometric pressure over the sampling period.

Short-term ambient particulate levels can also be obtained by using either piezoelectric or beta attenuation monotors. These devices provide quick read-outs of ambient dust levels around a source. A number of readings can be obtained over a long period of time. Analysis of the collections on the substrate can be achieved as with the Hi-vol filter.

A particle size distribution of fugitive dust levels can be accomplished by attaching size - selective units (impactors) to the inlet of a high volume sampler. Particles are then collected on a substrate in each stage, depending upon the aerodynamic diameter of the incoming particles.

Particles less than 15 µm (EPA's definition of inhalable particulates) can be measured using dichotomous samplers. These devices consist of an elutriator in series with an impactor. The elutriator collects particles less than 15 µm and the impactor divides them into two fractions (<2.5 µm and >2.5 µm to 15 µm) which are collected on preweighed filters. Filters are then weighed and analyzed as necessary.

Particles can also be classified using a beta attenuation device by employing a small cyclone (inertial separator) in series with the pump. The cyclone collects the >10 µm particles, which then allows an attenuation readout of the <10 µm levels.

Measurement of Gases--Certain techniques for quantifying the fugitive gaseous emission levels from sources are available, which can obtain either (1) hydrocarbon-less-methane values or (2) if high enough concentrations exist, detection of individual components. In the latter case, a tandem-coupled gas chromatograph/mass spectrometer unit or GC alone would be employed for analysis with samples obtained by capture in a plastic bag for subsequent analysis.

Charcoal and porous polymer tubes connected to air pumps to draw ambient air across the median can be employed. The collection median is then solvent eluted for laboratory analysis.

Direct reading of ppm levels can be accomplished using Drager® tubes which are reactant impregnated substances. Ambient air is hand pumped through the collection median and the ppm levels read according to a color change.

Ambient total hydrocarbon levels can be measured using portable field gas chromatographs or hand-held flame ionization detectors. These devices operate on the same principle as the laboratory GC's except they have field use capabilities.

5.13 MATERIALS OF CONSTRUCTION

Materials of construction have been discussed for specific equipment throughout this chapter. This section is a repository of general information on various materials which may be encountered at a hazardous waste incineration

facility. Included is information regarding trade names, corrosion resistances, and typical uses of both ferrous and nonferrous metals and other nonmetallic materials.

The general corrosion resistance properties are discussed. In most incinerator, receiving, storage, feed situations, and residue handling, the flow stream will contain contaminants, so corrosion problems will be maximal. This section will allow the permit writer to augment his knowledge of the materials involved and check the recommended application.

5.13.1 Metals

(1) Cast Iron - This material is found in many cast process components such as pump bodies, impellers, valve parts, etc. Cast iron is a general term applied to high carbon-iron alloys containing silicon. Common varieties are: gray, white, malleable, ductile, and nodular. The material is quite susceptible to oxidation or "rust".

Increasing the silicon content to over 14% produces an extremely corrosion resistant material; e.g., Duriron, which is very hard and resists erosion-corrosion (notable exception: hydrofluoric acid). The alloy is sometimes modified by the addition of 3% molybdenum; e.g., Durichlor or Durichlor 51, for increased resistance to hydrochloric acid and chlorides.

In addition to alloys using silicon and molybdenum, other alloys using nickel, chromium and copper also produce improved corrosion resistance. Copper addition causes the metal to better withstand attack from sulfuric acid. High nickel-chromium cast irons with and without copper; e.g., Ni-Resist and Ni-Hard, produce very tough castings to resist erosion-corrosion in near-neutral and alkaline solutions or slurries.

(2) Carbon Steel - Carbon steel is alloyed, in various combinations, with chromium, nickel, copper, molybdenum, phosphorous, and vanadium. Low-alloy steels (2% total maximum alloying elements or less) are generally the more corrosion resistant. However, like cast iron, it is very susceptible to rusting.

Steel products are cast and also readily available in sheet, plate, and structural forms, as well as in a variety of products. Steels can be easily field cut and welded.

(3) Stainless Steel - Stainless steel has the same versatility of usage as carbon steel, with greatly improved corrosion resistance. Desired corrosion resistant properties are produced by alloying at least 11 percent of chromium. The chromium is reactive, but sets up a passive film to inhibit further corrosion. The following is a brief description of the five types of corrosion resistant alloys most commonly used in chemical applications:

5-129

Type 304	The basic 18% Cr-8% Ni type for relatively mild corrosion resistance.
Type 316	The "18-8" type with 2.0/3.0% Mo for superior resistance to pitting and to most types of corrosion, particularly in reducing and neutral solutions.
Type 317	The "18-8" type with 3.0/4.0% Mo, which has moderately better resistance than type 316 in some conditions, such as high concentrations of acetic anhydride and hot acetic acid.
"20"	A 29% Ni-20% Cr steel with copper and molybdenum, developed specifically for resistance to sulfuric acid.
Ni-o-nel	A 42% Ni-21.5% Cr alloy with copper and molybdenum, developed to meet more severe corrosion and stress-corrosion conditions than can be handled by the stainless steels but where nickel-base alloys are not needed.

A popular fallacy is that stainless steels are generally resistant to all environments. Stainless steels do have widespread application in resisting corrosion, but also have limitations. In fact, under conditions involving chloride-bearing solutions and stressed members, stainless steels are subject to chloride stress corrosion cracking and thus are much less suitable than alloyed steels. Stainless steels are also more susceptible than regular steels to localized corrosion such as intergranular, crevice, and pitting attack.

Consequently, many corrosion failures have resulted from the indiscriminate use of stainless steels on the assumption that they were the "best." In practice, stainless steels represent a class of highly corrosion-resisting materials of moderate strength and cost that are the bulwark of the chemical process industries when used with discretion.

(4) Aluminum and Alloys - Next to carbon steel and stainless steel, aluminum represents a versatile metal for construction, available in cast form and sheet, plate, and structural forms and in a variety of commercially available process components.

Aluminum is reactive but develops a passive oxide film which protects it from further corrosion in many environments. This film remains stable in neutral and many acid solutions, but is attacked by alkalies. The passive film is produced after contact with the chemical environment, unless the film has been artificially produced through anodizing. Structural members are typically produced from high-copper alloys, whereas process components are usually constructed of the low-copper or copper-free alloys, which have better corrosion resistance.

(5) Magnesium and Alloys - A lightweight material often found on portable devices and vehicles, however one of the least corrosion

resistant. It must generally be physically separated from other metals or it will become a sacrificial anode for them. It is capable of forming a good passive film; however, the film breaks down in salty air conditions, necessitating special coatings or other surface preparations. Magnesium is susceptible to erosion-corrosion. It is much more resistant to alkalies than is aluminum. It is attacked by most acids except chromic and hydrofluoric. The corrosion product in HF acts as a protective film.

(6) <u>Lead and Alloys</u> - Used often on corrosion resistant applications in such forms as: sheet linings, solder, cable sheath, bearings, and piping. Lead forms protective films consisting of corrosion products such as sulfates, oxides, and phosphates. It is subject to erosion-corrosion because of its softness. Chemical-resistant lead, containing about 0.06% copper, is resistant to sulfuric, chromic, hydrofluoric, and phosphoric acids, neutral solutions, and seawater. It is rapidly attacked by acetic acid and generally not used in nitric, hydrochloric, and organic acids.

(7) <u>Copper and Alloys</u> - Copper alloys are found in pump bodies and impellers, process component bodies and parts, and in pipe tubing and fittings, tanks, bearings, wire and screen.

A good chemically resistant material, copper is not corroded by acids unless oxygen or other oxidizing agents (e.g., HNO_3) are present. Copper-base alloys are resistant to neutral and slightly alkaline solutions (exception: ammonia). Common alloys are: brass, bronze, and cupernickel. Bronze, aluminum brass, and cupranickel are stronger and harder than copper and brass and less subject to erosion-corrosion.

(8) <u>Nickel and Alloys</u> - A workhorse in severe corrosion applications, nickel and its alloys are found in many commercially available process components, expecially pumps, valve parts, and other critical process parts. Nickel is resistant to many corrosives and is a natural for alkaline solutions, found in many tough applications on caustics. It shows good resistance to neutral and slightly acid solutions. It is not resistant to strongly oxidizing solutions; e.g., nitric acid, ammonia. Among the common varieties:

> Monel - natural for hydrofluoric acid

> Chlorlmet 3 and Hastelloy C - two of the most generally corrosion-resistant materials commercially available

> Chlorlmet 2 and Hastelloy B - very good in cases where oxidizing conditions do not exist

(9) <u>Zinc and Alloys</u> - Not a corrosion-resistant metal, chiefly used in galvanized steel.

(10) <u>Tin and Tin Plate</u> - Usually found as a coating and used in solder and babbit bearings, it is corrosion resistant, easily formed and soldered; and provides a good base for organic coatings. Tin has good resistance to dilute mineral acids in the absence of air, and many organic acids, but is corroded by strong organic acids; generally not used for handling alkalies.

(11) <u>Titanium and Alloys</u> - A newcomer to corrosion resistant construction, is available as castings in pumps, valves, and other process components. Titanium is a reactive metal which depends on a passive oxide film for corrosion resistance. Titanium has resistance to seawater and other chloride salt solution; hypochlorites and wet chlorine; and nitric acid. Salts such as $FeCl_3$ and $CuCl_2$, which tend to pit other metals do not corrode titanium. It is not resistant to relatively pure sulfuric and hydrochloric acids.

5.13.2 <u>Nonmetallics</u>

(1) <u>Natural and Synthetic Rubbers</u> - Rubber is an important process material with an extensive range of uses: hoses, tanks, tubing, gaskets, pump diaphrams and impellers, sheets, liners, etc. Rubber has excellent chemical resistance, and has been a standard for handling of hydrochloric acid containers. Generally, the synthetic rubbers have better chemical resistance than the natural rubbers. Vulcanization, the process of hardening rubber by adding sulfur and heating, can produce a wide range of hardnesses from soft gaskets to hard pump impellers. Corrosion resistance generally increases with hardness.

A wide variety of synthetic rubbers is available, including combinations with plastics. In developing the various products, plasticizer fillers and hardeners are compounded to obtain a large range of properties, including chemical resistance. Table 5-19 presents a list of brand names of plastic materials and the corresponding generic type of plastic.

Table 5-20 shows chemical resistance and other properties of commercially available rubber products. One of the newer elastomers which should be added to the list is Hypalon, which has excellent resistance to oxidizing environments such as 90% sulfuric acid and 40% nitric acid at room temperature.

(2) <u>Plastics</u> - Used extensively in chemical process applications as process component bodies and parts, tanks and tank liners, pipe, valves, tubing, and fittings, sheets, structurals, etc., plastics are high-molecular weight organic materials that can be shaped into a variety of useful forms.

When comparing plastics to metals, the former are softer and weaker, more resistant to chloride ions and hydrochloric acid, less resistant to concentrated sulfuric ad oxidizing acids such as nitric, less

TABLE 5-19. BRAND NAMES OF POLYMERIC MATERIALS

Material	Chart classification	Material	Chart classification
Aeroflex	Polyethylene	Mylar	Polyester
Alathon	Polyethylene	Nylon	Nylon
Araldite	Epoxy	Penton	Polyether
Avisco	Urea	Plexiglas	Methyl methacrylate
Bakelite	Phenolic	Plioflex	Vinyl
Beelte	Urea	Polythene	Polyethylene
Dacron	Polyester	Pro-Fax	Polypropylene
Durcon	Epoxy	PVC	Polyvinyl chloride
Durez	Phenolic	Resinox	Phenolic
Dypol	Polyester	Saran	Vinyl
Epon	Epoxy	Styron	Polystyrene
Excon	Polypropylene	Teflon	Fluorocarbon
Kel F	Fluorocarbon	Tygon	Vinyl
Lauxite	Urea	Vibrin	Polyester
Lucite	Methyl methacrylate	Vinylite	Vinyl
Lustrex	Polystryene	Viton	Fluorocarbon
Moplen	Polypropylene		

resistant to solvents, and have definitely lower temperature limitations.

Plastics, when subjected to corrosive environments do not fail as metals do. Rather than dissolving, they are degraded or corroded because of swelling, loss in mechanical properties, softening, hardening, spalling, and discoloration. Table 5-21 lists the properties of some commercially available plastics.

