



**CONTRACT NO. A832-155
FINAL REPORT
JANUARY 1992**

Survey of Medical Waste Incinerators and Emissions Control

CALIFORNIA ENVIRONMENTAL PROTECTION AGENCY



**AIR RESOURCES BOARD
Research Division**

SURVEY OF MEDICAL WASTE INCINERATORS AND EMISSIONS CONTROL

Final Report Contract No. A832-155

Prepared for:

Research Division
California Air Resources Board
1800 15th Street
Sacramento, CA 95814

Submitted by:

Energy and Environmental Research Corporation
18 Mason
Irvine, CA 92718

Prepared by:

R.G. Barton, D.W. Hansell, D. Furlong, G.R. Hassel,
W.S. Lanier, and W. R. Seeker

January 1992

ACKNOWLEDGEMENTS

The authors acknowledge the contribution of California Air Resources Board Project Manager Ralph Propper. This report was submitted in fulfillment of Contract No. A832-155 by Energy and Environmental Research Corporation under the sponsorship of the California Air Resources Board and the Risk Reduction Engineering Laboratory, U.S. Environmental Protection Agency. Work was completed as of January 16, 1992.

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ABSTRACT

Medical waste treatment and disposal is an increasingly imposing public health crisis. Incineration has proven to be an effective means of reducing the volume and hazard of medical waste. However, recent studies indicate that medical waste incinerators may emit high concentrations of some toxic compounds, including chlorinated dioxins, toxic metals and acid gases.

Volume I of this report assesses the state-of-the-art of medical waste thermal treatment. The program involved a survey of existing information on medical waste treatment. This information was combined with data from municipal and hazardous waste combustion to identify potential mechanisms responsible for toxic emissions. Manufacturers of combustion and flue gas cleaning equipment were contacted. Information on current design practice was obtained.

It was determined that many of the same mechanisms responsible for toxic emissions from municipal and hazardous waste incineration systems are also responsible for emissions from medical waste incinerators. However, medical waste incinerators present unique challenges due to their size and the heterogeneity of the waste.

The California Air Resources Board (CARB) has determined that the emissions of polychlorodibenzo-p-dioxins and polychlorodibenzofurans (PCDD/PCDF) from medical waste incinerators represents a significant risk to public health. In response to this determination, CARB has developed regulations to control PCDD/PCDF emissions from medical waste incinerators. These regulations were promulgated as Section 93104, Title 17, of the California Code of Regulations. Section 93104 places restrictions on PCDD/PCDF emission levels and several medical waste incinerator operating parameters which may affect PCDD/PCDF emissions. Volume II of this report was prepared to assist local air pollution management districts implement the regulations. This volume consists of two parts. Part I provides direct guidance for implementing the regulations. Part II provides background information on the operation and capabilities of flue gas cleaning systems to control PCDD/PCDF emissions.

This report was submitted in fulfillment of contract A832-155 by Energy and Environmental Research Corporation under the partial sponsorship of the CARB.

VOLUME I

STATE-OF-THE-ART ASSESSMENT OF MEDICAL WASTE THERMAL TREATMENT

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NOMENCLATURE

acfm	actual cubic feet per minute
ACI	Advanced Concepts Incorporated
AF	automatic feed (incinerator class designation used by Simonds Manufacturing)
AIDS	acquired immunodeficiency syndrome
APCD	air pollution control device
atm	atmosphere
B	batch (incinerator class designation used by Simonds Manufacturing)
Btu/hr	British thermal units per hour
Btu/hr-ft ²	British thermal units per hour per square foot
Btu/hr-ft ³	British thermal units per hour per cubic foot
Btu/lb	British thermal units per pound
CDC	Centers for Disease Control
Ci/g	curie per gram
cm	centimeter
CVAAS	cold vapor atomic adsorption spectroscopy
d ₀	droplet diameter
DI/FF	dry sorbent injection and fabric filter
d _p	particle diameter
EP	Extraction Procedure
EPA	Environmental Protection Agency
ESP	electrostatic precipitator
°F	degree Fahrenheit
ft	foot
ft ²	square foot
ft ³	cubic foot
ft/sec	feet per second
gal	gallons
GC/MS	gas chromatography and mass spectroscopy
g/m ³	grams per cubic meter
g/Ncm	grams per normal cubic meter (1 normal cubic meter = 1 dry standard cubic meter)
gph	gallons per hour
gr/dscf	grains per dry standard cubic foot (7000 grains = 1 pound)
hr/day	hour per day
hrs/yr	hours per year
IIA	Incineration Institute of America
in	inches
IWI	International Waste Industries (incinerator manufacturer)
K	degree Kelvin
k	x 1000
K _c	Cunningham correction factor

kg	kilogram
kg/hr	kilograms per hour
kg-mole	kilogram-mole
kg/patient-day	kilogram per patient per day
Kwh	kilowatt-hour
Kwh/h	kilowatt-hour per hour
IC	ion chromatography
ICAP	inductively coupled argon plasma atomic emission spectroscopy
J/g	joules per gram
J/s	joules per second
J/s-m ²	joule per second per square meter
J/s-m ³	joule per second per cubic meter
L	liquid feed rate for venturi
lbs	pounds
lb/hr	pound per hour
lb-mole	pound-mole
lb/patient-day	pound per patient per day
L/D	length to diameter ratio
m	meter
m ²	square meter
m ³	cubic meter
Mg	megagram (1 megagram = 1 x 10 ⁶ g)
Mg/day	megagrams per day
ml	milliliter
m/s	meter per second
m ³ /s	cubic meters per second
min	minutes
N	normal
NASA	National Aeronautics and Space Administration
Ni	impaction number
NITEP	National Incinerator Testing and Evaluation Program
NRC	Nuclear Regulatory Commission
NSWMA	National Solid Waste Management Association
NY	New York
Pa	pascal
PAH	polynuclear aromatic hydrocarbon
PCDD/PCDF	Polychlorodibenzo-(p)-dioxin and polychlorodibenzofuran
PM ₁₀	particulate matter with effective diameters of less than 10 mm
ppm	parts per million
ppmv	parts per million by volume
Q	design point gas flow rate
RCRA	Resource Conservation and Recovery Act
RfD	reference dosage
scfm	standard cubic feet per minute
SD/FF	spray dryer and fabric filter
SIP	State implementation plans
T _∞	temperature needed for 99 percent destruction at a two-second gas residence time and substoichiometric conditions
TCLP	Toxicity Characteristic Leaching Procedure
TM	trade mark
ton/day	standard english tons per day (1 ton = 2000 lbs)

U	relative velocity between the particle and droplet in venturi scrubber
V	gas throat velocity
W.G.	water gauge
wt-percent	percent by weight
yr	year
ΔP	pressure drop
$\mu\text{Ci/g}$	microcuries per gram (1 microcurie = 1×10^{-6} curie)
μ_s	gas viscosity
μm	micrometer (1 micrometer = 1×10^{-6} meter)
ρ_p	particle density

SECTION 1

EXECUTIVE SUMMARY

The handling and disposal of medical waste is an area of significant concern for the public and the EPA. This study was conducted in response to that concern. Three phases of waste management can be identified – pre-treatment, treatment and post-treatment. This study focused on the most common method of treatment of medical waste – incineration and the subsequent post-treatment waste handling.

MEDICAL WASTE CHARACTERISTICS

At present a comprehensive evaluation of the pertinent characteristics of medical waste is not available. Even estimates of the total amount of waste generated vary significantly. Estimates for the total amount of medical waste generated in the United States' 7,000 hospitals vary between 3800 Mg/day (4180 ton/day) and 13,000 Mg/day (14,000 ton/day) (1,2). A wide range of smaller medical facilities generate an unknown additional amount of waste. The part of this waste that is expected to be infectious depends on the definition used to define infectious nature. Estimates indicate that 10 percent of medical waste would be classified as infectious using the guidelines in the Medical Waste Tracking Act of 1988 and 3 to 5 percent using Center for Disease Control guidelines. However, the actual portion of the waste generated in any given facility that is treated as infectious can range from 3 to 90 percent depending on procedures used.

The characteristics of medical wastes are not yet well established. Each department generates and bags its own waste. Because of this, each bag may have very different properties. However, surveys have

TABLE 1. COMPARISON OF THE COMPOSITION OF MEDICAL AND MUNICIPAL WASTE^(1*)

Waste Component	Amount in Waste, Percent by Weight		
	Medical Waste	Municipal Waste	Hazardous Waste*
Dry Cellulosic Solids	45.1	54.2	0
Wet Cellulosic Solids	18.0	12.2	0
Plastics	14.2	7.4	12
Rubber	0.7		
Solvents			58
Non-Combustibles	20.4	26.2	30
Pathological	1.6		
Heating Value	6000 Btu/lb	4335 Btu/lb	6030 Btu/lb

* For a typical commercial incinerator accepting a broad range of wastes.
1 Btu/lb = 2.324 J/g

summarized the general composition of medical waste. This information is shown in Table 1. These surveys indicate that the bulk make-up of medical waste is similar to municipal waste except for pathological materials and the significantly higher levels of plastics and rubber. Hazardous waste composition varies significantly from facility to facility.

There is a large variation in the properties of medical wastes. Materials ranging from pure paper to food products to pathological waste may be incinerated during a day. These variations can have a dramatic effect on the performance of thermal treatment equipment.

COMBUSTION SYSTEMS

Most medical waste incinerators being offered today in the United States fall into one of three classes:

- Starved-air modular systems
- Excess-air modular systems (batch)
- Rotary kilns

Examples of these types of systems are shown in Figure 1. Twenty different manufacturers that could provide the incinerators in sizes varying from less than 45 kg/hr (100 lb/hr) to over 3600 kg/hr (8000 lb/hr) were identified. The design practices for these units vary somewhat from manufacturer to manufacturer.

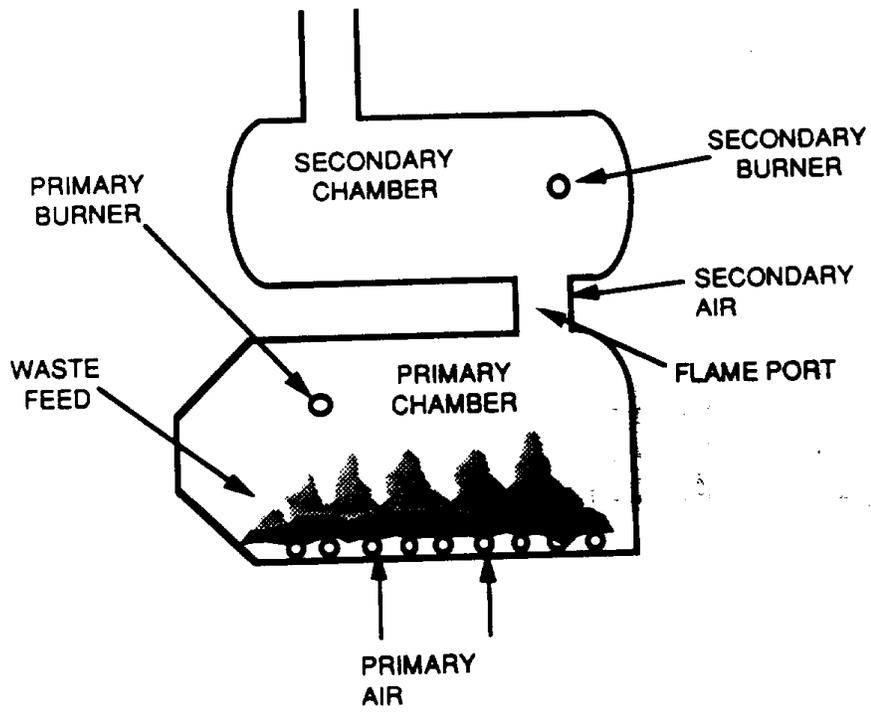
STARVED-AIR MODULAR INCINERATORS

The major product line of most of the manufacturers contacted consists of "controlled" or "starved-" air incinerators (Figure 1a). Waste is fed into the lower combustion chamber which is supplied with only about half of the air theoretically required to completely burn the waste. Thus, the lower chamber is operated in a "starved-air" mode. The waste fed to the incinerator contains moisture, volatile matter, fixed carbon, and ash. The distinction between volatile matter and fixed carbon is that upon heating, volatile matter is released from the solid (not necessarily burned) while fixed carbon is not.

When waste is fed into the lower chamber, moisture and volatile matter are rapidly released and the volatiles burn to release heat. The fixed carbon on the incinerator hearth also burns but only at high temperature when an oxidizer diffuses to the surface. To ensure the complete destruction of fixed carbon, air enters the primary chamber from beneath the burning bed of waste. This air, often called underfire air, aids in the transport of oxygen to the fixed carbon. Because of the limited quantity of air admitted into the primary chamber, combustion gases above the bed are not fully burned and contain significant (>1 percent level) concentrations of CO, H₂, and unburned hydrocarbons.

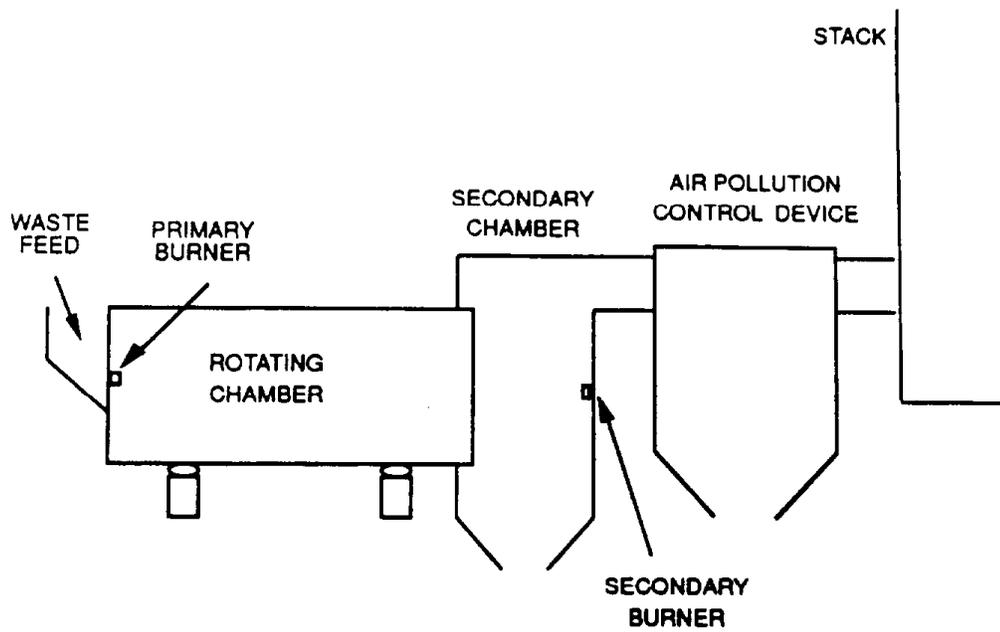
The partially burned primary gases exit the lower chamber and enter a connecting duct to the second stage. Approximately 75 percent of the total combustion air (three times the underfire air rate) is introduced through ports in this connecting duct. The short connecting duct is referred to as the flame port and the extra air is called main flame port air or secondary air. This terminology is derived from the fact that a substantial secondary flame is formed in the flame port when air is added to the fuel-rich gases leaving the primary chamber. The quantity of air added in the flame port is sufficient to completely consume all combustible material in the gas mixture. The secondary chamber ideally provides ample oxygen, mixing and reaction time, and temperature to complete the combustion of hydrogen and carbonaceous material (CO, hydrocarbon gas and carbonaceous solids) exiting the lower chamber. At the exit of the secondary zone, the combustion products consist mainly of CO₂, water vapor, excess oxygen, and nitrogen.

U.S. EPA, Office of Medical Waste Management, 1990

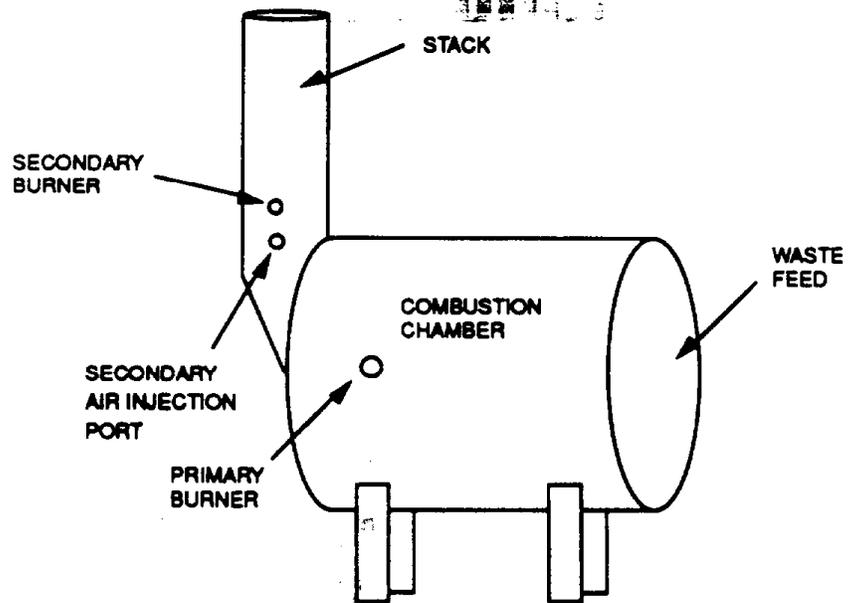


(A) Modular Starved Air Incinerator

Figure 1. Examples of medical waste incinerators.



(B) Rotary Kiln



(C) Modular Excess Air (Batch) Incinerator

Figure 1. Examples of medical waste incinerators. (Continued)

The volume of the primary zone in a controlled air incinerator is sufficiently large; so that, the gas velocity is low. By maintaining low velocities only a small quantity of non-combustible matter is entrained and carried through the remainder of the system. This design feature is the reason controlled-air incinerators can meet 0.18 g/Ncm (0.08 gr/dscf) exhaust particulate loading without use of air pollution control devices.

Both the primary and secondary chamber in controlled-air incinerators consist of a steel shell lined with refractory material to minimize heat losses. Gas temperature at the primary zone exit is typically adjusted to about 1030-1140 K (1400-1600°F) by controlling the amount of underfire air. The upper chamber is designed to provide the residence time and exit temperature specified in local regulations. Typically, the exit gas temperature is about 1260 K (1800°F) and the gases have a dwell time of 1 second or more. An auxiliary fuel fired burner is provided in the secondary chamber to deliver supplemental heat if the minimum exit temperature cannot be maintained by waste combustion.

EXCESS AIR MODULAR INCINERATORS

While these units may be operated continuously, they are usually operated in a batch mode. Thus, they are commonly called batch or retort incinerators.

Waste is manually placed in the combustion chamber. The charging door is then closed and the afterburner ignited. Once the stack reaches a target temperature, the primary burner is ignited. The primary burner ignites the wastes. Initially, moisture and volatile organic material vaporize. The volatile gases burn in the primary chamber and the stack. The waste itself then begins to burn. Air is supplied at constant rate throughout the combustion process. During the initial period, insufficient quantities of air are typically supplied. As the organic material is consumed, less air is needed. Eventually, the chamber operates with excess amounts of available air.

Once the wastes are consumed, the primary burner shuts off. After a set time the afterburner shuts off. When the chamber cools, the residual ash is manually removed and a second charge is placed in the chamber. The cycle may be controlled by a timer only or may involve a more complex control system which uses chamber temperature as a criterion as well.

ROTARY KILNS

These systems consist of a slowly rotating cylinder or kiln. The kiln is slightly inclined. The rotation and incline serve to induce mixing of the solids and to move the wastes through the incinerator. Waste is fed from a hopper into the kiln. The kiln walls are made of acid resistant refractory brick. An auxiliary fuel burner and a port to admit combustion air are both located in the front face of the unit. The auxiliary fuel burner is fired during start-up and intermittently after that based on measured kiln exit gas temperature. Combustion air to the kiln is admitted through the port(s) on the front face as well as through seal leakage and is controlled by kiln operating pressure. Kiln pressure is typically maintained at -12 to -25 Pa gauge [-0.05 to -0.10 inches of water gauge (W.G.)].

Ash drops from the kiln onto an overlapping pan conveyor and is transported to a waste hopper. Typical carbon-in-ash is almost equal to starved air units with continuous ash removal.

Flue gas exits the kiln and flows into a secondary chamber which is equipped with an auxiliary fuel burner and a temperature control system. Secondary air is added to ensure thorough mixing. An auxiliary fuel burner is located in the secondary chamber but is mainly used for start-up. The combination of kiln plus secondary burner equals the full load rating of the incineration system. Typically, the secondary chamber is sized and controlled for 1 or 2 seconds gas residence time at 1366 K (2000°F).

SELECTION CONSIDERATIONS

The choice of the most appropriate system was not attempted in this study since the best design must be tailored to the particular needs of the medical institutions. It is worth noting, however, that the technologies now offered will be severely challenged if comprehensive and stringent performance criteria (such as those enacted by New York State) are placed on them. Specifically, their ability to meet stringent environmental requirements such as limits on PCDD/PCDF emissions, metal emissions, pathogen destruction and acid gas control in a cost effective manner has not yet been proven. The important design and operating parameters expected to affect emissions of each pollutant were identified and will be discussed in later sections.

FLUE GAS CLEANING EQUIPMENT

To date, only a few (<1 percent in California) medical waste thermal treatment facilities include flue gas cleaning equipment. Most of those that do have flue gas cleaning equipment have wet scrubbing technology such as the venturi scrubber shown in Figure 2. This choice is based largely on economics, ease of operation

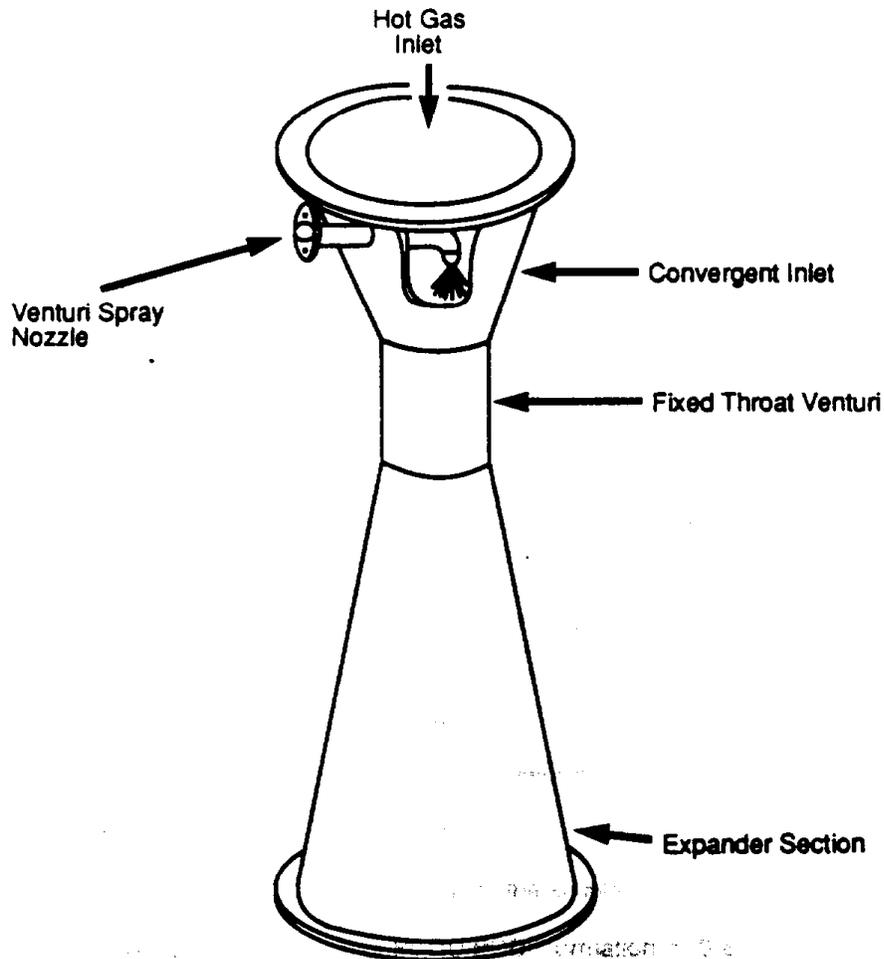


Figure 2. Typical venturi scrubber.

and emissions limits. These types of technologies have been successfully applied to medical waste incinerators. However, it is difficult to achieve high levels of particulate control using this technology. Thus, stringent particle control, metals, or HCl emission standards may require use of alternative technologies. Spray dryer/fabric filter technology as shown in Figure 3 has been successfully applied to municipal solid waste systems to achieve high levels of acid gas removal and particulate control. However, more stringent control has not yet been required for medical waste incinerators and manufacturers indicated spray dryer/