For ease of using this table, commonly used tradenames and other designations are listed here alphabetically in reference to the chart classification to which they belong:

(3) Other Nonmetallics - Used as materials of construction and lining of process systems:

Ceramics - compounds of metallic and nonmetallic elements; include magnesia, brick, stone, fused silica, stoneware, glass, clay tile, procelain, concrete, abrasives, mortar, high temperature refractories. Most ceramics exhibit good chemical resistance, with the exception of hydrofluoric acid and caustic.

Carbon and Graphite - often used for shaft seals; inert to many chemical environments; good resistance to alkalies and most acids; attacked by oxidizing acids such as nitric, concentrated sulfuric, and chromic; also attacked by fluorine, iodine, bromine, chlorine, and chlorine dioxide.

TABLE 5-20.   PROPERTY COMPARISONS - NATURAL AND SYNTHETIC RUBBERS [12]

Property	Natural rubber	Butyl (GR-1)	Buna S (GR-S)	Neoprene	Nitrile (buna N)	Polyacrylic rubber	Silicone rubber
Hardness range (Shore "A")[a]	40-100	40-90	40-100	30-90	45-100	50-90	40-80
Tensile strength, psi[b]	4,500	3,000	3,500	3,500	4,000	1,500	900
Max. elongation.	900	900	600	1,000	700	200	250
Abrasion resistance[c]	Excellent	Good	Excellent	Very good	Excellent	Fair	Poor
Resistance to compression set at 158°F[c]	Good	Fair	Excellent	Good	Excellent	Good	Excellent
Resistance to compression set up to 2,500°F[c]	Poor	Poor	Excellent	Fair	Excellent	Good	Excellent
Aging resistance (normal temp.)	Good	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent
Max. ambient temp. allowable, °F	160	275	275	225	300	400	580
Resistance to weather and ozone[c]	Fair	Very good	Fair	Excellent	Fair	Excellent	Excellent
Resistance to flexing	Excellent	Excellent	Good	Excellent	Fair	Excellent	Poor
Resistance to diffusion of gases	Fair	Excellent	Fair	Very good	Fair		
Resilience	Excellent	Poor at low temperature; Good at high temperature	Fair	Very good	Fair	Poor	
Resistance to petroleum oils and greases	Poor	Poor	Poor	Good	Excellent	Very good	Good
Resistance to vegetable oils	Good	Good					
Resistance to nonaromatic fuels and solvents	Poor	Poor	Poor	Fair to good	Very good		Fair
Resistance to aromatic fuels and solvents	Poor	Poor	Poor	Fair	Good		Poor
Resistance to water and antifreezes[c]	Good	Good	Good	Fair	Excellent	Poor	Fair
Resistance to dilute acids	Good	Good	Good	Good	Good		
Resistance to oxidizing agents	Poor	Fair	Poor	Poor	Poor		
Resistance to alkali	Fair	Fair	Fair	Good	Fair		
Bielectric strength[c]	Excellent	Good	Excellent	Fair	Fair		
Flame resistance	Poor	Poor	Poor	Good	Poor		
Processing characteristics	Excellent	Good	Good	Good	Good	Fair	Poor
Low temperature resistance[c]	Very good	Fair	Good	Fair	Good	Poor	Excellent
Tear resistance	Excellent	Excellent	Good	Good	Good	Fair	Poor

[a]100 durometer reading is bone hard and indicates that ebonite or hard rubber can be made.

[b]Indicates soft-rubber type. Hard-rubber types run higher in value.

[c]These properties available in specific compounds.

TABLE 5-21. PROPERTIES OF COMMERCIALLY AVAILABLE PLASTICS [12]

Material	Acids		Alkalies		Organic solvents	Water absorption, %/24 hr	Oxygen and ozone	High vacuum	Ionizing radiation	Temperature resistance	
	Weak	Strong	Weak	Strong						High	Low
Thermoplastics											
Fluorocarbons	Inert	Inert	Inert	Inert	Inert	0.0	Inert	-	P	550	G-275
Methyl methacrylate	R	A-O	R	A	A	0.2	R	decomp.	P	180	-
Nylon	G	A	R	R	R	1.5	SA	-	F	300	G-70
Polyether (chlorinated)	R	A-O	R	R	G	0.01	R	-	-	280	G
Polyethylene (low density)	R	A-O	R	R	G	0.15	A	F	F	140	G-80
Polyethylene (high density)	R	A-O	R	R	G	0.1	A	F	G	160	G-100
Polypropylene	R	A-O	R	R	R	<0.01	A	F	G	300	P
Polystyrene	R	A-O	R	R	A	0.04	SA	P	G	160	P
Rigid polyvinyl chloride	R	R	R	R	A	0.10	R	-	P	150	P
Vinyls (chloride)	R	R	R	R	A	0.45	R	P	P	160	-
Thermosetters											
Epoxy (cast)	R	SA	R	R	G	0.1	SA	-	G	400	L
Phenolics	SA	A	SA	A	SA	0.6	-	-	G	400	L
Polyesters	SA	A	A	A	SA	0.2	A	-	G	350	L
Silicones	SA	SA	SA	SA	A	0.15	R	-	F	550	L
Ureas	A	A	A	A	A	0.6	A	-	P	170	L

Note: R = resistant, A = attacked, SA = slight attack, A-O = attacked by oxidizing acids, G = good, F = fair, P = poor, L = little change.

Wood -   Typical chemically resistant woods are cypress, pine, oak, and redwood; generally limited to dilute chemicals; strong acids, oxidizing cards, and dilute alkalies attack wood.

5.14 MISCELLANEOUS CONCERNS

5.14.1 Personnel Health and Safety

The health and safety of the public and of plant employees should be considered of major importance in any industrial installation design or operation. Although the greater part of this manual deals with possible injury to public health and property, the effect of plant emissions on the plant employees is also a primary concern. Often, plant employees in direct contact with the industrial processes for extensive periods of time are in the greatest immediate danger. This section will not attempt to define the multitude of work-related hazards facing hazardous waste incinerator workers, but will concentrate on these areas of concern: equipment for worker protection and procedures for worker protection [39].

- Synthetic Gloves - These provide skin protection for the hand and arm, as required. Synthetic means rubber, polyethylene, or other impervious materials. Full-arm-length gauntlets or sleeve protectors can also be used.

- Synthetic Aprons - Materials specified for synthetic gloves also apply to aprons. Disposable-type coveralls or laboratory coats may be preferred for many tasks at an incinerator facility.

- Respiratory Protective Devices - There are three types of these devices: (1) air-purifying respirators, (2) supplied-air respirators, and (3) self-contained breathing apparatuses.

  The air-purifying respirators utilize an aerosol filter for protection against particulate matter and/or a chemical cartridge for protection against certain known gases of vapors. The choice of cartridge is dictated by the hazard involved.

  The supplied-air respirators are supplied with air remote from the hazardous location, usually through a breathing-air manifold and hoses. The self-contained breathing apparatus is normally used only in emergency situations. Use only devices that are certified by NIOSH.

- Adequate Ventilation - Ventilation in an area must be sufficient to prevent harmful exposure to toxic materials. The threshold-limit value (TLV) for an individual chemical vapor or type of dust refers to the time-weighed concentration for a normal workday, under which it is believed that nearly all workers may be repeatedly exposed, day after day, without harmful effect. If this value is exceeded, then a "ceiling" value applies. This ceiling value should not be exceeded (emergency situations such as spills require the use of protective equipment). Exposure to concentrations above the TLV

5-136

up to the ceiling value are not desirable, but are permitted as long as the overall eight-hour time-weighted average (TWA) does not exceed the TLV.

If inadequate ventilation is indicated (TLV is exceeded) for any operation or area, immediate use of a personal air-supply system is engaged. A permanent solution involving good engineering practices is then desirable and should be implemented as soon as possible.

- Full Suit - This is a suit that provides head-to-toe protection for the hazard involved.

- Line Breaks - Line breaks include broken flanges on lines not previously exposed to the atmosphere, and drained and repacking of valves and pumps, where there exists a potential for hazardous streams in concentrated form or under pressure. In this type of operation, the following protective equipment is usually required: full-rubber acid-suit consisting of rubber coat, rubber pants, acid gloves, rubber boots under the pants, and rubber hood.

- Repairs - Repairs apply to work performed on equipment or lines that handled hazardous waste streams, which had previously been opened to the atmosphere, and which have been drained and proven to be under no pressure. Since the hazardous potential still exists, goggles or an approved hood and gloves are typically required. After flushing with water--or a neutralizer agent where feasible--and the danger potential no longer exists, as determined by supervision, hazardous-material protection is no longer required. If the underfoot area is still puddled or wet from flushing and draining, rubber overshoes are usually required.

If a pump is not delivering, and troubleshooting or priming is necessary, goggles and gloves with coat or apron are worn even though no breaks in the line have occurred.

5.14.2 Facility Housekeeping

Good housekeeping plays a key role in occupational health protection. Basically, it is another tool in addition to those other facility safeguards listed for preventing dispersion of dangerous contaminants. Housekeeping is always important; where there are toxic materials, it is paramount.

Immediate cleanup of any small spills of toxic material is a very important control measure. A regular cleanup schedule using vacuum cleaners or lines is the only truly effective method of removing dust from a work area. an air hose for blowing away dust is never used.

A high standard of housekeeping is the most important single factor in the prevention of fire. Many types of waste and rubbish are susceptible to spontaneous ignition. Practically all organic materials have a tendency to heat spontaneously. This tendency is greater for those containing oil, solids when pulverized, and vegetable or animal fibers, especially when wet. Many materials which are safe at room temperature will heat spontaneously after prolonged

exposure to high temperatures, such as accumulations occurring in ducts or on heated pipes.

Accumulations of all types of dust are cleaned at regular intervals from overhead pipes, beams, and machines, particularly from bearings and other heated surfaces. It must be understood that all organic as well as many inorganic materials, if ground finely enough will burn and propagate flame. Roofs also are kept free from combustible refuse. Such cleaning perferably is done by vacuum removal, because blowing down with air may disperse dusts into dangerous clouds.

5.14.3 Maintenance

Testing is a prime activity in a maintenance program, particularly for a hazardous waste incineration facility. While alarm systems, spill-alert systems, and fail-safe devices are available, a testing program usually periodically creates situations which require fail-safe devices to demonstrate their operation. For instance, pressure testing of pipe, valves, and fittings along with hydrostatic testing of storage tanks will do this. Other tasks such as visual and electronic inspections will make up the remainder of a maintenance program and are included on prepared forms. These forms state the optimum timing for each inspection as well as the required frequency.

Incidences of excess emissions can be reduced by good operation and maintenance (O&M) practices and a comprehensive preventative maintenance program. With these practices, control equipment can provide maximum benefit.

While maintenance activities are not repetitive in the same manner as operating tasks, the maintenance function can be formalized. Available to facility management are maintenance management information systems, inventory and materials control systems, scheduling algorithms, work standards, indirect work measurement, and replacement theory.

A mechanism which is becoming more prevalent as equipment and technologies increase in sophistication is contract maintenance. Air pollution control equipment lends itself particularly well to this concept and appears attractive to new facilities which own several pieces of control equipment [40].

From the vendor's perspective, the advantages of providing a maintenance contract are:

(1) Close surveillance of the system's performance, especially during the warranty period.

(2) Immediate identification and troubleshooting of malfunctioning components.

(3) Avoidance of customer complaints.

(4) Operational experience that facilitates product improvement.

(5) Quick handling of emergency situations.

(6) A well functioning system that is the best recommendation for sales of additional systems.

From the user's point of view, the benefits of contract maintenance are:

(1) Plant personnel do not have to be thoroughly trained in equipment maintenance, thus allowing them to devote their time to process equipment.

(2) Technological troubleshooting and problem diagnosis are not usually in-house resources.

(3) Plant personnel do not necessarily have the knowledge to improve equipment performance.

(4) Plant personnel may lack awareness of alternative supplies and suppliers.

(5) Expenditures for larger crews, repair facilities, tools, and measurement instruments are reduced.

(6) Previous experience on similar equipment and applications can be used.

(7) Intrepretations of causes of component failure can be provided.

(8) Contract maintenance programs are more effectively regulated and administered than are in-house programs.