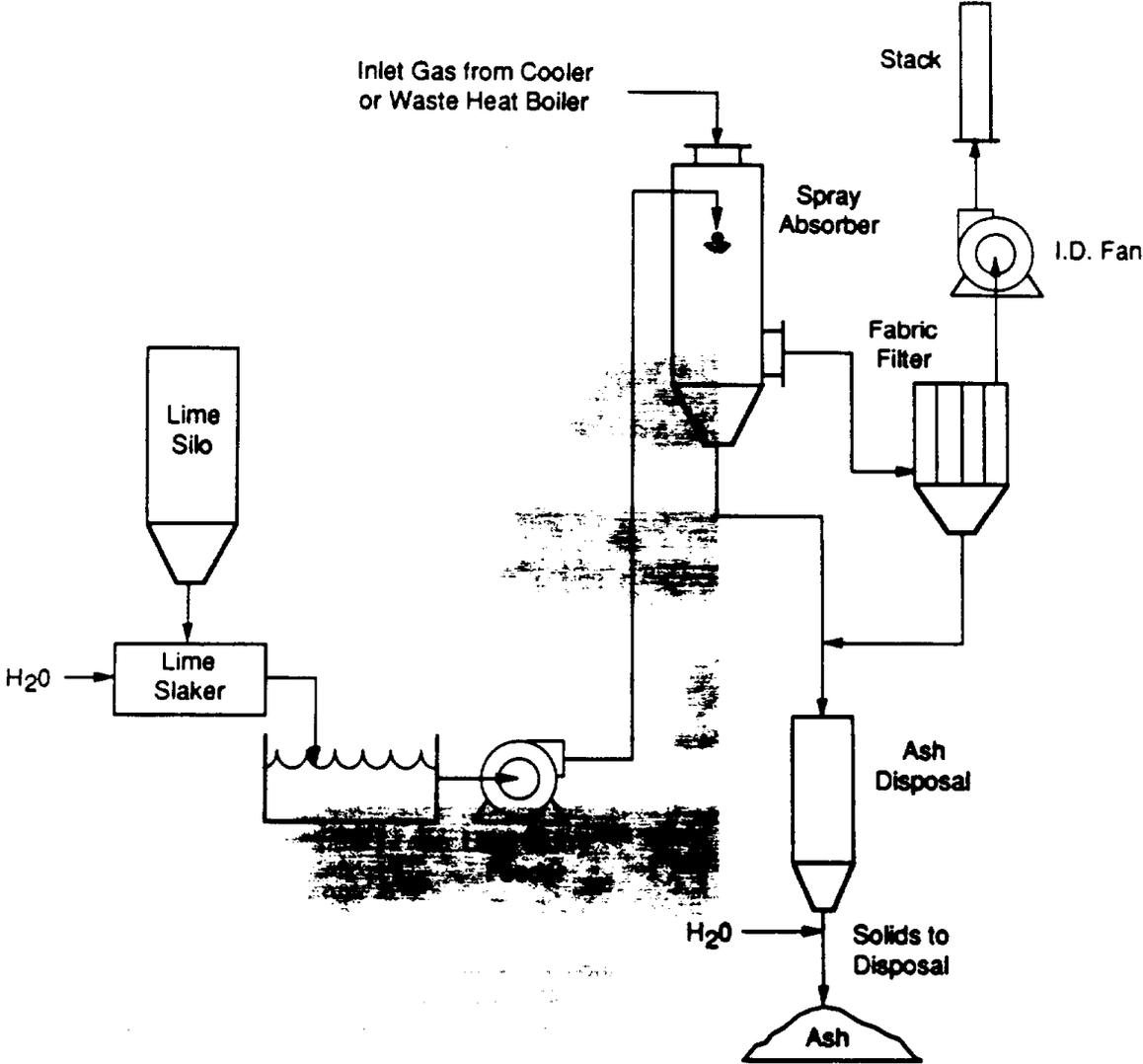


Figure 3. Spray dryer/fabric filter.

fabric filter systems are not currently competitive with wet scrubber systems. More stringent regulations may favor spray dryer/fabric filter systems in the future.

The cost of flue gas cleaning systems can be a significant if not the dominant cost element in the complete system. For example, the cost of the starved air combustion systems, based upon vendor data was found to vary directly with the size of the equipment as shown in Figure 4. For the larger quantities of waste, rotary kilns were competitive with starved-air systems. A venturi scrubber/acid gas absorber for 454 kg/hr (1000 lb/hr) incinerator was estimated to cost \$200,000. In addition, the operation and maintenance costs could be nearly \$90,000 for the first year for this same system. A spray dryer/fabric filter system may cost as much as \$800,000 for a similar sized facility. However, the cost of spray dryer/fabric filter systems does not increase as rapidly with unit size as venturi scrubber/acid gas absorber systems do. Thus, spray dryer/fabric filters are more competitive for larger facilities.

FORMATION AND CONTROL OF POLLUTANTS

The current state of understanding about the formation and control of pollutants was reviewed. Both air emissions and solid effluents were examined.

AIR EMISSIONS

PCDD/PCDF--

The concentrations of PCDD/PCDF in emissions from medical waste incinerators were higher than most municipal waste incinerators as shown in Figure 5. This was hypothesized to be due to the lack of air pollution control and the design and operation of the combustion equipment. Four mechanisms of PCDD/PCDF formation/emissions were identified:

- **Poor destruction of PCDD/PCDF in the waste**
- **Incomplete destruction of long-chain organics which convert to PCDD/PCDF**
- **Formation from precursors**
- **Low-temperature catalyzed reactions.**

The database is currently insufficient to evaluate which of these mechanisms is most important. However, the emissions data did correlate with entrained particulate matter from the combustion device suggesting the importance of particle precursors. Based on analogies with hazardous waste, and municipal solid waste incineration and analysis of the special features of medical waste incinerators, the parameters expected to affect PCDD/PCDF emissions are as follows:

- **Primary zone gas velocities which influence particle entrainment**
- **Primary zone combustion air flow which determines gas velocity and stoichiometry**
- **Secondary zone temperature which determines the organic destruction level**
- **Uniformity of temperature (both spatial and temporal) in the secondary zone**
- **Particle holdup at temperatures found to favor PCDD/PCDF formation [520-620 K (480-660°F)]**
- **Temperature of the particle control device which determines condensation of PCDD/PCDF on particles**

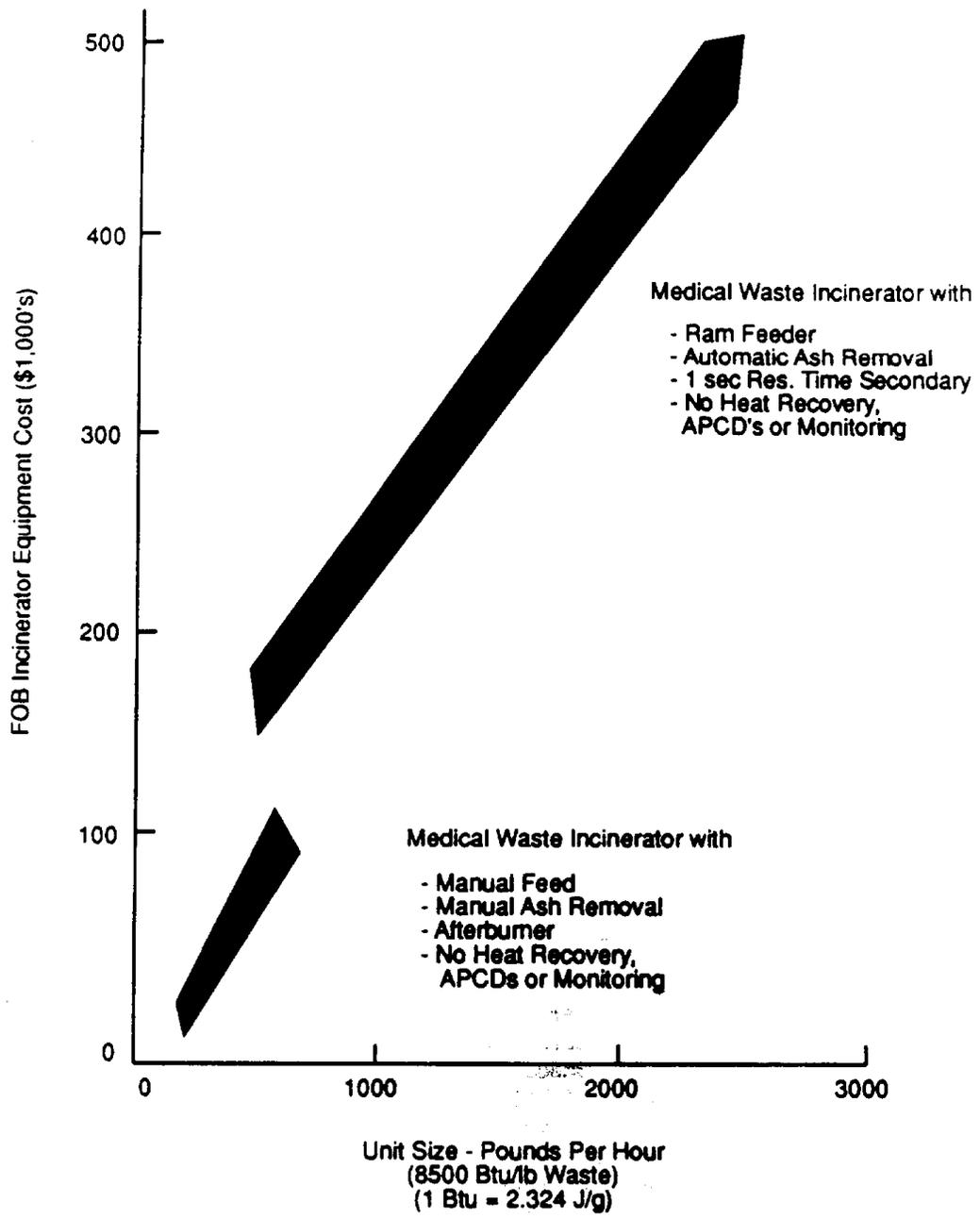
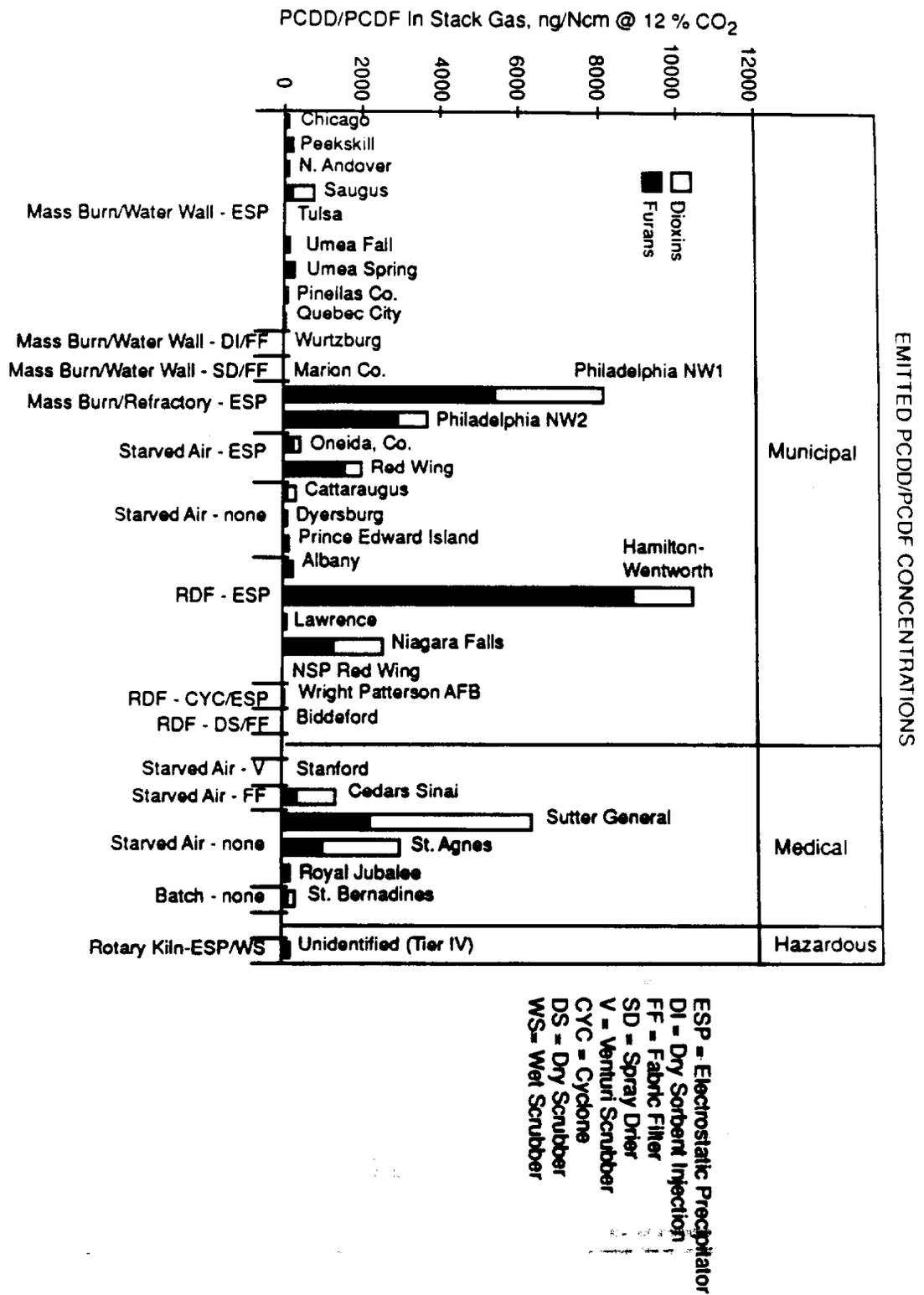


Figure 4. Equipment cost for controlled air incinerators as a function of unit scale.

Figure 5. Comparison of PCDD/PCDF emissions from a variety of incinerators.



- Fine particle control which determines the amount of PCDD/PCDF on particles that is removed from the flue gas

The performance data are not currently sufficient to allow an evaluation of these parameters for medical waste incinerators.

Toxic and Carcinogenic Metals--

The emissions of several metals have been evaluated for medical waste incinerators, municipal waste incinerators, and hazardous waste incinerators. The dominant emissions from medical waste incinerators include arsenic, lead, cadmium, and chromium. Generally, the uncontrolled emissions (either without or before APCDs) of these metals are lower for medical waste incinerators than for municipal solid waste systems, as shown in Figures 6 through 9. This is either due to a lower concentration of these metals in medical waste or due to combustion conditions in medical waste incinerators which are less likely to drive metals out of the solids. A comparison of starved-air systems burning either medical waste or municipal waste also indicates that a smaller amount of certain metals escape medical systems suggesting that medical waste probably contains less of these metals.

There are only limited data on the capture efficiency of metals by flue gas cleaning systems as applied to medical waste incinerators. These data show moderate capture of cadmium but poor capture of chromium and lead when a wet scrubber system is used. A fabric filter system was found to have excellent performance on all metals tested.

At the conditions in the primary zone of starved-air systems, arsenic, cadmium and lead are probably volatile while chromium will probably remain a solid. Over the range of typical conditions, this phenomenon should not change. The emission of the volatile species from uncontrolled incinerators will be dictated by the amount of these metals in the waste stream. Most of the volatile metals are released from the solid. These metals are expected to form fine aerosols as they recondense. Fine particle capture combined with flue gas cooling may be necessary to achieve high capture levels. For chromium, which is not expected to be volatile except at higher temperatures, the combustion conditions are more important. Chromium escapes primarily by entrainment which is influenced by the primary zone gas velocity and the characteristic size of the chromium in the waste. Once out of the primary chamber, chromium should be easier to capture because of the larger particle sizes. However, larger fractions of chromium volatilize at high temperatures when chlorine is present. Under those conditions, chromium is expected to behave more like volatile metals.

Pathogens--

The pathogens present in infectious waste are a complex mixture of bacteria, mycobacteria, fungi, parasites, viruses and rickettsia. At the severe conditions that exist within incinerators, pathogenic organisms are very fragile and easy to destroy. The tests conducted to date on operating incinerators have shown that pathogens do not survive except at very low temperatures [866 K (1100°F)]. However, there is some evidence that pathogens from the environment around the incinerator can get into the stack. These pathogens can bypass the combustion zone and are thus not destroyed. The pathogens are probably released into the air as wastes are handled in the area around the incinerator. The control of pathogen emissions appears to be similar to the minimization of trace organics emissions. In addition, however, care must be taken to ensure that all gases which enter the system pass through the combustion zone.

Cytotoxic Compounds--

Cytotoxic compounds are substances generally used in chemotherapy that are highly toxic to cells. Because of the acute nature of the hazards associated with these compounds, the goal is complete

Arsenic

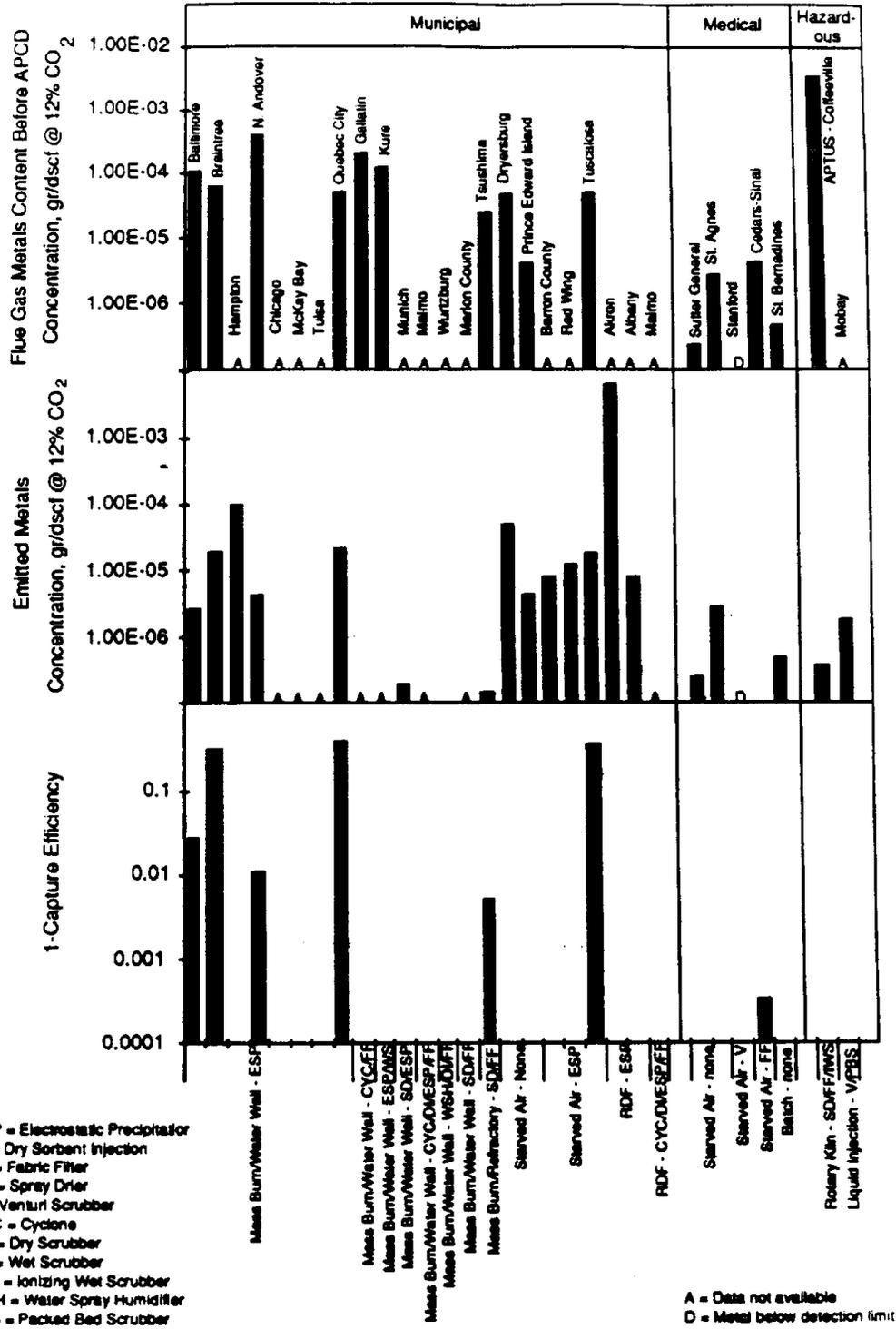
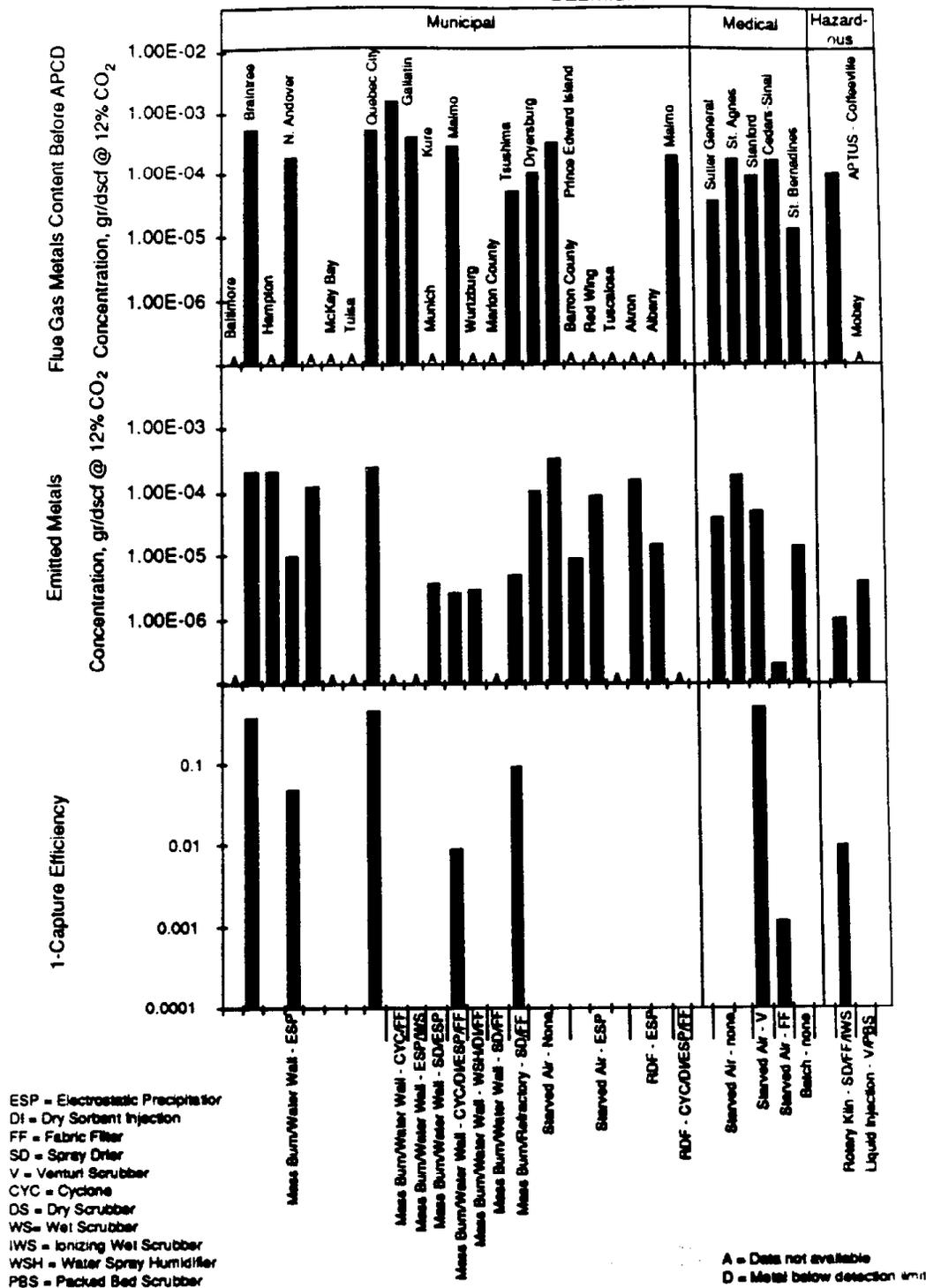


Figure 6. Data on arsenic emissions from a variety of incinerators.

Cadmium



1 gr/dscf = 2.29 g/Ncm

Figure 7. Data on cadmium emissions from a variety of incinerators.