(9) Dirty and hazardous jobs do not have to be performed by plant personnal.

(10) Fluctuating workloads due to startup and seasonal variations can be handled easily.

An in-house regular maintenance/repairs program entails:

(1) Establishing a record system wherein periodic maintenance of each incinerator component is scheduled for completion by a qualified person.

(2) Cleaning, lubricating, and adjusting equipment by operating personnel as part of their daily or weekly task.

(3) Certifying that maintenance has been performed.

(4) Recording major repairs separately and completely.

(5) Thoroughly reporting each inspection, including condition of furnace, repairs performed, and expectation of future repairs or major overhaul.

(6) Inspecting components subject to rapid wear or damage weekly, at a time when such components are not being operated.

5.14.4 Firefighting/Emergency Personnel and Equipment

In addition to automatic sprinkler and extinguisher equipment, an incident confined to a limited area and that can be safely handled by a select emergency squad does not directly involve the overall emergency control program. If, however, such an incident should escalate beyond the capability of these forces, they have the authority to request the activation of the emergency program.

A fire emergency plan includes:

(1) An emergency squad composed of personnel from operations, maintenance, front office supervision, and guard force--specifically selected and trained in emergency control techniques and equipment.

(2) Emergency planning taking into account the plant's alarm system, communications, organization responsibilities, evacuation possibilites, available emergency equipment, mutual aid arrangements, and traffic control.

(3) Emergency crews engaged in continual training.

(4) Emergency squad members thoroughly trained in comprehensive first-aid treatment.

(5) Emergency squad members familiar with firefighting equipment.

The emergency squad composed of personnel from operations, maintenance, front office supervision, and guard force -- specifically selected, and trained in emergency control techniques and equipment. The exact number of employees on an emergency squad will vary depending on the potential hazard and size. Only if an emergency cannot be handled by this select squad, should the emergency control organization be activated.

Emergency planning also take into account the plant's alarm system, communica tions, organizational responsibilities, evacuation possibilities, available emergency equipment (and where it is located), dangers and emergency situations both inside and outside the plant (such as bomb threats), mutual-aid arrangements and traffic control. A manual containing the relevant information is prepared and distributed to those responsible for executing the plan. This is reviewed at least annually, and updated as needed.

Emergency crews must undergo continual training because the time available to respond to an actual emergency is usually quite limited. Furthermore, the infrequency of calls to action can, with time, erode the ability of crews to respond with the speed usually required. Crews are typically provided for all shifts, and be trained to handle all types of emergencies: fire, toxic-gas releases, chemical spills, serious injury, and personnel rescue.

Emergency-squad members are usually thoroughly trained in comprehensive first-aid treatment, including cardiopulmonary resuscitation, handling of breathing apparatus, and emergency rescue procedures, and are familiar with station and ambulance first-aid equipment. In addition, they learn the different types of fires, extinguishing agents, the proper protective clothing for firefighting, and become familiar with firefighting equipment, including hoses, nozzles, portable extinguishers, wheel units, fire trucks, and with the plant's fire-protection systems. Finally, field training in firefighting with protective clothing includes experience extinguishing "Christmas-tree," impingement, pan and spill, and other types of fires.

At a sprinklered property, the most important function of men assigned to the emergency organization is to assure at all times that the automatic sprinkler protection will operate as intended. At the start of the fire it must be made certain that sprinkler valves are open and fire pumps operating as needed; during the fire, that valves are not closed too soon; and after the fire, that opened sprinklers are replaced and protection restored promptly.

An emergency squad is designed to be capable of containing small fires, preventing them from developing into large, uncontrollable ones that can cause loss of life and property.

5.14.5   Stormwater Diversion

Stormwater drainage and other innocuous discharges are segregated and handled within the battery limits of the incinerator facility. These streams are normally collected and directed by pipe, drainage ditches, or area grading through one outlet from the area to a local feeder ditch. The single outlet or outfall also contain a spill control structure and gate which can be closed to contain contaminated drainage that may occur due to leaks or spills in the facility area. Feeder ditches generally border the plant sites along roadways and eventually drain outside the plant [41].

Facility process areas are usually paved and curbed or diked to contain leaks, spills, and washdowns, and these directed to a process sump area. The process sumps are pumped to the appropriate waste treatment facility.

Outlying facility storage tanks, pumps, and unloading facilities are curbed, diked, or paved for leak and spill control to prevent contamination of area drainage. The contained areas are then drained and valved to allow normal storm water drainage. These valves, which are normally closed, are opened for storm water drainage. In the event a contamination occurs, it is contained for subsequent treatment and appropriate disposal.

Other general features relative to plant drainage are:

(1) Valves used for the drainage of diked areas are normally manual, open-and-close design. The condition of the retained stormwater is determined before drainage, especially if such drainage of impounded waters goes into water courses and not into wastewater treatment plants.

(2) All plant drainage systems, if possible, flow into ponds, lagoons, or catchment basins designed to retain materials less dense than water. Consideration is also given to possible chemical reactions, if spilled chemicals are commingled.

(3) If plant drainage is not engineered as above, the final discharge of all in-plant drainage ditches is equipped with a diversion system that could, in the event of an uncontrolled spill, be returned to the plant for treatment, the objective being to work toward a closed-cycle system.

(4) Where drainage waters are chemically treated in more than one treatment unit, natural hydraulic flow is usually used. If pump transfer is needed, two pumps are typically provided, and at least one of the pumps is permanently installed.

5.15 TECHNICAL ASSISTANCE

Other books and manuals which have applicability to overall facility design, operation, and monitoring for hazardous waste incinerators are:

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CHAPTER 6

ESTIMATING INCINERATION COSTS

(This Chapter was Undergoing Revisions at the
Time of Publication of this Document. A Revised
Chapter 6 will be Available Upon request at a
Later Date.)

APPENDIX A

SUBJECT INDEX

APPENDIX A

SUBJECT INDEX[a]

Abrasion, 2.4.1.1
Absorption, 4.3.2
Acoustic analysis, 5.10.2
Activation energy, 4.2.3
Afterburner, 2.4.1, 4.2, 6.3.2.5
Air pollution
  emissions (see emissions)
  fugitive, 5.1.4.1-2
  monitoring, 5.3.2, 5.5-6, 6.2
Air pollution control device
  absorption (see absorption)
  applicability, 4.3.1
  baghouse (see baghouse)
  cost, 6 3
  cyclone (see cyclone)
  design, 4.3 2
  electrostatic precipitator
    (see electrosatic precipitator)
  evaluation, 5.3.1-3, 2.4
  scrubber (see scrubber)
Air requirements
  excess air, 4.2.3, 4.4
    (worksheets, 4-4, 4-7, 4-8)
  stoichiometric, 4.2.2, 4.4
    (worksheets, 4-1, 4-3)
Ash, 5.11.1.3 5 11 4
Atomization
  evaluation, 4.2.2
  general, 2.2.1
  rotary cup, 4 2.2
  single fluid, 4.2.2
  sonic, 4.2 2
  two fluid, high pressure air, 4.2.2
  two fluid, high pressure steam, 4.2.2
Auto ignition temperature, 5 2.2.3, 5.2 2.8
Automatic sprinkler system, 5.5.5.1
Baghouse monitoring, 5 7.2
Bibliography, Appendix D
Bonding, 5.3.3.2
Bottom ash, 5.7.23
Burner
  atomization (see atomization)
  evaluation, 4.2.2
  general design, 4.2.1
  placement, 4.2.1
  suspension, 4.2.1
Catalytic afterburner (see afterburner), 2.4.1
Chain of custody, 3.3
Co-incineration, 2.2.4.1, 2.2.5
Coding, pipe, 5.5.3 4
Combustor (see afterburner)
Compatibility matrix, 5.5.1

Construction materials (see corrosion), 5.13
Container (see storage)
Contract maintenance, 5.14.3
Control system, 5.6
Conversion tables, Appendix C
Conveyors
  mechanical, 5.3.5.1
  pneumatic, 5.3.5.2
Corrosion, 2.4.2.1, 4.3.6
Cost
  air pollution control device, 6.3
  capital, 6.2.1
  facility modification, 6.4
  operating, 6.2.2
  trial burn, 6.5
Current practices, 2.2, 2.3
Cyclone costs, 6.3.2.1, 5.7.4
Dichotomous sampler, 5.12.3.4
Differential absorption, 5.9.2.2
Dikes, 5.4.3.1
Dragertubes, 5.12.3.4
Duct design, 4.3.4
Dust tight, 5.5.63
Efficiency
  destruction and removal, 4.2.3, 4.3.1-2
  removal, 4.3.1-2
Effluent (see water pollution)
Electric heating cable, 5.5.3.4
Electrostatic precipitator
  cost, 6.3.2.4
  dry, 2.4.6
  dwell time, 5.7.3.4
  removal efficiency, 5.7.3.2
  step-up transformer, 5.7.3.3
  two stage, 2.4 6
  wet, 2.4.7
Emergency handbook, 5.2.2.3
Emergency squad, 5.14.4
Emission factor, Appendix G
Emissions
  air pollution, 4.2.2, 4.3.1, 4.4
    (worksheet 4-11)
  fugitive, 5.12
Evaluation
  air pollution control, 4.3
  incinerator, 4.2
  safety systems, 4.2.5, 4.3.5
Fan selection, 4.3.4
Feed systems
  batch feeding, 2.2.1.2
  charging doors, 2.2.5
  conveyor, 2.2.1.2

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[a] The references are to section numbers in the Handbook.

A-1

APPENDIX B

GLOSSARY OF TERMS

APPENDIX B

GLOSSARY

This appendix is a glossary of terms used throughout this Handbook.

activation energy: The quantity of heat needed to destabilize molecular bonds and form reactive intermediates so that the reaction will proceed

afterburner (or combustor): A pollution control device that uses combustion to reduce the emission levels of organic gaseous and particulate matter.

ambient concentration (ac): The appropriately time-averaged concentration of a substance at a location to which the general public has access.

analyzer: A device used to monitor emissions, such as: (1) a nondispersive infrared analyzer (monitors SO_2, NO_x, CO, CO_2, and other gases that absorb light in the infrared region of the spectrum, including hydrocarbons), (2) a nondispersive ultraviolet analyzer (monitors gases that absorb light in the ultraviolet and visible regions of the spectrum), (3) a polarographic analyzer (monitors SO_2, NO_2, CO, O_2, and H_2S), (4) an electrocatalytic oxygen analyzer, and (5) a paramagnetic oxygen analyzer.

angle of repose: The angle at which matter will lie or stack in a stationary configuration.

ANSI: American National Standards Institute.

APCD: Air pollution control device.

ash: The solid residue that remains after a material is incinerated. There are two types: (1) bottom ash remains in the combustion chamber after incineration, and (2) fly ash is entrained in exhaust gases leaving the incinerator.

ash fusion temperature (or melting temperature of ash): The temperature at which ash has the potential to melt.

ASME: American Society of Mechanical Engineers.

baghouse: An air pollution abatement device used to trap particulates by filtering gas streams through large fabric bags.

BaP: benzo(a)pyrene.

beta attenuation monitor: An instrument that measures the absorption of β-radiation as it traverses a small area onto which aerosol particles are collected by means of inertial impaction.

blowdown: The portion of scrubbing fluid that is purged in order to prevent buildup of dissolved solids.