Chromium

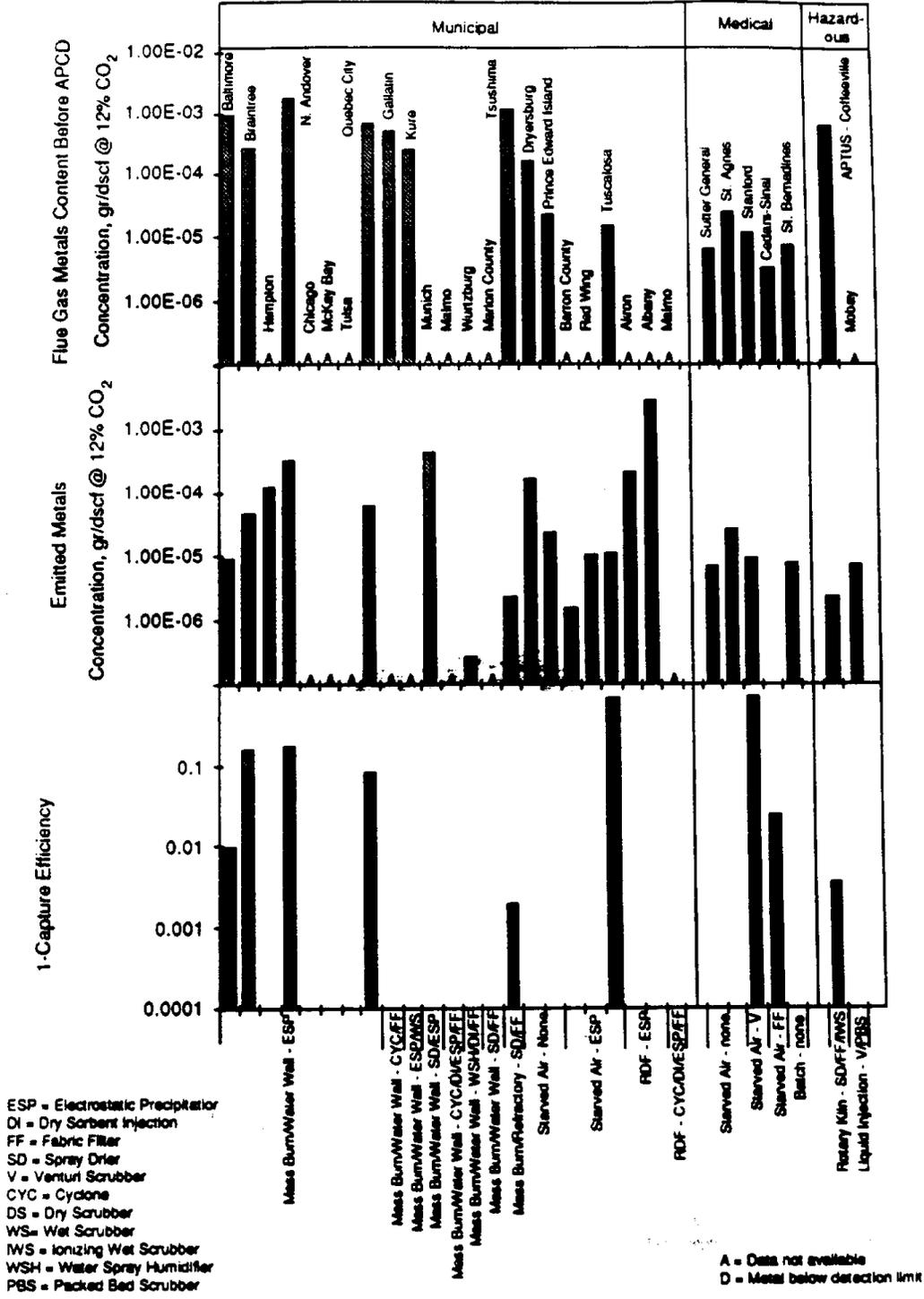
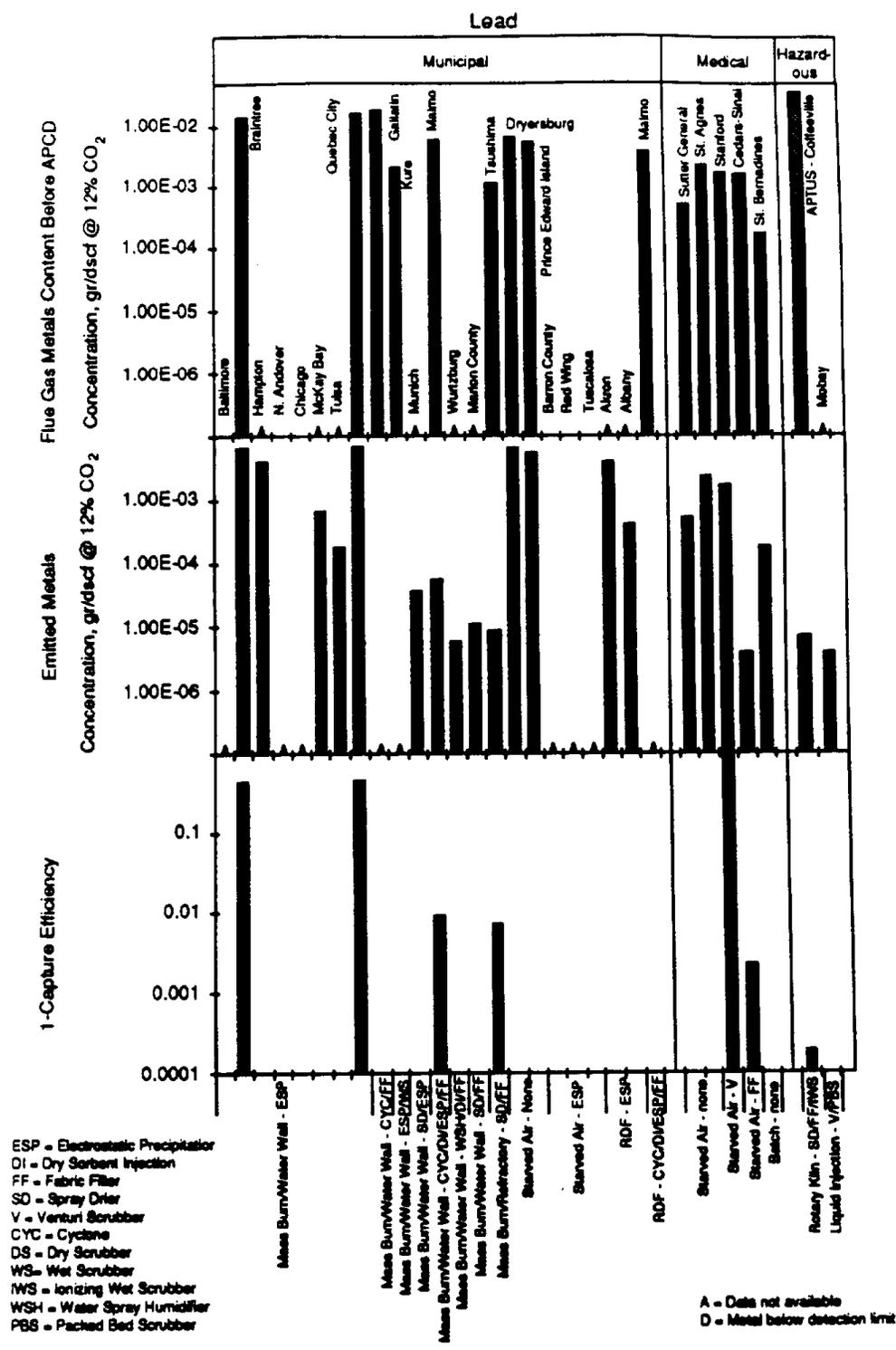


Figure 8. Data on chromium emissions from a variety of incinerators.



1 gr/dscf = 2.29 g/Ncm

Figure 9. Data on lead emissions from a variety of incinerators.

destruction. No data on emissions of cytotoxic compounds are currently available. Since these compounds are organic, the control techniques should be similar to those for both trace organics and pathogens. The temperature needed to destroy cytotoxic compounds with high efficiency has been estimated to be 1170 K (1650°F) (3). This estimate is based on consideration of thermal decomposition of the more refractory compounds.

Acid Gases--

Three species were considered acid gases: nitrogen oxides, sulfur oxides and hydrogen chloride. Medical waste typically contains 0.2 percent sulfur, 4 percent chlorine and 0.5 percent nitrogen (4). Large portions of sulfur and chlorine are converted to SO₂ and HCl, without significant dependence on combustion conditions. Control of these species must be accomplished by removal of sulfur and chlorine bearing constituents from the waste before burning or by flue gas scrubbing. The formation of NO_x is dependent upon combustion peak temperature, fuel/air mixing and primary zone stoichiometry. The gas scrubbing for NO_x is not a viable alternative because of the low solubility of these components.

Radioactive Materials--

Low-level radioactive materials are sometimes found in medical waste; however, radioactive emissions from general medical waste incinerators have not been measured. The radioactivity of the materials cannot be altered by incineration but the physical form can be dramatically changed. The radioactive materials behave like their non-radioactive counterparts; so that, the fate of the radioactivity depends on factors such as operating chamber temperature, air volume and velocity, extent of combustion, chemical and physical form of the waste and the elements involved.

SOLID AND LIQUID EFFLUENTS

Solid and liquid effluents from incinerators are also of concern. Solid effluents are composed primarily of ash from the combustion chamber of an incinerator. If the system is equipped with some type of flue gas cleaning equipment, then captured fly ash and liquid effluents may also be present. Both solid and liquid effluents may contain materials which threaten human health and the environment.

Organic Material--

Potentially dangerous organic materials include:

- Trace organics (PCDD/PCDF)
- Pathogens
- Cytotoxic materials

High concentrations of PCDD and PCDF have been found in ash from some incinerators (Figure 10). However, no pathogens have been observed in ash from incinerators operated above 866 K (1100°F). No studies have examined the survival of cytotoxic materials in ash.

Similar methods are used to ensure the destruction of all three classes of potentially dangerous organic material. Ash is retained in the combustion chamber for long periods of time. Air is supplied from beneath the bed to ensure adequate amounts of oxygen are available for the complete gasification of fixed carbon. Modular starved-air incinerators and rotary kiln systems also mix the solids to break up dense clumps which may form cold pockets.

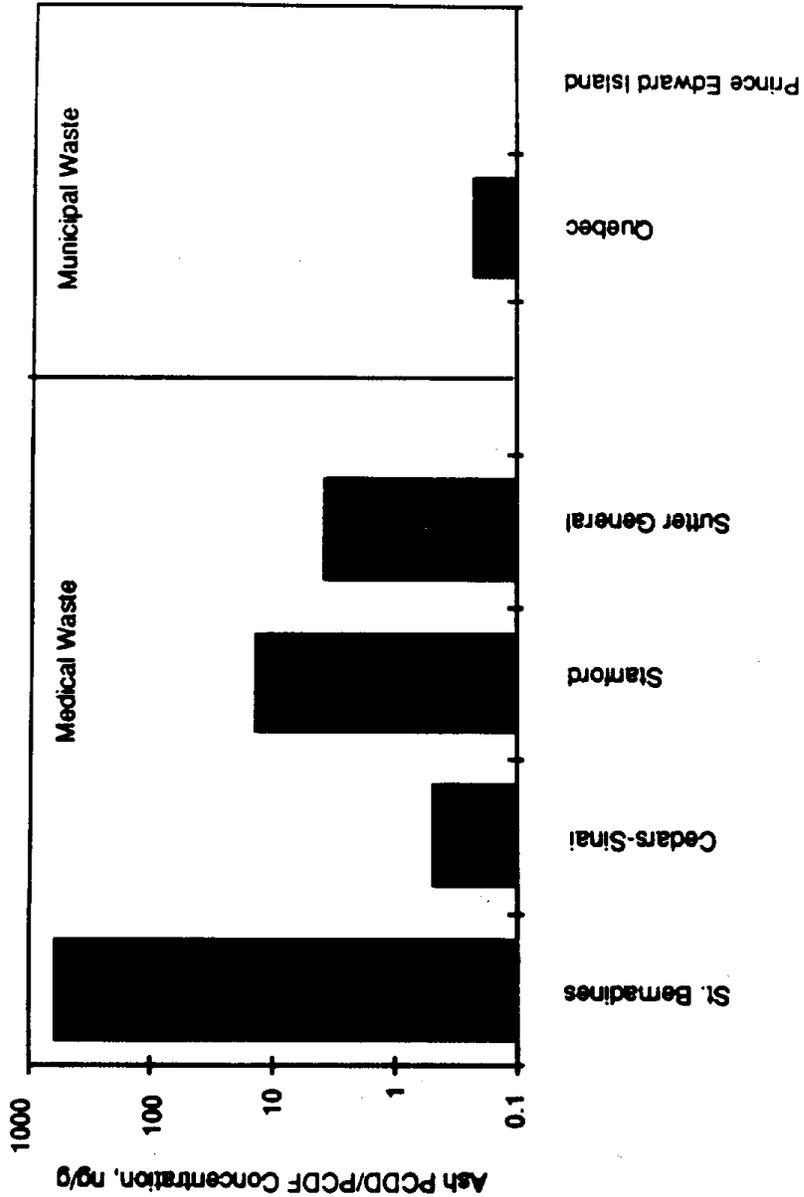


Figure 10. Comparison of PCDD/PCDF concentration in medical and municipal waste residuals.

Inorganic Material--

Potentially dangerous inorganic materials include:

- Toxic and carcinogenic metals
- Radioactive material

Inorganic materials cannot be destroyed by the incineration process. Current designs focus on forcing each material into the effluent stream most easily handled. Conditions which promote retention of toxic and carcinogenic metals in the residual ash are used. This mainly involves operating the primary combustion chamber at the lowest practical temperature. Most radioactive materials are volatile and vaporize during incineration. They are diluted by combustion air and emitted to the atmosphere.

STATE REGULATIONS

With no federal medical waste incineration regulations, state requirements are of primary concern. Currently state regulations vary significantly. Some states do not have specific medical waste incineration regulations while others impose emissions limits stricter than those imposed on incinerators burning other types of waste. Table 2 summarizes some current state medical waste incineration standards.

TABLE 2. SELECTED STATE MEDICAL WASTE INCINERATION STANDARDS

State	PM (gr/dscf)	HCl	Time/Temp	CO (ppm)	Other	Reg Impact
NY	0.03 (Existing) 0.015 (New)	90% reduction	1260 K for 1s (1800°F)	100	Opacity	Testing and Risk assessment required
SC	0.03-0.1	Monitor	1260 K for 2s (1800°F)	Monitor	Opacity	
CA			1260 K for 1s (1800°F)	Monitor	Opacity	Exhaust <300°F Primary Chamber >1400°F PCDD Equivalent < 10 ng/kg waste or 99% reduction
MA			1140 K for 1s (1600°F)			
PA	0.015-0.08	90% reduction	1370 K for 2s (2000°)	100	Opacity	

Note: 1 gr/DSCF = 2.290 g/Ncm

SYSTEM MONITORING

Monitoring medical waste incinerators is becoming increasingly important. Regulations being developed often require that emissions monitoring equipment be installed on medical waste incinerators. System manufacturers are building incinerators equipped with more sophisticated control systems which make use of data from various system operation monitors.

Two classes of parameters to be monitored can be identified:

- Emissions
- Operating parameters

Emissions monitoring identifies and quantifies material leaving an incinerator while operating parameter monitors measure key variables associated with the operation of a system. The two classes are not exclusive. Some emissions measurements may also be good indicators of system operation.

System monitoring can be expensive. A continuous emissions monitoring system may cost from \$10,000 to over \$100,000. Compliance test costs vary depending on the materials to be monitored. Tests involving the determination of PCDD/PCDF emissions may cost as much as \$100,000.

RESEARCH NEEDS

Several data gaps were identified in this study. These gaps must be filled to confidently develop design and operating practices which minimize pollutant emissions from medical waste incinerators. Many areas were also identified at the workshops on medical waste disposal sponsored by the EPA's Risk Reduction Engineering Laboratory. These workshops brought together leading workers in medical waste disposal and provided an effective forum for the communication of information and ideas. The research needs include the following:

- **Medical Waste Characterization.** Medical wastes have not been studied in detail. This lack of information hampers all thorough examinations of medical waste disposal. A detailed examination of medical waste composition is needed. Toxic metals content, trace organics content, and properties which affect thermal treatment are of particular interest.
- **Medical Waste Management Practices.** A wide variety of techniques are used to manage medical wastes. These techniques vary with the type of facility generating the waste and even between different facilities of the same type. This data will aid in the characterization of medical waste and in the evaluation of various potential treatment techniques.
- **Field Performance and Process Data.** There are several emission tests recently conducted or planned on full-scale operating medical waste incinerators. Investigations using large-scale equipment which evaluates a broader range of conditions are needed. The proposed mechanisms of formation and control should be directly evaluated in these tests by appropriate selection of the test conditions, collection of process data along with emissions data, and analysis of the results in terms of formation mechanisms.
- **Demonstrate Other Treatment Technologies.** Many medical waste sterilization technologies have been proposed. These include established technologies like steam sterilization and new technologies like microwave treatment. Though some techniques have been examined in detail, no systematic effort has been made to quantify and compare the performance of the different technologies.

- **Risk Assessment.** Medical wastes contain many materials which may constitute a threat to human health. At the workshops it was concluded that to develop appropriate regulations, it would first be necessary to define the risk associated with all emissions by all exposure routes.
- **Pathogen Sampling and Analysis Methodology.** A wide variety of techniques have been used to sample incinerator effluents to determine the quantity of pathogens which survived destruction. However, no systematic evaluation of the effectiveness of the techniques has been carried out. This information is important to the determination of the risk associated with infectious residues and emissions.
- **Incinerator Retrofit.** Most incinerators in the U.S. are old facilities which may not be able to achieve the stringent regulations now being promulgated across the country. A systematic analysis of the costs and effectiveness of various retrofit options available to these incinerators' operators is needed.
- **Performance Assurance.** Currently operating incinerators are not equipped with extensive monitoring systems. The current systems may not be capable of assuring continual compliance of a facility with new regulations. Various methods of performance assurance should be examined and evaluated.

SECTION 2

INTRODUCTION

OVERVIEW

The handling and disposal of medical waste is an area of significant concern for the public and the EPA. Recent, highly publicized examples of medical waste mismanagement have focused attention on the need for a re-examination of all of the issues related to medical waste management. This study was initiated as part of that re-examination.

Three phases of medical waste management can be identified. These are: Pre-treatment, treatment and post-treatment.

Pre-treatment waste management includes generation and segregation practices. Treatment involves modification of the waste to reduce disposal costs and reduce potential environmental impact. Post-treatment management addresses the issues associated with disposal of the products of waste treatment. Pre-treatment waste management is being actively studied by the EPA's Office of Solid Waste and is one of the primary focuses of the Medical Waste Tracking Act of 1988. Thus, this study focuses on medical waste treatment and post-treatment waste management.

PRE-TREATMENT

Pre-treatment waste management focuses on three objectives:

- Protecting health care workers and the general public
- Minimizing the quantity of material requiring treatment
- Facilitating waste treatment

When examining this area, several issues must be addressed. The primary purpose of any phase of medical waste treatment is the protection of the health of any potentially exposed people. This is particularly true of pre-treatment waste management. Those wastes which may pollute the environment are identified and segregated. This is the first step in a pollution prevention scheme. The segregated wastes are subjected to an appropriate form of treatment.

However, care must be taken not to simply classify every by-product of medical treatment as a potentially dangerous waste. Careless waste generation will create huge quantities of materials which will in the end have a greater impact on public health and the environment than if no segregation occurred. The amount of waste to be disposed of must be minimized. Minimization involves accurate schemes to classify and segregate dangerous materials, and the use of material recovery and recycling to the greatest extent feasible.

TREATMENT

Once wastes have been generated and appropriately segregated, they must be treated. A variety of treatment methods are available which can reduce the dangers associated with the segregated wastes, the quantity of segregated waste to be disposed of, or both. Treatment methods include: incineration, steam sterilization, microwave heating, gas sterilization, chemical disinfection, irradiation and thermal inactivation. Of these techniques, incineration is the most versatile and the most widely used. Thus, this study focused on the use of incineration to treat medical wastes and on the disposal of the products formed.

The goals of medical waste incineration are to destroy any hazardous organisms in the waste, reduce the waste's volume and mass, and render the waste unrecognizable. This last objective is unique to medical waste incineration where the waste may present significant aesthetic concerns. This study examined the technologies currently used to incinerate medical waste and examined the strengths and weaknesses of these technologies.

Two key areas are important when assessing incineration systems — degree of destruction of organic materials and quantity of toxic by-products produced. Organic destruction can be maximized by following well-established good combustion practices. The abilities of medical waste incinerators to follow these practices were examined. Toxic by-product formation is one of the most significant concerns related to incineration systems. Emissions of concern include — dioxins, toxic metals, and acid gases.

Performance assurance plays an integral role in the operation of medical waste incinerators. Monitors are available for some of the emissions of interest. Other emissions can only be determined during prolonged, costly testing. The principal monitoring techniques available were examined and assessed.

POST-TREATMENT

Once a waste has been treated, the by-products must be disposed of. Often, disposal of treatment products can be almost as costly as disposal of the original waste. The principal by-product of incineration systems is ash. Ash is generally placed directly into municipal waste landfills. The principal concern during post-treatment management of incinerated medical wastes is the metals content of the ash. Metals may be leached from the ash into ground water. Because of this, encapsulation/solidification procedures have been developed which trap the ash in an inert matrix and immobilize the toxic metals. The metals content and the leachability of those metals present in medical waste incinerator ash were examined as part of this study.

OBJECTIVE

The goal of this study was to assess the state of the knowledge about the thermal treatment of wastes from medical institutions. Specifically, the study focused on determining what thermal treatment methods are currently used to dispose of medical wastes and how these methods may affect human health and the environment.

SCOPE OF PROGRAM

To achieve the objectives, this program consisted of three tasks. These tasks were:

1. Identify and describe medical waste thermal treatment technology
2. Evaluate the potential impact of the treatment technology on human health and the environment
3. Identify current regulations

Incineration is the most widely used thermal treatment method. In addition, incineration is the focus of much regulatory attention because of its potential impact on the environment. The major air pollutants generated during medical waste incineration include: trace organics [especially polychlorinated dibenzo(p) dioxin (PCDD)], toxic metals (such as cadmium, lead and mercury), acid gases (such as HCl and SO₂), pathogens, radioactive materials, and particulate matter.

For each of these classes of pollutants, the available data were gathered and analyzed to define what is known about emission levels, formation mechanisms, and control techniques.

TECHNICAL APPROACH

The technical approach used in this assessment is summarized in Figure 11. All activities in this program were integrated with the series of EPA sponsored workshops on medical waste disposal. These workshops gathered experts on medical waste disposal to discuss the current state of knowledge in the field and suggest areas where more work was needed. The initial activities in this program involved the evaluation of the waste characteristics which influence the thermal treatability of the waste. The waste components which influence the thermal treatability of the waste and the components which influence pollutant emissions were identified. Literature surveys, as well as hospital tours and telephone surveys, were used.

The next activity involved a comprehensive definition of the current design practice used by U.S. medical waste incinerator manufacturers. Detailed face-to-face discussions were held with 13 manufacturers who were chosen to represent the range of systems now offered in the United States. The discussions covered the design practices currently followed and control schemes used. The discussions also addressed special design practices focused on the control of pollutants and changes to current designs made in response to emerging regulations. Similar discussions were held with seven manufacturers of air pollution control devices who were identified by incinerator manufacturers as representing systems currently installed on medical waste incinerators.

A telephone survey was conducted of 205 medical institutions in California to evaluate certain aspects of the use and operation of the thermal treatment system. These hospitals are probably typical of all institutions in the U.S. Visits were made to five incineration facilities to view the operation of incinerators and the management of medical waste. Specifically, the visits were designed to evaluate operator training levels and determine if the incinerator was being operated in a manner consistent with the design.

The data collected from literature, test reports, design basis discussions and operation visits were then analyzed to the extent possible. The focus of this analysis was on the formation and control of pollutants of interest. Each of the pollutants identified to be of concern were evaluated. Attempts were made to evaluate design and operation parameters which influence the emission using both performance data from medical waste incinerators as well as similar data from other types of waste incinerators. Engineering analysis procedures developed for hazardous waste incineration systems were used to evaluate performance data. In this manner, knowledge gained from other waste combustion systems was applied to medical waste incinerators to evaluate parameters which control performance.

The final activity involved a definition of the limitations of current knowledge of medical waste thermal treatment. Particularly, those limits which prevent the development of definitive design and operating parameters which will provide optimum performance of medical waste thermal treatment equipment were identified. The limits were combined into an unprioritized list of research needs.