BOD: Biological oxygen demand.

catalytic combustion: A type of combustion employing a catalyst bed.

coburning: The burning of waste and a fuel.

coincineration: The joint incineration of hazardous waste and refuse and/or sludge.

combustor (or afterburner): A pollution control device that uses combustion to reduce the emission levels of organic gaseous and particulate matter.

dedicated incinerator: A privately owned incinerator used to burn only the owner's wastes.

deflagration: The act of burning down very suddenly.

destruction and removal efficiency (DRE): This term is defined by the following equation:

$$DRE = \frac{W_{in} - W_{out}}{W_{in}} \times 100\%$$

where:

DRE = Destruction and removal efficiency
W_{in} = Mass feed rate of principal toxic organic component(s) in the waste stream feeding the incinerator (kg/min)
W_{out} = Mass emission rate of principal toxic organic component(s) present in exhaust emissions (kg/min).

destruction efficiency (DE): See destruction and removal efficiency.

dry sorption process: A process that involves contacting the gas stream with a solid phase that can remove one or more of the gaseous contaminants.

dwell time: See residence time.

effluent: A discharge of pollutants (either gases, liquids, or solids) into the environment.

electrostatically augmented scrubbers: Control devices that couple the mechanisms of electrostatic attraction and inertial separation by charging particles prior to entry into a wet collector.

electrostatic precipitator (ESP): An air pollution control device that removes particulate matter by imparting an electrical charge to particles in a gas stream, causing their collection on an electrode.

excess air: The air flow rate above that required to achieve theoretically complete combustion.

fabric filter: A device for removing dust and particulate matter from industrial emissions by filtration through cloth or other porous materials.

flash point: The lowest temperature at which a material will volatilize to yield sufficient vapor to form a flammable gaseous mixture with air.

flooding velocity: The gas velocity or narrow range of gas velocities in a packed bed or plate tower scrubber at which (for a given packing or plate design and liquid flow rate) the liquid flow down the column is impeded, and a liquid layer is formed at the tip of the column. Eventually, liquid is blown out the top of the column.

fluid: Any substance (for example, a liquid or slurry) that tends to flow or conform to the outline of its container.

fluidized bed incinerator: An incinerator consisting of a refractory-lined vessel containing inert granular material through which gases are blown at a rate sufficiently high to cause the bed to expand and act as a theoretical fluid. The gases are injected through nozzles that permit upward flow the bed but restrict downward flow of the material.

fugitive emissions: Pollutants arising from sources other than stacks and effluent pipes.

GC: Gas chromatograph

general purpose incinerator: An incinerator that burns miscellaneous types of wastes, usually from numerous sources and customers.

HCB: Hexachlorobenzene

heating value: The quantity of heat released when waste is burned, commonly expressed as Btu/lb. The higher heating value includes the heat of condensation of the water present in the waste and the heat formed in the combustion reaction; the lower heating value represents the heat formed in the combustion reaction; and the net heating value is the lower heating value minus the energy necessary to vaporize any moisture present.

heat of combustion: The heat evolved from the union of combustible elements with oxygen.

hygroscopicity: Act of attracting moisture from the air.

incinerator: An engineered apparatus used to burn waste substances in which all the combustion factors (temperature, retention time, turbulence, and combustion air) can be controlled.

incinerator, similar: Incinerator A is similar to incinerator B if, based on the best engineering judgement, while incinerating identical waste as incinerator B, the stream leaving the combustion chamber of incinerator A contains equal or lower amounts of each, but no additional, potentially hazardous components as the stream leaving the combustion chamber of incinerator B.

kinematic viscosity: The ratio of absolute viscosity to density.

liquid injection incinerator: An incinerator that uses an atomization device or nozzle to feed liquid waste.

mass spectrometer: An instrument that analyzes samples by sorting molecular or atomic ions according to their masses and electrical charges.

MEG: See multimedia environmental goals.

microwave plasma destruction (or plasma destruction): A method of destruction that uses microwave energy to excite the molecules of a carrier gas (such as helium or air), thus raising electron energy levels and forming highly reactive free radicals.

mist eliminator: A control device used to reduce emissions of liquid droplets, usually from scrubbers. There are three types: (1) cyclone mist eliminators (used to collect heavy liquid loadings), (2) fiber bed mist eliminators (used for collecting fine acid mists), and (3) wire mesh eliminators (used to collect other mists).

molten salt incinerator: An incinerator in which waste is injected below the surface of a molten salt bath.

multimedia environmental goals (MEG's): The levels of contaminants (in ambient air, water, or land, or in emissions or effluents conveyed to ambient media) that (1) will not produce negative effects in the surrounding populations or ecosystems, or (2) represent control limits demonstrated to be achievable through technology.

multiple chamber incinerator: An incinerator in which wastes are thermally decomposed in the presence of oxygen in the primary chamber, and decomposition products are oxidized in the secondary chamber(s).

multiple hearth incinerator: An incinerator containing multiple refractory-lined hearths, vertically aligned, designed for staged drying and combustion of wastes.

NFPA: National Fire Protection Association.

nitrogen oxides (NO_x): The collective term used for the gaseous oxides of nitrogen, primarily nitric oxide (NO) and nitrogen dioxide (NO_2).

NPDES: National pollutant discharge elimination system.

packed tower: An air pollution control device in which polluted air is forced upward through a tower packed with materials (such as raschig rings, ceramic saddles, tiles, marbles, crushed rock, or wood chips) while a liquid is sprayed downward on the packing material. The pollutants in the air stream either dissolve or chemically react with the liquid.

PAH: Polycyclic aromatic hydrocarbons

particulates: Minute solid or liquid particles in the air or in an emission. Particulates include dust, smoke, fumes, mist, spray and fog.

PCB: Polychlorinated biphenyls.

piezoelectric monitor: A type of particle monitor which measures mass concentration by utilization of a vibrating piezoelectric crystal driven by a standard oscillation circuit.

PNA: Polynuclear aromatic compounds.

POM: Polycyclic organic matter.

pyrolysis: The thermal decomposition of a compound in the absence of oxygen.

pyrophoric: Capable of igniting spontaneously.

quench: To cool rapidly.

removal efficiency: The ratio of the mass rate of flow of the contaminants going into a control device minus the mass rate of the contaminants going out of the control device to the mass rate of flow of the contaminants going into the control device.

residence time: The period of time that the waste is exposed to the reported temperature in the incinerator.

retention time: See residence time.

rotary kiln incinerator: An incinerator with a cylindrical, horizontal, refractory-lined shell that is mounted at a slight incline. Rotation of the shell causes mixing of the waste with the combustion air.

scrubber: An air pollution control device that uses a liquid to remove pollutants from a gas stream by absorption or chemical reaction. (Scrubbers also reduce the temperature of the emission.)

similar waste: Waste A is similar to waste B if, based on best engineering judgement, the incineration of waste A in the same facility and under the same operating conditions as those used for waste B would yield a stream leaving the combustion chamber that contains equal or lower amounts of each, (but no additional) potentially hazardous pollutants compared to the amounts yielded by waste B incineration.

sludge: A nonpumpable mixture of solids and liquids.

slurry: A pumpable mixture of solids and liquids.

solifluction: Liquid seepage.

SSU (standard saybolt universal): A unit for measuring kinematic viscosity.

starved air combustion (or thermal gasification): A process that utilizes equipment and process flows similar to those for incineration; but, in this process, uses less than the theoretical amount of air for complete combustion is supplied.

TCDD: Tetrachlorodibenzo-p-dioxin.

TDAS: Thermal decomposition analytical system.

TDD: Thermal decomposition device

TDI: Toluene diisocyanate.

temperature: A measure of the level of thermal energy in molecules to which a waste is exposed during the incineration process.

TLV (threshold limit value): Exposure levels representing conditions under which it is believed that nearly all workers may be repeatedly exposed day after day without adverse effects. For airborne substances, the exposure levels are stated as airborne concentrations and durations of exposure, including:

- Time-weighted average concentrations for a normal 8-hour workday or 40-hour workweek (threshold limit value - time-weighted average).
- Maximal concentrations to which workers can be exposed for a period up to 15 minutes (threshold limit value - short-term exposure limit).
- Concentrations that should not be exceeded even instantaneously (threshold limit value - ceiling).

These values are published annually by the American Conference of Governmental Industrial Hygienists.

TOD: Total oxygen demand.

trial burn: Any attempt to incinerate the waste in question for a limited period. A trial burn is designated to establish the conditions at which incineration of waste in a given facility must be carried out to assure protection to public health and environment.

trial burn proposal: A detailed plan which describes the procedure that will be used and the precautions that will be taken during a trial burn.

turndown ratio: Maximum to minimum operating range of a parameter.

UDRI: University of Dayton Research Institute.

viscosity: The property of a fluid or semifluid that enables it to develop and maintain an amount of shearing stress (dependent upon the velocity of flow) and then to offer continued resistance to flow.

volatile organic compounds: Organic compounds that are readily vaporized at a relatively low temperature.

WG: Water gage.

wet air oxidation: A process that operates on the principle that the rate of oxidation of organic compounds is increased at high pressures. By pressurizing an aqueous organic waste, heating it to an appropriate temperature, and then introducing atmospheric oxygen, liquid-phase oxidation reaction is produced, destroying most of the organics.

wet electrostatic precipitator (WEP): An electrostatic precipitator which achieves particle collection by the introduction of liquid droplets to the gas stream through sprayers located above the electrostatic field section of the precipitator.

wet scrubber: An air pollution control device used to remove pollution by bringing a polluted gas stream into contact with a liquid.

APPENDIX C

CONVERSION FACTORS

TABLE C-1. CONVERSION FACTORS

To convert from	To	Multiply by
acre	square kilometer (km^2)	0.00404047
	square meter (m^2)	4,046.86
	square mile (mi^2)	0 0015625
Btu (British thermal unit)	calorie (cal)	251.99576
	joule (J)	1,054.35
	kilocalorie (kcal)	0.251996
Btu/minute (Btu/min)	joule/second (J/s)	17.5725
Btu/pound (Btu/lb)	calorie/gram (cal/g)	0.555555
Btu/(pound·°F)[Btu/(lb·°F)]	calorie/(gram·°C) [cal/(g·°C)]	1.0
Btu/second (Btu/s)	Kilocalorie/hour (kcal/h)	970.185
	kilocalorie/minute	15.1197
calorie (cal)	Btu	0.0039683207
	kilocalorie (kcal)	0.001
	joule (J)	4.184
calorie/gram (cal/g)	Btu/pound (Btu/lb)	1.8
calorie/hour (cal/h)	Btu/hour (Btu/h)	0.0039683207
	erg/second (erg/s)	11,622.222
centigrade (°C)	Fahrenheit (°F)	°F = (1.8 x °C) +32
	Kelvin (°K)	°K = °C + 273.17
centimeter (cm)	inch (in.)	0.39370079
centipoise (cP)	gram/(centimeter·second) [g/(cm·s)]	0.01
centistokes (cSt)	saybolt seconds (SSU)	See Table C-2
cubic centimeter (cm^3)	cubic foot (ft^3)	3.5314667 x 10^{-5}
	cubic inch (in.^{3})	0.061023744
	cubic yard (yd^3)	1.3079506 x 10^{-6}
cubic foot (ft^3)	cubic centimeter (cm^3)	28,316.847
	cubic meter (m^3)	0.028316847
	gallon (U.S. liquid)	7 4805195
	liter (L)	28.316847
cubic meter (m^3)	cubic foot (ft^3)	35.314667
	cubic yard (yd^3)	1.3079506
	liter (L)	1,000
dyne/square centimeter (dyne/cm^2)	atmosphere (atm)	9.86923 x 10^{-7}
	bar	1 x 10^{6}
	centimeter of mercury @ 0°C (cm Hg @ 0°C)	7.50062 x 10^{-5}
	centimeter of water @ 4°C (cm H$_2$O @ 4°C)	0.00109745
	inch of mercury @ 32°F (in. Hg @ 32°F)	2.95300 x 10^{-5}
	inch of water @ 4°C (in. H$_2$O @ 4°C)	0.000401474
	pascal (Pa)	0.1
	pound/square inch (lb/in.^{2})	1.450377 x 10^{-5}
Fahrenheit (°F)	Centigrade (°C)	°C = 0.5556 (°F - 32°)
	Rankin (°R)	°R = °F + 459 7°
foot (ft)	centimeter (cm)	30.48
	inch (in.)	12
	meter (m)	0.3048
	millimeter (mm)	304.8

(continued)

C-1

TABLE C-1 (continued)

To convert from	To	Multiply by
gallon (U K liquid) [gal]	gallon (U S liquid) [gal] liter (L)	1.20095 0.00668932
gallon (U.S liquid) [gal]	cubic centimeter (cm^3) cubic foot (ft^3) cubic inch (in.^{3}) cubic meter (m^3) liter (L)	3,785.4118 0.133680555 231 0.0037854118 3.7854118
grains/standard cubic foot (gr/scf)	milligrams/standard cubic meter	2288.3
gram (g)	kilogram (kg) pound (lb)	0.001 0.0022046226
gram/(centimeter·second)	poise (P)	1
gram/cubic centimeter (g/cm^3)	grain/milliliter (gr/mL) gram/milliliter (g/mL) pound/cubic foot (lb/ft^3) pound/cubic inch (lb/in.^{3}) pound/gallon (U.S. liquid) (lb/gal)	15.43279 1 62.427961 0.036127292 8.3454044
gram/cubic meter (g/m^3)	grain/cubic foot (gr/ft^3)	0.43699572
gram/liter (g/L)	part/million (ppm) pound/cubic foot (lb/ft^3)	1,000 0.06242621
gram/milliliter (g/mL)	gram/cubic centimeter (g/cm^3) pound/cubic foot (lb/ft^3) pound/gallon (U.S.) (lb/gal)	1 62.4261 8.345171
inch of water @ 4°C (in. H$_2$O @ 4°C)	atmosphere (atm) inch of mercury @ 32°F (in. Hg @ 32°F) kilopascal (kPa) pascal (Pa) pound/square inch (psi)	0.0024582 0.0735539 249,082 249.082 0.03612628
joule (J)	Btu	0.000948451
joule/second (J/s)	Btu/minute (Btu/min) Btu/hour (Btu/h)	0.0569071 3.414426
kilocalorie (kcal)	Btu erg joule (J)	3 9683207 4.184 x 10^{1L} 4,184
kilogram (kg)	pound (avoirdupois) [lb (avdp)] ton (short, 2,000 lb mass)	2.2046226 0.0011023113
liter (L)	cubic foot (ft^3) quart (U.S. liquid) (qt)	0.035314667 1.0566882
meter (m)	foot (ft) inch (in.) mile (statute) (mi) millimicrons (mµ) yard (yd)	3.2808399 39.370079 0.00062137119 1 x 10^9 1.0936133
pascal (Pa)	atmosphere (standard) (atm) dyne/square centimeter (dyne/cm^2) inch of water @ 39.2°F (in. H$_2$O @ 39.2°F) inch of water @ 60°F (in. H$_2$O @ 60°F) pound-force/square inch (lb-force/in.^{2}) (psi)	9.869233 x 10^{-6} 10 0.004014742 0.004018647 0.0001450377

(continued)

TABLE C-1 (continued)

To convert from	To	Multiply by
pascal·seconds (Pa·s)	Poise	10.00
poise (P)	centipose (cP)	100.00
	dyne·second/square centimeter	1
	gram/(centimeter·second) [g/(cm·s)]	1
	pound/(second·foot) [lb/s·ft]	0.0672
pound (lb)	gram (g)	953.59237
pound/(foot·second) [lb/(ft·s)]	poise (P)	14.88
pound/cubic foot (lb/ft^3)	gram/cubic centimeter (g/cm^3)	0.016018463
	kilogram/cubic meter (kg/m^3)	16.018463
pound/cubic inch (lb/in ^{3})	gram/cubic centimeter (g/cm^3)	27.679905
	gram/liter (g/L)	27.68068
	kilogram/cubic meter (kg/m^3)	27,679.905
pound/gallon (U.K. liquid) [lb/gal]	pound/cubic foot (lb/ft^3)	6.228839
pound/gallon (U.S liquid) [lb/gal]	gram/cubic centimeter (g/cm^3)	0.11982643
	pound/cubic foot (lb/ft^3)	7.4805195
pound/square inch (psi)	atmosphere (atm)	0.0680460
saybolt seconds (SSU)	centistokes (cSt)	see Table C-2
square foot (ft^2)	acre	2.295684 x 10 ^{5}
	square centimeter (cm^2)	929.0304
	square inch (in.^{2})	144
	square meter (m^2)	0.09290304
square kilometer (km^2)	acre	247.10538
	square meter (m^2)	1,000,000
	square mile (mi^2)	0.38610216
square meter (m^2)	acre	0.00024710538
	square foot (ft^2)	10.763910
	square kilometer (km^2)	0 000001
stoke (St)	centistoke (cSt)	1 x 10^2
	saybolt seconds (SSU)	See Table C-2
	square centimeter/second (cm^2/s)	1
	square foot/hour (ft^2/h)	3.875
	square foot/second (ft^2/s)	0 001076
ton (metric)	kilogram (kg)	1000.
	ton (short, 2,000 lb mass)	1.1023113

TABLE C-2. KINEMATIC VISCOSITY CONVERSION FACTORS
FOR CENTISTOKES TO SSU UNITS[a]

Centi-stokes	Saybolt seconds at (SSU)			Centi-stokes	Saybolt seconds at (SSU)		
	100°F	130°F	210°F		100°F	130°F	210°F
2.0	32.6	32.7	32.8	28.0	132.1	132.4	133.0
3.0	36.0	36.1	36.3	30.0	140.9	141.2	141.9
4.0	39.1	39.2	30.4	32.0	149.7	150.0	150.8
5.0	42.3	42.4	42.6	34.0	158.7	159.0	159.8
6.0	45.5	45.6	45.8	36.0	167.7	168.0	168.9
7.0	48.7	48.8	49.0	38.0	176.7	177.0	177.9
8.0	52.0	52.1	52.4	40.0	185.7	186.0	187.0
9.0	55.4	55.5	55.8	42.0	194.7	195.1	196.1
10.0	58.8	58.9	59.2	44.0	203.8	204.2	205.2
11.0	62.3	62.4	62.7	46.0	213.0	213.4	214.5
12.0	65.9	66.0	66.4	48.0	222.2	222.6	223.8
14.0	73.4	73.5	73.9	50.0	231.4	231.8	233.0
16.0	81.1	81.3	81.7	60.0	277.4	277.9	279.3
18.0	89.2	89.4	89.8	70.0	323.4	324.0	325.7
20.0	97.5	97.7	98.2	80.0	369.6	370.3	372.2
22.0	106.0	106.2	106.7	90.0	415.8	416.6	418.7
24.0	114.6	114.8	115.4	100.0	462.0	462.9	465.2
26.0	123.3	123.5	124.2				

[a]For kinematic viscosity levels above 100 centistokes, use the
same ratio as the ratio in the table above for 100 centistokes
(at the temperature of the fluid); e.g., 120 centistokes
(@ 130°F) = 120 x 4.629 = 555.5.

To obtain the saybolt universal viscosity at a temperature not
shown in te table above, multiply the saybolt universal viscosity
@ 100°F by [1 + (t - 100) 0.000064], where "t" is the temperature
in degrees farhenheit, e.g., 10 centistokes @ 220°F = 58.8 x
[1 + (220-100) 0.000064]; = 58.8 x 1.00768 = 59.25

APPENDIX D

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APPENDIX E

LABORATORY-SCALE THERMAL DECOMPOSITION ANALYTICAL DATA

CONTENTS

APPENDIX E

LABORATORY-SCALE THERMAL DECOMPOSITION ANALYTICAL DATA

1. INTRODUCTION

Laboratory-scale thermal decomposition data for hazardous wastes may be help-
ful in screening incinerator permit conditions, in establishing sampling and
analytical protocols for incinerator performance monitoring, and in determining
potential operating conditions for incinerator trial burns. Such data may be
developed using laboratory-scale thermal decomposition systems such as the
Thermal Decomposition Analytical System (TDAS) employed at the U.S Environmental
Protection Agency research program at the University of Dayton Research
Institute (UDRI). The EPA intends to develop these data for a broad range of
hazardous wastes and substances over the next 3 years. The objective of this
appendix is to describe how the data are collected, to provide guidance on
their use, and to provide a repository for data as these are generated
during this period.

2. THERMAL DECOMPOSITION ANALYTICAL SYSTEM (TDAS)

2.1 General Description

This system is designed to evaluate the thermochemical behavior of volatile
materials under controlled conditions. As indicated in Figure E-1, it consists
of a modular control panel (where the operating parameters for tests are
established), several gas cylinders (that supply reaction atmospheres with
known compositions), a sample insertion and vaporization chamber, a special
quartz tube reactor in a furnace (for the decomposition of samples), a product
collection trap, a gas chromatograph, a mass spectrometer, and a minicomputer.
Figure E-2 is a block diagram showing a simplified representation of the
operational relationships of the various components.

2.2 Operation

In operation, several micrograms of a solid sample (or several microliters of
a liquid or gaseous sample) are introduced into a sample insertion chamber
(location K in Figure E-1). The chamber is then sealed and flushed with the
controlled atmosphere to be used for the experiment. Solid and liquid samples
are heated, vaporized at temperatures up to 300°C (over a controlled time
interval), and mixed with a continuous stream of the reaction atmosphere.
Samples may be flash pyrolyzed or gradually vaporized, depending on the desired
reaction conditions. The mixture then passes through a reactor (location M)
consisting of an 98-cm long, 0.097-mm inside diameter, thin walled, helical
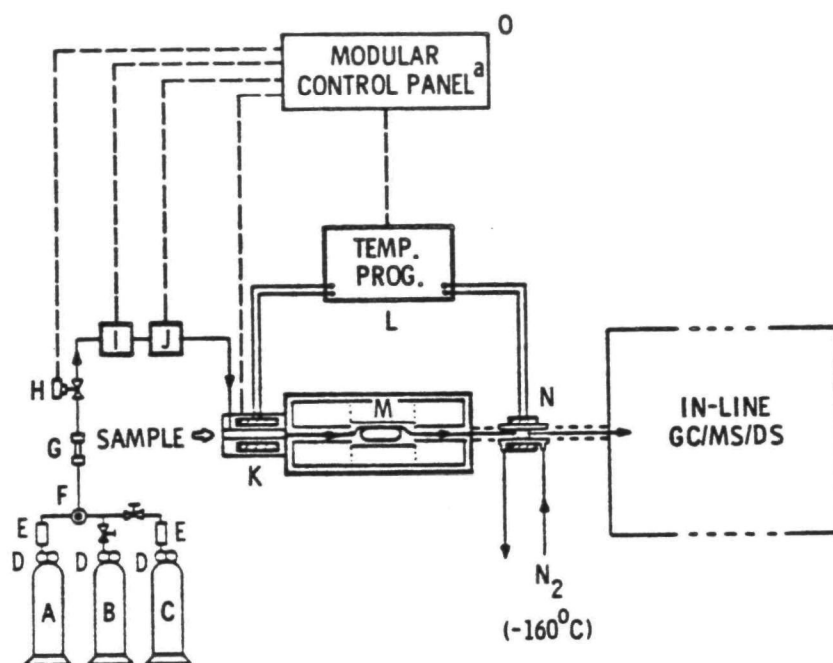
A	HELIUM GAS	I	FLOW TRANSDUCER
B	COMPRESSED AIR	J	PRESSURE TRANSDUCER
C	INERT CARRIETR	K	INSERTION CHAMBER
D	PRESSURE REGUALTOR	L	TEMPERATURE PROGRAMMER
E	OXYGEN SCRUBBER	M	REACTOR IN FURNACE
F	DIRECTIONAL VALVE	N	PRODUCT COLLECTION TRAP
G	FILTER	O	MODULAR CONTROL PANEL
H	FLOW CONTROL VALVE		

[a] THE MODULAR CONTROL PANEL DID NOT APPEAR IN THE ORIGINAL PUBLICATION

Figure E-1. Simplified schematic of TDAS [1].