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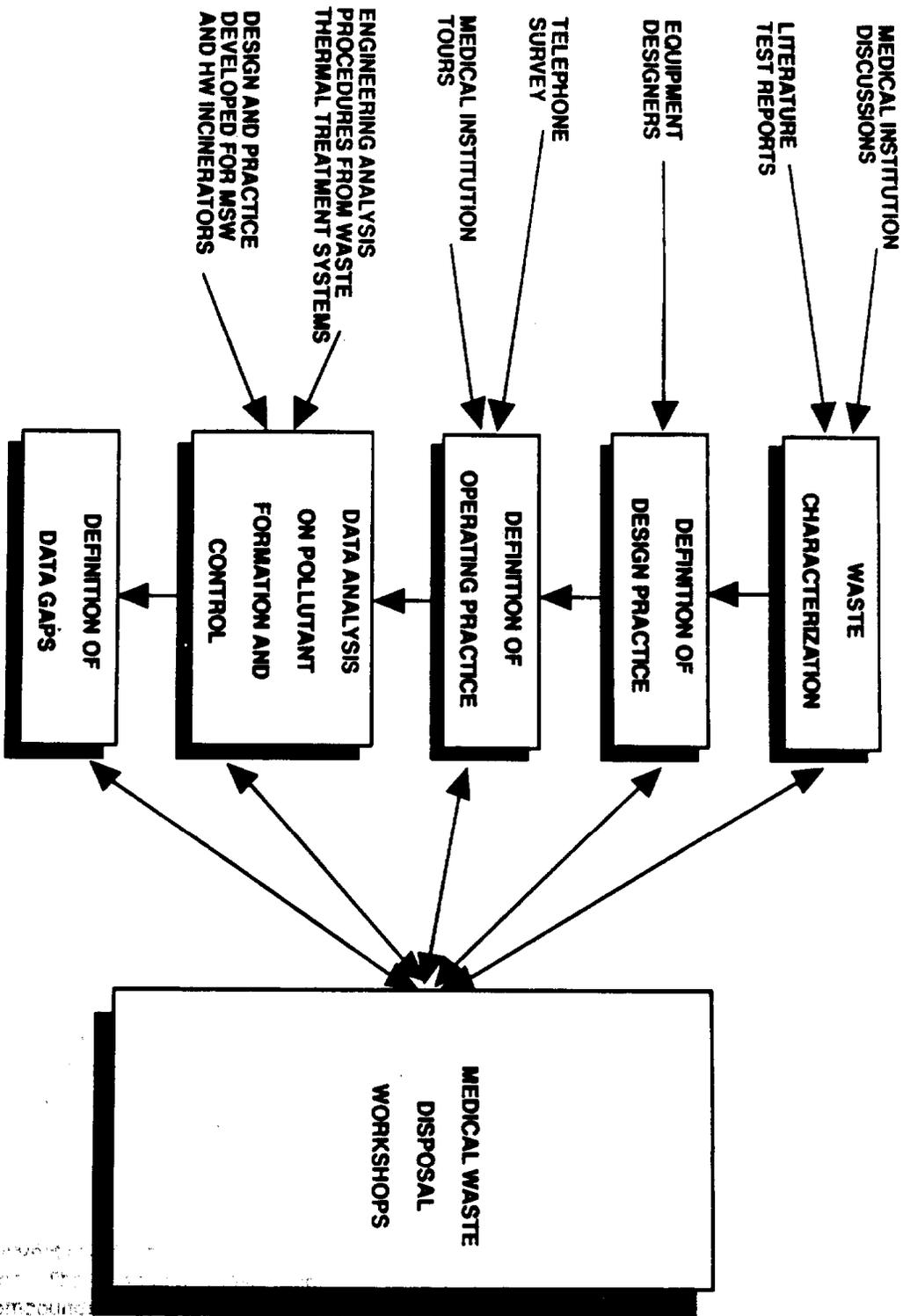


Figure 11. Program approach.

SECTION 3

WASTE CHARACTERIZATION

An investigation of the thermal treatment of medical waste must begin with an understanding of what medical waste is. This, however, is not a simple task. In the Medical Waste Tracking Act of 1988 (5), "medical waste" is defined as follows:

"... any solid waste which is generated in the diagnosis, treatment, or immunization of human beings or animals, in research pertaining thereto, or in the production or testing of biologicals. Such term does not include any hazardous waste identified or listed under Subtitle C or any household waste as defined in regulations under Subtitle C."

The activities described in this definition generate many different materials which are all combined to form medical waste. Thus, medical waste is not a single material but a complex and varying mixture of materials with a broad range of properties. The quantities and types of materials in a given sample of medical waste can vary depending on many factors including the type of facility which generated the waste, the waste management practices within the facility, and the time at which the sample was collected.

Despite the variations in medical waste, some key properties can be identified. This chapter examines:

- Components of medical waste which require special consideration
- Properties of medical waste which have an impact on the effectiveness of thermal treatment and disposal techniques
- The total quantity of waste produced.

KEY COMPONENTS OF MEDICAL WASTE

The overriding characteristic of medical waste is its heterogeneity. A sample of medical waste can contain paper, plastics, food wastes, pathological wastes, animal carcasses, blood soaked bandages, intravenous bags and many other types of materials.

The components of medical waste which may require special attention are:

- Pathogens
- Cytotoxic chemicals
- Hazardous chemicals
- Toxic metals
- Radioactive materials

PATHOGENS

Infectious organisms or pathogens are the source of most of the concern over medical waste handling. However, no practical definition of infectious waste is generally accepted. The definition used to classify wastes as infectious can have a significant impact on a facility's waste disposal costs. For example, one 600 bed hospital found that it could save \$250,000 annually by simply changing its practical definition of infectious wastes (6).

Most medical facilities use either the EPA guidelines or the Centers for Disease Control (CDC) guidelines (7) to determine if a waste should be considered infectious. According to the EPA guidelines, infectious waste is medical waste which can produce infectious disease due to the presence of pathogens of sufficient virulence and exposure routes to the host (8). The EPA designates the following materials as regulated medical waste (9):

- Cultures and stocks of infectious agents and associated biologicals
- Pathological waste
- Human blood and blood products
- Contaminated sharps
- Contaminated animal carcasses, body parts, and bedding
- Isolation wastes
- Unused sharps

EPA recommends that these materials be designated infectious waste and segregated from general medical waste.

The CDC guidelines issued in August 1987 and clarified in June 1988 state materials are infectious if they contact blood and other body fluids of an infected person (7).

Estimates indicate that 10 percent of medical wastes would be classified as infectious using the EPA guidelines and 3 to 5 percent using the CDC guidelines (10). In practice, an average of between 10 and 15 percent of all hospital waste is designated infectious. However, this fraction varies from 3 to 90 percent depending on the definitions and procedures used at any given hospital or medical facility (10).

CYTOTOXIC CHEMICALS

Cytotoxic chemicals are substances capable of impairing, injuring, or killing cells. These hazardous pharmaceuticals are used in chemotherapy. Because of the hazards associated with these compounds, they must be completely destroyed during disposal. Some information indicates that these compounds are not effectively destroyed at temperatures below 1260 K (1800°F) (11). However, incinerability data generated by the University of Dayton Research Institute shows that 980 K (1300°F) is high enough to ensure high levels of destruction (>99 percent) of the cytotoxic compounds examined (3).

HAZARDOUS CHEMICALS

Several laboratory solvents are found in medical waste, especially waste from research laboratories and pharmaceutical companies. The Resource Conservation and Recovery Act (RCRA) lists many of these solvents as hazardous compounds. Table 3 lists some hazardous solvents (11). The solvents themselves are not considered "medical waste" in the Medical Waste Tracking Act because they are defined as hazardous

TABLE 3. HAZARDOUS SOLVENTS TYPICALLY FOUND IN MEDICAL WASTE

Acetone	Ethyl alcohol	Petroleum ether
2-Butanol	Heptane	2-Propanol
Butyl alcohol	Hexane	Sec-butyl alcohol
Cyclohexane	Methyl alcohol	Tert-butyl alcohol
Diethyl ether	Methyl cellosolve	Tetrahydrofuran
Ethyl acetate	Pentane	Xylene

waste under RCRA. However, they are often so intimately mixed with medical wastes that separation is impractical. In addition to their hazardous characteristics, these compounds may also form PCDD/PCDF when in the presence of chlorine.

TOXIC METALS

Medical waste contains toxic metals such as lead, cadmium, and mercury. As discussed later, metals may follow one of several pathways to reach the atmosphere. Since metals can not be destroyed by any type of thermal treatment, they present a special control problem.

Researchers at the University of California at Davis conducted a study to identify the sources of toxic metals in medical wastes (12). The research effort focused on lead and cadmium and concluded that plastics in the waste contributed most of these two metals. Cadmium is a component in common dyes and thermo- and photo-stabilizers used in plastics. Lead was found in many materials including plastics, paper, inks, and electrical cable insulation. However, the primary source of lead appeared to be plastics. Like cadmium, lead is used to make dyes and stabilizers which protect plastics from thermal- and photo-degradation. It is ironic to note that the dyes made from lead and cadmium are used to color red bags. Thus, part of the lead and cadmium emissions could be due simply to the red bags that infectious waste is placed in.

RADIOACTIVE MATERIALS

Low-level radioactive waste ($< \mu 100$ Ci/g) (13) is sometimes present in medical waste. As with other components of medical waste, it is difficult to estimate the quantities of low-level radioactive wastes generated at medical facilities. The U.S. Food and Drug Administration estimates that more than 7 million radiopharmaceuticals are administered, 11 million nuclear medicine procedures performed, and 100 million radio-immunology procedures performed as in-vitro diagnostic studies yearly in the U.S. (14). Each of these procedures may generate low-level radioactive waste.

The Nuclear Regulatory Commission (NRC) considers incineration to be an excellent means of disposing of low-level radioactive medical waste and has deregulated some types of low-level radioactive medical waste such as scintillation vials and research animal carcasses with less than 0.05 microcuries of tritium or carbon-14 per gram (11).

PROPERTIES AFFECTING THERMAL TREATMENT

DATABASE

The heating value of a material has a strong effect on its incinerability. The heating value of components of medical waste vary from nearly zero for some pathological wastes and other materials with very high moisture contents to around 35,000 J/g (15,000 Btu/lb) for plastic packaging materials. In the past, medical waste contained large amounts of glass, metal and other durable materials. This caused the waste to have a low average heating value, around 12,000 J/g (5000 Btu/lb). However, plastic has recently replaced the

glass and metal materials. The average heating value is now closer to 14,000-19,000 J/g (6000-8000 Btu/lb) (15).

Environment Canada analyzed the approximate composition of medical and municipal waste (16). Table 4 summarizes the results. Medical waste contains twice the amount of plastics as municipal waste (14.2 percent vs 7.4 percent). EPA estimates plastic content of medical waste to be as high as 20 percent (7). Partly as a result of this difference in plastic content, medical waste has a much higher heating value on average than municipal waste [14,000 J/g vs. 10,070 J/g (6000 Btu/lb vs. 4335 Btu/lb)].

TABLE 4. COMPARISON OF THE COMPOSITION OF MEDICAL, MUNICIPAL AND HAZARDOUS WASTE⁽¹⁶⁾

Waste Component	Amount in Waste, Percent by Weight		
	Medical Waste	Municipal Waste	Hazardous Waste*
Dry Cellulosic Solids	45.1	54.2	0
Wet Cellulosic Solids	18.0	12.2	0
Plastics	14.2	7.4	12
Rubber	0.7		
Solvents			58
Non-Combustibles	20.4	26.2	30
Pathological	1.6		
Heating Value	6000 Btu/lb	4335 Btu/lb	6030 Btu/lb

* For a typical commercial incinerator accepting a broad range of wastes.
1 Btu/lb = 2.324 J/g

Cross/Tessitore Associates conducted a survey of 17 hospitals in the Miami, Florida area to determine the amount of waste produced (17). Researchers classified the waste as pathological, infectious, general, food, or cardboard. Table 5 summarizes the results of the survey. The average heating value of the waste produced was 21,790 J/g (9375 Btu/lb), significantly higher than that of municipal waste.

TABLE 5. AVERAGE COMPOSITION OF MEDICAL WASTES IN MIAMI AREA HOSPITALS⁽¹⁷⁾

Waste Type	Waste Concentration, (Percent by Weight)
Pathological	0.5
Infectious	10.0
General	50.0
Food	30.0
Cardboard	9.5
Heating Value, Btu/lb	9375
Waste Production Rate, lb/bed/day	23
1 Btu/lb = 2.324 J/g	

However, examining the overall composition of medical waste can be misleading. Incinerator operators usually burn waste as it is received. Thus, the waste in the incinerator is rarely an average mixture of all the waste produced in the medical facility. For example, the janitorial staff from one large hospital collects waste from one department at a time. Janitors transport the waste to the incinerator in carts which are dumped directly into the feed chamber. Thus, one or two charges may consist entirely of computer printouts from the accounting department and the next three charges of shipping containers from the warehouse. Later in the day the incinerator may burn several loads of kitchen waste in succession. The refuse burned early in the day when most of the waste consists of paper will be significantly different from the waste burned later on which consists mainly of wet food waste.

Table 6 lists typical heating values and moisture contents of various components of medical wastes (18). These values illustrate the range of material that may be in an incinerator at any given time. Incinerator designs must not only account for the average heating value of the waste, but must also consider the possible variations in heating value.