HIGH TEMPERATURE
TRANSFER

| CAPTURE OF EFFLUENT PRODUCTS | CONTROLLED HIGH TEMPERATURE EXPOSURE | SAMPLE INSERTION AND VAPORIZATION | PRESSURE AND FLOW REGULATION | COMPRESSED GAS AND PURIFICATION |

IN LINE
GAS CHROMATOGRAPH
(HIGH RESOLUTION)

COUPLED
MASS SPECTROMETER
(MAGNETIC)

COMPUTER SYSTEM

NIH/EPA
CHEMICAL INFORMATION
SYSTEM

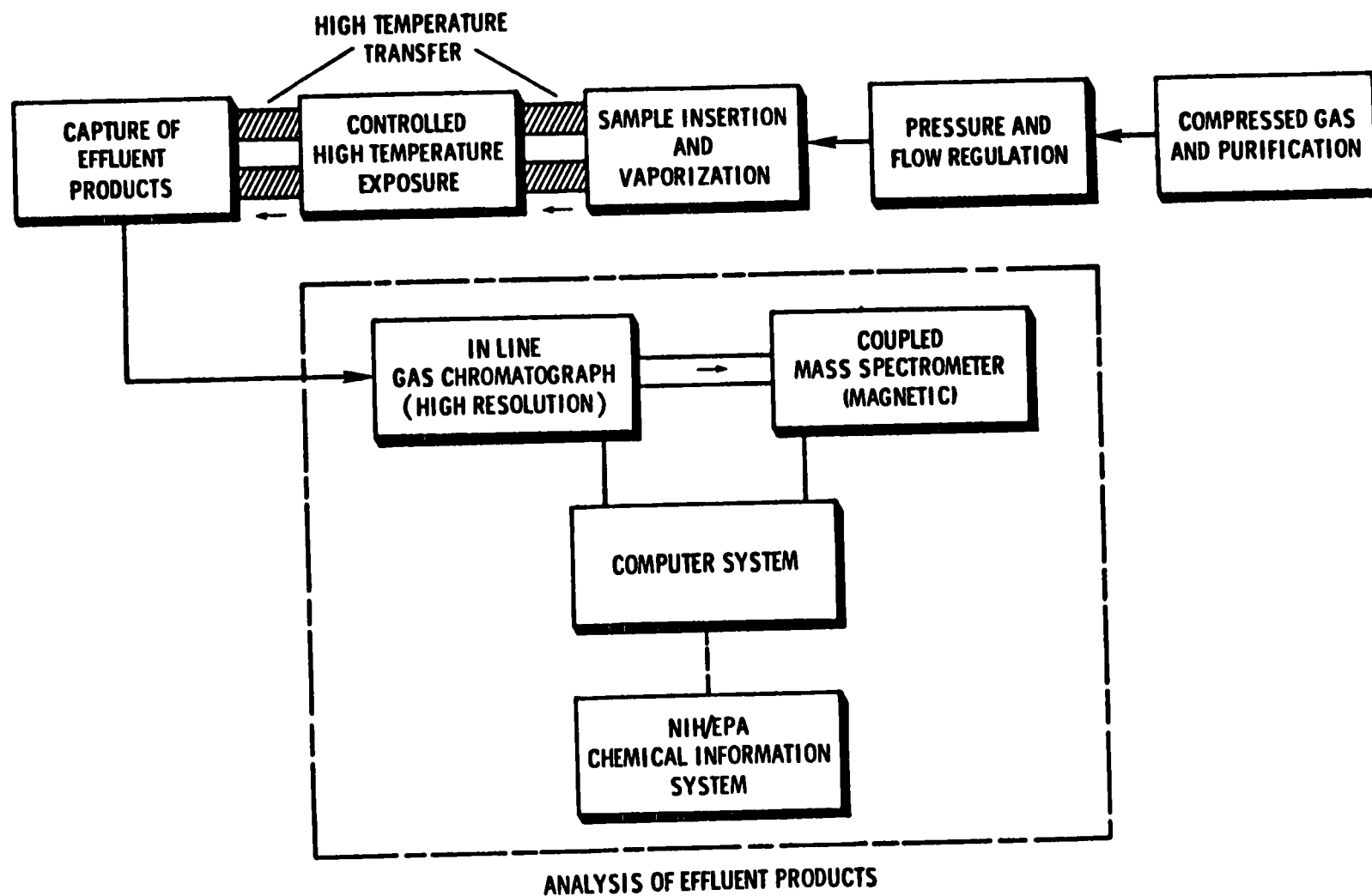ANALYSIS OF EFFLUENT PRODUCTS

Figure E-2. Block diagram of TDAS [1]

quartz tube enclosed in an electric furnace. The furnace and tube can be operated at temperatures up to 1,150°C (±2°). The temperature of the reactor is monitored by a thermocouple located at a point representing the mean temperature for the reactor furnace [1].

It is estimated that a typical reaction mixture entering the TDAS reactor heats to the reactor temperature within 0.005 seconds. Ninety five percent of the molecules are estimated to be exposed to the reported temperature over time intervals with a maximum deviation of 4% to 10% from the reported mean residence time, depending on the conditions of the test (personal communication with Don Duvall, August, 1980). The percent deviation increases as the mean residence time decreases. The temperature is controlled to within ±2°C across the operating range of the device. Mean residence times between 0.25 and 5.0 seconds may be selected [1]. It is possible to operate the reactor at pressures up to two atmospheres.

The effluent from the TDAS reactor enters a sorbent trap (Location N) that can be maintained at -110°C. In the trap, reactions are quenched and reaction products and unreacted sample are collected with a sorbent (usually Tenax, although other materials, such as quartz wool, have also been used). The chemicals collected are then thermally desorbed directly into a capillary column gas chromatograph/mass spectrometer for identification and quantification of reaction products and unreacted sample.

The chromatograph has been used with glass and fused silica capillaries coated with selected materials (such as a 0.1-μm layer of Supelco SP 2100) [4]. The mass spectrometer contains a total ion detector upstream of the magnetic sector. This detector may be calibrated and used to measure quantities of pure substances leaving the gas chromatograph at different times. A photomultiplier tube downstream of the magnetic sector of the mass spectrometer responds to the ionic fragments of molecules emerging from the magnetic field. The identity of chemicals and mixtures of chemicals emerging from the gas chromatograph can be determined by comparing observed ion fragment patterns with those of known compounds. The NIH/EPA Chemical Information Mass Spectral Data Base is routinely used to help identify compounds and mixtures. Software is being installed to make it possible to measure the amounts of individual chemicals in mixtures entering the mass spectrometer from ion fragment data.

Samples of effluent from the reactor may be collected on activated carbon (or other sorbents) simultaneously with the samples collected in the cold sorbent trap described above. These samples could be desorbed with solvents and injected into laboratory gas chromatographs or other analytical devices not directly connected to the TDAS.

3. THERMAL DECOMPOSITION DEVICE (TDD)

3.1. General Description

Figure E-3 is a schematic diagram of the thermal decomposition device (TDD). It consists of a compressed air cylinder (to supply the reaction atmosphere), pressure regulators, flow regulators (to adjust the residence time), a sample insertion and vaporization chamber, a quartz reactor in an electrically heated
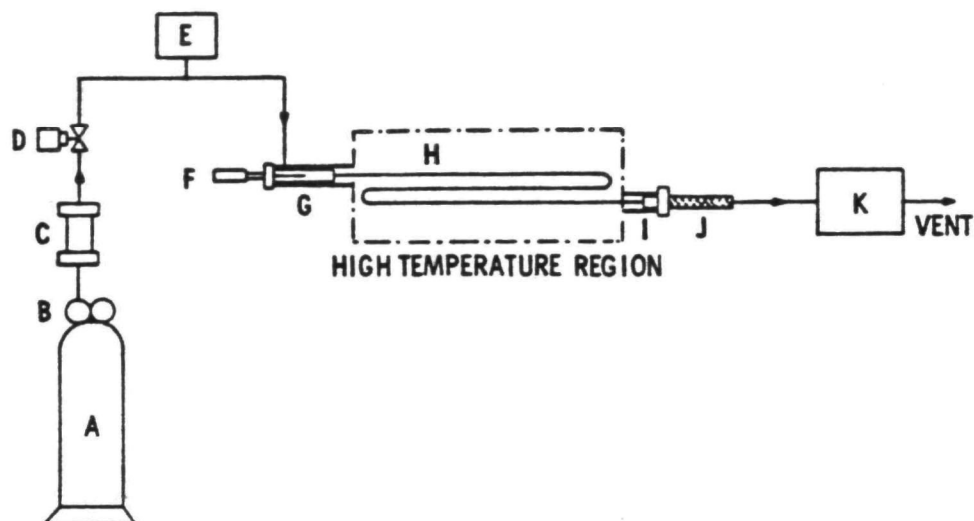
A COMPRESSED AIR, BREATHING QUALITY GRADE

B TWO STAGE PRESSURE REGULATOR

C "HYDROPURGE" FILTER

D FLOW CONTROL VALVE

E PRESSURE TRANSDUCER

F SAMPLE HOLDER, PYREX

G HEATED INLET CHAMBER

H QUARTZ TUBE

I HEATED OUTELET CHAMBER

J EFFLUENT TRAP, TENAX-GC OR CHARCOAL

K FLOW METER

Figure E-3. Schematic of thermal decomposition device [3].

furnace (for the decomposition of samples), a product collection trap, and a flow meter. This device is the predecessor to the TDAS, and is no longer in use.

3.2 Operation

The TDD was operated in the following manner. Compressed air was filtered (see location C in Figure E-3) and its flow rate adjusted (location D) to provide the desired residence time. The gas entered the inlet chamber (location G) which surrounds a sample holder containing several micrograms of sample (location F). The chamber was gradually heated to a maximum temperature of about 300°C to vaporize the sample [3]. As material from the sample vaporized, it was swept into the reactor chamber (location H) by the compressed air flow. In the reactor chamber, the reaction mixture was thermally stressed at a controlled temperature (up to 1,000°C). An 84-cm by 0.8-mm ID quartz reaction chamber and an 84-cm by 2.14-mm ID quartz reaction chamber were available. The average temperature of the reactor furnace was controlled to ±5°C; but there were temperature gradients in the furnace of ±25°C, compared to the reported average temperature (personal communication with Wayne Rubey, University of Dayton Research Institute, Dayton, Ohio, 8 August 1980). In most experiments, the residence times in the reactor were approximately one second (±0.04 s); but residence times between 0.5 s and 3.0 s were possible [3].

After the mixture passed through the reactor, it was cooled to approximately 300°C [3]. The partially cooled mixture then entered the effluent trap (location J), where it rapidly cooled to ambient temperatures. The effluent trap and sorbent (Tenax GC or charcoal) collected unreacted sample and the products of decomposition of the waste. The sorbents used were generally suitable for materials with molecular weights at or above 78 at room temperature (personal communication with Wayne Rubey, 8 August 1980).

At the end of a run, the effluent trap was removed from the TDD. If Tenax was the sorbent, the trap was inserted directly into an adapter on a separate laboratory gas chromatograph (GC). The trap was then heated to desorb the products, which were flushed into the GC by a carrier gas. If activated carbon was used as the sorbent, the products had to be desorbed with a suitable solvent. A sample of the solvent/product mix was then injected directly into the GC for analysis.

4. DIFFERENCES BETWEEN THE TDAS AND TDD

Both of these devices were designed for the purpose of studying the thermal chemical decomposition of various materials, and their basic designs and methods of operation are quite similar. However, there are differences in several important specifications (see Table E-1).

5. DIFFERENCES BETWEEN INCINERATORS AND LABORATORY DEVICES

While the results obtained with the previously described laboratory devices may resemble the performance of an incinerator that vaporizes materials before introducing them into a well mixed combustion zone with high levels of excess oxygen, highly controlled retention times, and highly controlled uniform temperatures, there are differences. Detailed quantitative comparisons have not been reported.

TABLE E-1. DIFFERENCES BETWEEN THE TDD AND TDAS

Parameter	TDD [3]	TDAS [1]
Sample type	Liquid or soluble solids, low volatility only (MW≥ ~78)	Gas, liquid or solid samples (MW< ~800)
Reactor construction	Heavy-wall folded quartz 840-cm X 0.8-mm ID (an 84.0-cm X 2.14-mm tube was also available)	Thin-wall helical quartz (98 cm X 0.97 mm ID)
Regulation of mean reactor temperature	±5°C	±2°C
Maximum operating temperatures	1,000°C[a]	1,150°C[b]
Range of temperatures in reactor	±25°C[c]	±2°C
Residence time range	0.5 - 3.0 s[c]	0.25 - 5.0 s
Effluent traps	Ambient temperature trap	Cryogenically cooled trap
Sampling and analysis	Sample must be manually removed from unit for analysis on a nearby GC	Sample normally thermally desorbed in-situ and carried directly to GC/MS by the carrier gas.

[a]Limited by the heating unit.

[b]Limited by the properties of quartz.

[c]Personal communication with Wayne Rubey, 8 August 1980.

The operating conditions in most incinerators are not as simple as those in the laboratory devices. Among the potential complications associated with real incinerators (compared to the TDAS and TDD systems) are the following:

- Wastes may enter the combustion chamber of an incinerator as liquids or solids, while only gases enter the reaction zones in the TDAS and TDD.

- Direct combustion of fuel and/or waste supplies the heat required for the reactions in incinerators, and the waste in an incinerator may pass directly through a distinct flame or flame front. The TDAS and TDD are indirectly heated.

- There may be a significant lack of homogeneity in the temperature profiles of incinerators, and the temperature may not be as closely controlled as in the laboratory devices. Furthermore, the maximum temperature in an incinerator may be higher than the highest temperature at which laboratory devices can be operated.

- The residence times reported for incinerators may not really represent the exposure times of wastes at the reported operating temperatures. An upper bound residence time is the only valve reported for some incinerators. This represents the total volume of the incinerator combustion chamber (whether or not it is all at the reported temperature) divided by the volume rate of flow of flue gas out of the chamber. The mean residence times in the laboratory devices are well controlled and represent true residence times at the reported temperatures with a degree of accuracy seldom achieved for incinerators.

- Physical and chemical interactions between components of mixtures of wastes and reaction products (such as adsorption on particulates and catalysis) might inhibit or accelerate the rate of waste decomposition and combustion product formation. Furthermore, interaction of the combustion products with the walls of the incinerator might affect the degree of combustion and the products. Some of these effects cannot be studied in the TDAS and TDD laboratory units, since solids and liquids cannot enter the reaction chambers of those devices.

- Mixing in an incinerator will be different from mixing in laboratory devices, resulting in changes in the relative proportions of uncombusted, partially combusted, and completely combusted waste.

- In an incinerator, the conditions to which various molecules are exposed can vary greatly in terms of temperature, oxygen concentration, and concentrations of free radicals. These variables can be too complicated to simulate in the laboratory units.

- The laboratory devices were usually operated in such a manner that the amounts of oxygen leaving the reactors were not significantly different from the amounts going into the reactors. Furthermore, many experiments were performed with 21% oxygen. Incinerator flue gas often contains much less oxygen.

- The feed rate of incinerators may be constant, allowing steady state conditions to occur. The laboratory devices are batch fed.

6. COMPARISON OF KEPONE DECOMPOSITION IN THE TDD TO DECOMPOSITION IN A PILOT-SCALE INCINERATOR

In a series of pilot-scale test burns of Kepone, an afterburner was reported to have a Kepone destruction and removal efficiency of 99.98%[a] at 1,093°C to 1,260°C and residence times between 2.15 and 2.44 seconds. There was 3.0% to 4.8% excess oxygen in the flue gas [5]. A 99.999655% destruction and removal efficiency was calculated for the thermal decomposition device at 900°C, a residence time of about 1 second, and 21% oxygen. According to these calculations, the pilot incinerator emitted 58 times as much Kepone per gram burned as the laboratory device, even when operated at a higher temperature and residence time than the laboratory device (but with less excess oxygen). This illustrates the uncertainty that can occur when comparing laboratory device results to pilot burn results.

No data were reported on emissions of products of pyrolysis and incomplete combustion in the pilot-scale test burn. As a result, the utility of TDD data for identifying significant byproducts of Kepone incineration could not be verified.

7. POSSIBLE APPLICATIONS OF LABORATORY EXPERIMENTS

No systematic studies of the performance of the TDAS or TDD compared to incinerators of different sizes, designs, and operating conditions have been reported. Furthermore, no systematic studies of the quantitative limitations of scaleup factors are available. As a result, great caution must be exercised when using data from the laboratory device, since the applicability of the data has not been demonstrated. However, some potential uses for laboratory experiments exist:

- The TDAS and TDD devices have been used to aid in identifying byproducts of decomposition of hazardous materials and the conditions under which they are formed.

- It may be possible for experienced combustion chemists to obtain some evidence that will aid in understanding the detailed operating conditions within an incinerator by comparing the results of laboratory decomposition experiments to the results of full-scale test burn experiments under similar conditions.

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[a]The pilot burn results were based on sampling flue gas downstream of a quench and a scrubber and sampling quench and scrubber water, rather than sampling flue gas before the quench and scrubber. The accuracy of these results is unknown. For more details see Reference 5.

- Data from the laboratory devices may have some value for checking the accuracy of various theoretical thermochemical modeling techniques used to predict the behavior of full scale incinerators. Such data may also be compiled and used to develop empirical modeling techniques.

- Data from the device might be used to help determine research priorities for hazardous waste incineration (when better data are unavailable) by considering the types, amounts, and potencies of the reaction products observed. Various risk assessment and prioritization models may be used for this purpose.

- Data from laboratory waste decomposition experiments may be of some value for helping to determine operating conditions at the beginning of trial burns. Temperature, retention time, turbulence, and excess air levels at the beginning of trial burns should be far enough above those associated with unacceptable emissions (based on laboratory data) to give a reasonable confidence of having acceptable emissions. Unfortunately, the margins of safety for this purpose have not been systematically studied.

- Data from laboratory tests might be used to help determine what to monitor at trial burns and at full-scale industrial installations.

Unfortunately, the limitations of using the data from the laboratory devices for the above purposes have not been demonstrated. Additional tests will have to be performed under conditions that more nearly approximate those in an operating incinerator, if scaleup factors are to be systematically studied. Without such studies, any scaleup based on the data from laboratory experiments alone will only result in an educated guess, of unknown accuracy.

Figure E-4 shows the effects of oxygen concentrations on the thermal decomposition of a PCB in the thermal decomposition device. The high sensitivity to oxygen is clearly shown. This suggests that operating laboratory devices (or modifying them to operate) with amounts of excess air similar to those found in an incinerator may significantly improve the utility of the data generated. If the percent oxygen used in a laboratory experiment is equivalent to the percent oxygen in incinerator flue gas, the probability of a laboratory experiment yielding a lower destruction and removal efficiency than in an incinerator will be increased (compared to when it is operated at 21% oxygen). This may increase the utility of laboratory data for quickly making conservative estimates of acceptable operating conditions at the beginning of trial burns.
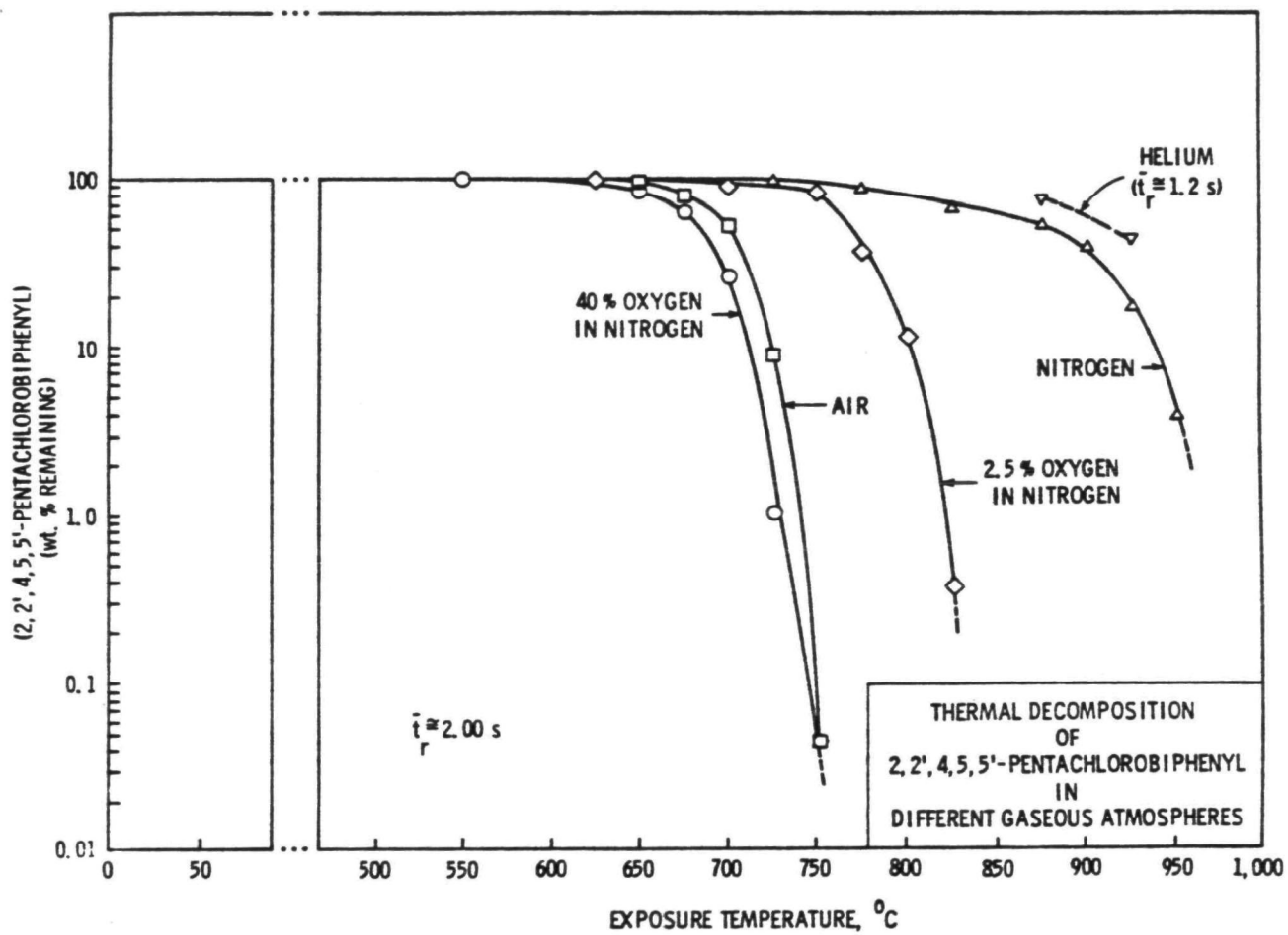
Figure E-4.   Effect of oxygen concentration [2].

8. RESULTS OF LABORATORY-SCALE DECOMPOSITION EXPERIMENTS

8.1 Kepone Results

Kepone decomposition experiments were performed in the thermal decomposition device. As can be seen from Table E-2, the destruction of Kepone increases with increasing temperature (at a relatively constant retention time). It is also apparent that there are several byproducts: hexachlorobenzene, hexachlorocyclopentadiene [3] and hexachloroindenone (the latter was identified in a personal communication with Don Duvall and Wayne Rubey, at the University of Dayton Research Institute in Dayton, Ohio on 4 August 1980). The amounts of byproducts formed are dependent upon the reactor temperature. This information is graphically represented in Figure E-5.

8.2 Method of Data Analysis

The Kepone destruction and removal efficiency was usually calculated based on changes in the response of a hydrogen flame ionization detector to Kepone. Hydrogen flame ionization detectors and associated electronics usually respond linearly to concentrations. The destruction and removal efficiency was calculated using the responses of the detector to samples collected in the trap with and without thermal stressing in the reactor, assuming linearity of response. The assumption of linearity of response was not verified experimentally.

TABLE E-2. KEPONE THERMAL DESTRUCTION SUMMARY [1[a]]

Waste: kepone; sample size: 40 µg;
laboratory device: thermal decomposition device.

Unit temperature, °C	Input atmosphere	Retention time, s	Destruction and removal efficiency, %	Byproducts identified[b]	Relative quantity of byproducts[c]
302	Air, 21% O_2	0.93	0	None	None
397	Air, 21% O_2	0.99	12	Hexachlorocyclopentadiene	0.05
				Hexachloroindenone[a]	0.05
435	Air, 21% O_2	0.94	48	Hexachlorocyclopentadiene	0.5
				Hexachloroindenone	0.75
463	Air, 21% O_2	0.93	96	Hexachlorocyclopentadiene	0.85
				Hexachloroindenone	0.65
495	Air, 21% O_2	1.10	≥99.55	Hexachlorocyclopentadiene	0.65
				Hexachloroindenone	1.2
				Hexachlorobenzene	-[d]
603	Air, 21% O_2	0.99	≥99.55	Hexachlorobenzene	0.04
				Hexachloroindenone	1.75
				Hexachlorocyclopentadiene	0.05
708	Air, 21% O_2	0.91	≥99.55	Hexachlorobenzene	1.10
				Hexachloroindenone	0.05
807	Air, 21% O_2	0.92	≥99.55	Hexachlorobenzene[e]	0.45
910	Air, 21% O_2	0.94	≥99.999655[e]	Hexachlorobenzene[e]	0.15
433	Air, 21% O_2	0.23	6	Not reported	NA[f]
433	Air, 21% O_2	1.04	53	Not reported	NA
433	Air, 21% O_2	1.79	68	Not reported	NA

[a] Hexachloroindenone identified in a personal communication with Don Duvall and Wayne Rubey, University of Dayton Research Institute, Dayton, Ohio, 4 August 1980.

[b] Byproducts collected on Tenax GC and detected in quantifiable amounts unless otherwise specified.

[c] Reported as relative peak heights on a flame ionization detector.

[d] Detected, but below measureable levels.

[e] Collected on activated carbon, desorbed with mixed solvent (Acetone, Benzene, CS_2) and quantified with an electron capture detector (residual kepone 138 pg; hexachlorobenzene ~200 mg).
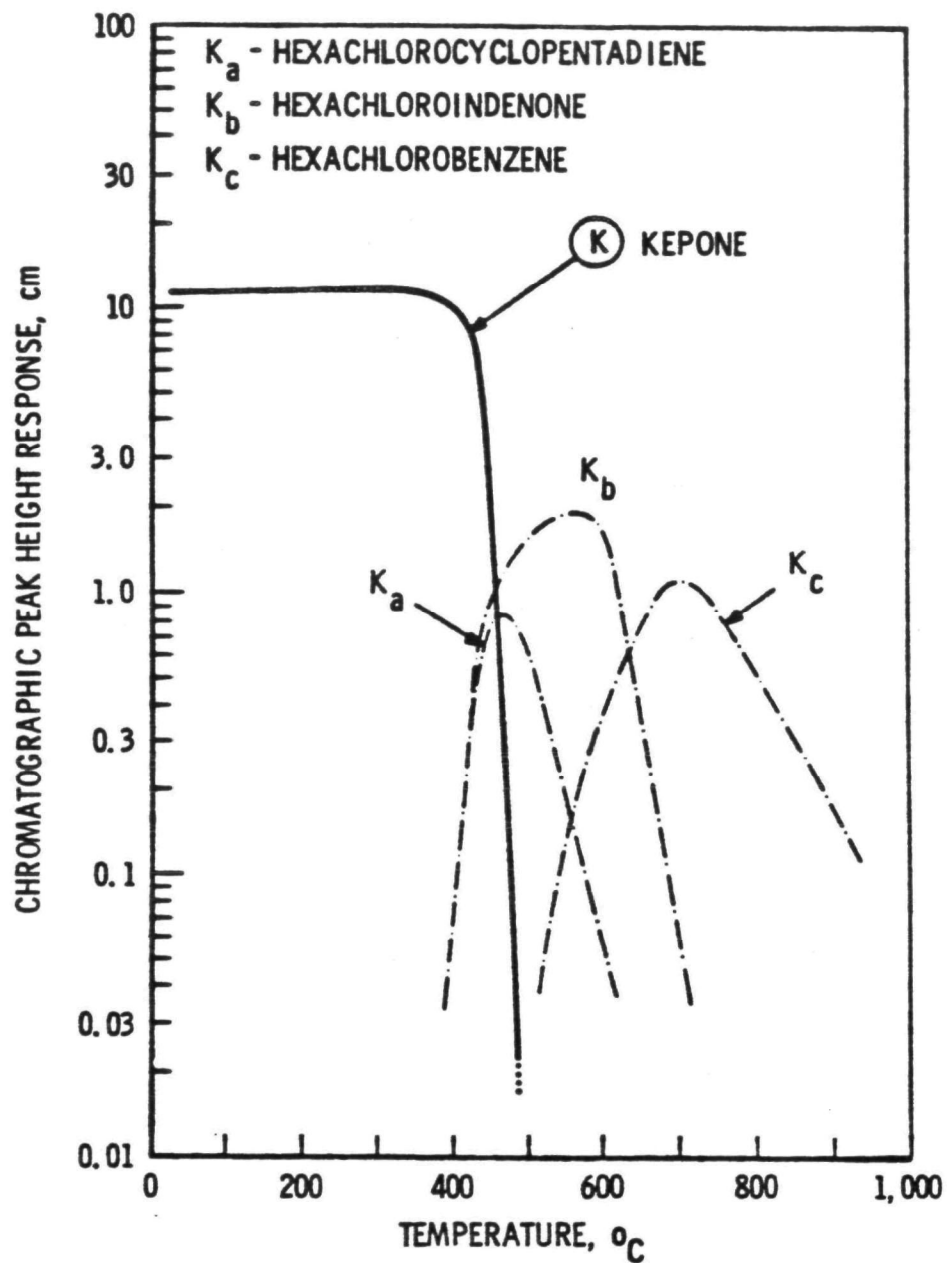
[f] Not applicable.

Figure E-5. Thermal destruction plot for Kepone [3].

[a]Hexachloroindenone identified in a personal communication with Don Duvall and
Wayne Rubey, University of Dayton Research Institute, Dayton, Ohio,
August 4, 1980.

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APPENDIX F

TRIAL BURN SUMMARIES

TABLE F-1. SUMMARY OF INCINERATOR DESTRUCTION EFFICIENCY TEST WORK

Waste	Incinerator	Performing organization	Destruction efficiency (DE)[a] of principle components, percent	
Shell aldrin (20% granules) [1]	Multiple chamber	Midwest Research	Aldrin	>99.99
			Total species	>99.99
Shell aldrite [1]	Multiple chamber	Midwest Research	Aldrin	>99.99
			Total species	>99.99
Atrazine - liquid [1]	Multiple chamber	Midwest Research	Atrazine	>99.99
			Total species	>99.99
Atrazine - solid [1]	Multiple chamber	Midwest Research	Atrazine	>99.99
			Total species	>99.99
Para-arsanilic acid [2]	Molten salt combustion	Rockwell International		>99.999
Captan - solid [1]	Multiple chamber	Midwest Research	Captan	>99.99
			Total species	>99.99
Chlordane 5% dust [3]	Liquid injection	TRW	Chlordane	>99.99
Chlordane, 72% emulsifiable concentrate and No. 2 fuel oil [3]	Liquid injection	TRW	Chlordane	>99.999
Chlorinated hydrocarbons, trichloropropane, trichloroethane, and dichloroethane predominating [12]	Two high temperature incinerators	M/T Vulcanus Ocean Combustion Services	Chlorinated hydrocarbons	99.92 - 99.98
Chloroform [2]	Molten salt combustion	Rockwell International	Chloroform	>99.999
DDT 5% oil solution [1]	Liquid injection	TRW	DDT	>99.99
DDT (solid) [14]	Municipal multiple hearth sewage sludge incinerator	City of Palo Alto	DDT	>99.970 - 99.983
DDT, 10% dust [1]	Multiple chamber	Midwest Research	DDT	>99.99
			Total species	>99.99

(continued)

F-1

Waste	Incinerator	Performing organization	Destruction efficiency (DE)[a] of principle components, percent	
20% DDT oil solution [3]	Liquid injection	TRW	DDT	>99.98
DDT 25% emulsifiable concentrate [3]	Liquid injection	TRW	DDT	>99.99
DDT 25% emulsifiable concentrate [1]	Multiple chamber	Midwest Research	DDT	>99.98 - >99.99
			Total species	>99.98 - >99.99 >99.99
DDT oil 20% emulsified DDT	Thermal oxidizer waste incinerator	General Electric Co.	DDT	99.9999
Waste oil - 1.7% PCB [13]			PCB	>99.9921 - >99.9995
DDT powder [2]	Molten salt combustion	Rockwell International		99.998
Dieldrin 15% emulsifiable concentrate [3]	Liquid injection	TRW		>99.999
Dieldrin - 15% emulsifiable concentrates and 72% chlordane emulsifiable concentrates (mixed 1:3 ratio) [3]	Liquid injection	TRW		>99.98
Diphenylamine-HCl [2]	Molten salt combustion	Rockwell International		>99.999
Ethylene manufacturing waste [5]	Liquid injection	Marquardt Co.	Waste constituents	>99.999
			Total organics	99.95 - 99.99
GB $(C_4H_{10}O_2PF)^2$	Molten salt combustion	Rockwell International		>99.9999998 >99.9999997

(continued)

Waste	Incinerator	Performing organization	Destruction efficiency (DE)[a] of principle components, percent	
Herbicide orange [19]	Two identical refractory-lined furnaces	M/T Vulcanus Ocean Combustion Services		99.985 - >99.99 (combined total)
Hexachlorocyclopentadiene [5]	Liquid injection	Marquardt Co.	Waste constituents	>99.999
			Total organics	99.94 - 99.99
Acetic acid, solution of kepone [6]	Rotary kiln pyrolyzer	Midland - Ross		>99.9999
Toledo Sludge & Kepone Co. - incineration [6]	Rotary kiln pyrolyzer	Midland - Ross		>99.9999
Lindane, 12% emulsifiable concentrate [3]	Liquid injection	TRW		>99.999
Malathion [2]	Molten salt combustion	Rockwell International		99.999 - 99.9998
Malathion, 25% wet power [1]	Multiple chamber	Midwest Research	Malathion Total species	>99.99 >99.99
Malathion 57% emulsifiable concentrate [1]	Multiple chamber	Midwest Research	Malathion Total species	>99.99 >99.98
Methyl methacrylate (MMA) [5]	Fluidized bed	Systems Tech	Waste constituents	>99.999
			Total organics	99.96 - 99.98

F-3

TABLE F-1 (continued)

Waste	Incinerator	Performing organization	Destruction efficiency (DE)[a] of principle components, percent	
0.3% Mirex Bait [1]	Multiple chamber	Midwest Research	Mirex	>98.21 - 99.98
			Total species	>97.78 - 99.96
Mustard [2]	Molten salt combustion	Rockwell International		>99.999982 >99.999985
Nitrochlorobenzene [5]	Liquid injection	Rollins	Waste constituents	>99.99 - 99.999
			Total organics	99.84 - 99.87
Nitroethane [2]	Molten salt combustion	Rockwell International		>99.993
Phenol waste [5]	Fluidized bed	Systems Tech	Waste constituents	>99.99
			Total organics	99.93 - 99.95
Picloram [1]	Multiple chamber	Midwest Research	Picloram	>99.99
			Total species	>99.63 - >99.99
Picloram (Tordon 10K pellets) [1]	Multiple chamber	Midwest Research	Picloram	>99.99
			Total species	>99.93 - >99.99
PCB's [8]	Rotary kiln	Rollins		>99.999964 >99.999977
PCB capacitors [7]	Rotary kiln	Rollins	Waste constituents	99.5 - 99.999
			Total organics	99.96 - 99.98
PCB [4]	Cement kiln	Swedish Water and Air Pollution Research Institute		>99.9998

(continued)

Waste	Incinerator	Performing organization	Destruction efficiency $(DE)_a$ of principle components, percent	
Polyvinyl chloride waste [9]	Rotary kiln	3 M Company	Total organics	99.80 - 99.88
			Chlorinated organics	99.99
Toxaphene 20% dust [1]	Multiple chamber	Midwest Research		>99.99
Toxaphene 60% emulsifiable concentrate [1]	Multiple chamber	Midwest Research		>99.99
Trichloroethane [2]	Molten salt combustion	Rockwell International		>99.99
2,4-D low volatile liquid ester [3]	Liquid injection	TRW		>99.99
2,4,5-T (Weedon^{TM}) [14]	Municipal multiple hearth sewage sludge incinerator	City of Palo Alto		99.990 - 99.996
2,4,5-T [10, 11]	Single hearth furnace	Swedish Water and Air Pollution Research Institute		99.995
2,4,5-T [4]	Single hearth furnace	Swedish Water and Air Pollution Research Institute		99.995
2,4,5-T [4]	Single hearth furnace	Swedish Water and Air Pollution Research Institute		92
2,4,5-T [4]	Single hearth furnace	Swedish Water and Air Pollution Research Institute		99.995

(continued)

Waste	Incinerator.	Performing organization	Destruction efficiency (DE)[a] of principle components, percent
VX $(C_{11}H_{26}O_2PSN)^2$	Molten salt combustion	Rockwell International	>99.999989 - 99.9999945
Zineb [1]	Multiple chamber	Midwest Research	>99.99

a

$$DE = \frac{W_{in} - W_{out}}{W_{in}} \times 100$$

Where:

W_{in} = mass feed rate of the principal toxic component

W_{out} = mass emission rate of the principle toxic component in the incinerator combustion zone

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