TABLE 6. TYPICAL MOISTURE AND HEAT CONTENTS OF VARIOUS COMPONENTS OF MEDICAL WASTE⁽¹⁸⁾

Waste Component	Bulk Density as fired, (lb/cu.ft.)	Moisture Content as fired, (Weight percent)	Heat Content as fired, (Btu/lb)
Human anatomical	50- 75	70-90	800- 3,600
Plastics	5-144	0- 1	13,860-20,000
Swabs, absorbents	5- 62	0-30	5,600-12,000
Alcohol, disinfectants	48- 62	0- 0.2	10,980-14,000
Infected animals	30- 80	60-90	900- 6,400
Glass	175-225	0	0
Bedding, shavings, paper, fecal matter	20- 48	10-50	4,000- 8,100
Gauze, pads, swabs, garments, paper, cellulose	5- 62	0-30	5,600-12,000
Sharps, needles	450-500	0-1	0- 60
Fluids, residuals	62- 63	80-100	0- 2,000

1 Btu/lb = 2.324 J/g
1 lb/cu. ft. = 16.03 kg/m³

Besides the heating value, the elemental or "ultimate" composition of a waste also has an effect on the incineration process. Table 7 lists the ultimate analysis for typical medical wastes generated at a hospital (4).

TABLE 7. TYPICAL ULTIMATE ANALYSIS OF MEDICAL WASTES.

Component	Weight Percent
Carbon	51.10
Hydrogen	6.23
Oxygen	21.31
Nitrogen	0.45
Sulfur	0.17
Chlorine	4.12
Moisture	9.00
Ash	7.62
Heating Value	9240 Btu/lb

$$1 \text{ Btu/lb} = 2.324 \text{ J/g}$$

Impact of Waste Properties

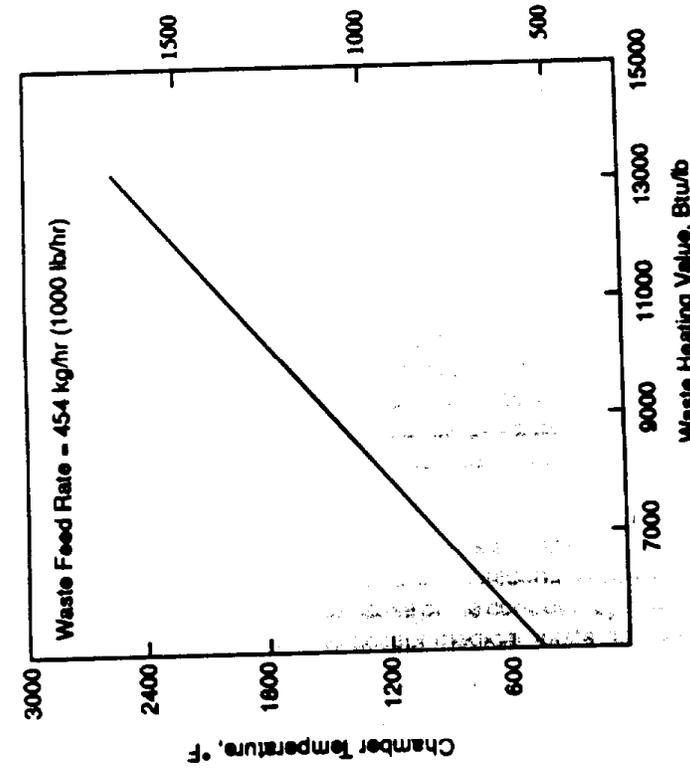
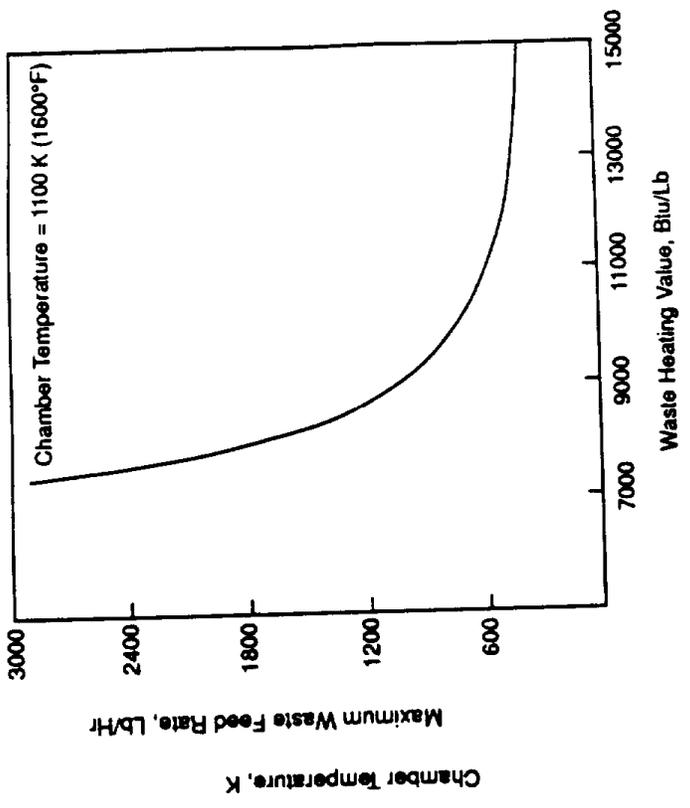
Energy and mass balance calculations were used to assess the potential impact of waste composition on incinerator operation. While the calculations are approximate, they do highlight the types of behavior that would be expected. Figure 12a illustrates the impact of waste heating value on chamber temperature. The heating value of medical waste can potentially vary from 33,000 J/g (14,000 Btu/lb) (packing material and plastic) to below 12,000 J/g (5000 Btu/lb) (pathological waste). If measures are not taken to control the chamber temperatures, variations of nearly 1700 K (3000°F) would be observed. As will be discussed later, the wide variations in waste heating value plays a key role in the design and operation of modern medical waste incinerators.

In addition to affecting the primary chamber temperature, the heating value of the waste affects the waste feed rate. Figure 12b illustrates the impact of waste heating value on maximum waste feed rate. The Figure is based on the assumption that the waste feed rate is used to control the primary chamber temperature. As will be discussed later, waste feed rate and combustion air are both used to control the temperature in the primary chamber. However, combustion air is mainly used to control fluctuations which occur between feed cycles (1-10 min) while waste feed rate is used to control long-term variations in temperature. As shown in Figure 12, the maximum feed rate decreases as the heating value of the waste increases. If the heating value of the waste drops below a critical value, the target temperature can no longer be maintained without the use of auxiliary fuel. For the example shown in Figure 12, this critical value is about 16,000 J/g (7000 Btu/lb).

AMOUNT PRODUCED

Waste definitions and tracking procedures vary significantly from State to State and facility to facility. This makes it very difficult to determine the exact quantity of medical waste produced. Small clinics, nursing homes and similar facilities complicate the problem because they are usually exempt from medical waste regulations.

Researchers have made several attempts to determine the quantity of waste generated by hospitals because hospitals represent the largest point sources of medical wastes. Table 8 summarizes several different estimates of amounts of medical waste generated in hospitals. Recent studies estimate there are 7,000 hospitals in the U.S., containing a total of 1.3 million beds. Using the estimates shown in Table 8, there



Note: 1 Btu/lb = 2.324 J/g
 1 lb/hr = 0.454 kg/hr

- a) Primary Chamber Temperature
- b) Maximum Feed aRate

Figure 12. Impact of waste heating value.

TABLE 8. COMPARISON OF ESTIMATES OF QUANTITY OF HOSPITAL WASTE PRODUCED

Source	Generation Rate, (lb/bed/day)	
	General	Infectious
EPA, 1988 ⁽¹⁾	21.6	0.28
NY Dept. of Health, 1988 ⁽¹⁾	20	
Rutala, 1988 ⁽²⁾	16 - 23	
Cross, 1988 ⁽¹⁷⁾	17 - 23	2.4
EPA, 1987 ⁽¹⁵⁾	13	
Environment Canada, 1986 ⁽¹⁶⁾	9.56	0.66
Rutala and Sarubbi, 1983 ⁽¹⁾	9.95	0.5 - 1.09

1 lb = 0.454 kg

is between 5600 Mg/day (6200 ton/day) and 13,000 Mg/day (14,000 ton/day) of general medical waste produced in U.S. hospitals. However, these numbers should be treated with caution. Many of those closely associated with the disposal of medical waste feel that waste production is not proportional to the number of beds in a hospital. Several other factors are important, including (19):

- Number of employees
- Degree of specialization
- Methods of work (e.g. do they double bag waste from isolation wards, and what protective clothing is used for different levels of isolation)
- Number of outpatients

The proportion of the waste generated in each department of a hospital illustrates the variations in waste production that occur within a single hospital. In 1987, the government of the Administrative Region of Puglia (Apulia), Italy, surveyed the waste produced by a university hospital in the region (20). Table 9 summarizes the results.

In another study, the Los Angeles County Sanitation Districts determined the quantity of waste produced at U.S. hospitals as a function of patient days. A patient day consists of a one-day stay by an inpatient, an emergency room visit, or an outpatient visit (21). Table 10 summarizes the data from this study.

Though it is recognized that the current method of estimating the total amount of medical waste produced by hospitals is limited, the data needed to make a more accurate estimate is not available.

TABLE 9. PROPORTION OF TOTAL MEDICAL WASTE STREAM CONTRIBUTED BY EACH HOSPITAL DEPARTMENT IN ITALY

Department	Quantity, wt- %
Internal medicine	9.2
Surgery	10.0
Obstetrics/gynecology	11.8
Pediatrics	10.5
Dialyses	51.2
Other Specialties	7.3

TABLE 10. MEDICAL WASTE PRODUCTION RATES AT A U.S. HOSPITAL

Month, 1973	General Medical Wastes		Infectious Wastes	
	lb	lb/patient day	lb	lb/patient day
May	260,560	16.0	861	0.082
June	277,560	17.7	1082	0.092
August	303,240	18.4	587	0.066
Average	280,450	17.4	843	0.053

1 lb = 0.454 kg

There have been a few efforts to determine the amount of waste produced by smaller clinics and doctors' offices. L. Yandell of Kaiser Hospital, San Francisco estimated that medical clinics typically generate 3.2 kg (7 lbs) of waste per patient visit (22). Brunner et al. (23) report that nursing homes produce about 1.2 kg/patient-day (3 lb/patient-day) and medical laboratories produce 0.23 kg/patient-day (0.5 lb/patient-day). Table 11 summarizes the total number of medical facilities in the U.S. (24).

Despite the disagreement about the exact amount of medical waste produced in the U.S. each year, there is little doubt that this number is quite large. Medical waste production increased in the 1970's as hospitals shifted to the use of disposable equipment. A second increase has been observed recently as hospitals implement "universal precautions" because of the controversy surrounding AIDS patients. Over this same period, the number of landfills willing to accept medical waste has decreased.

TABLE 11. NUMBER OF MEDICAL FACILITIES IN THE U.S.

Type of Facility	Number of Facilities
Hospitals	5,800
Nursing Homes	16,000
Outpatient Clinics	12,500
Doctors Offices	180,000
Dentist Offices	98,400
Funeral Homes	14,600
Medical Laboratories	13,200
Veterinary Facilities	Unknown

SECTION 4

COMBUSTION SYSTEMS

Incineration is the most commonly used method of thermal treatment for the disposal of medical waste. An incineration system generally consists of two classes of equipment:

- Combustion system
- Flue gas cleaning system

The combustion system burns the waste, and the flue gas cleaning system controls the emissions from the combustion system. This section provides a summary of the state-of-the-art equipment used in the United States to incinerate medical waste. The flue gas cleaning systems are described in later sections of this report.

HISTORICAL DEVELOPMENT

In the 1960's and early 1970's, incineration systems were almost exclusively designed and built to stringent standards published by the Incineration Institute of America (IIA) (25). This institute ceased operation in 1972 but many existing medical waste incinerators conform to the IIA design standards and generally perform according to IIA suggested performance standards. Pollutant emission performance standards for these older systems were generally restricted to maintaining visible smoke below Ringelmann No. 2 and to limiting particulate matter emissions below 0.46 g/Ncm (0.2 gr/dscf) (corrected to 12 percent CO₂).

In 1974, the U.S. EPA promulgated regulations for hazardous waste incinerators greater than 45 Mg/day (50 ton/day), limiting particulate emissions to 0.18 g/Ncm (0.08 gr/dscf). In response to that regulation, wide use of "controlled-air incineration" occurred since the two-stage, starved-air configuration was capable of regulatory compliance without add-on particulate control devices.

In the late 1970's, many incinerators were installed to recover energy from municipal solid waste. This was followed in the mid-1980's by concern for dioxin and furan emissions. Spray dryers used with fabric filters were shown to be effective in removing dioxins and furans from municipal waste combustion exhaust gas as well as controlling acid gas and particulate emissions. Largely in response to dioxin concerns, EPA recommended addition of spray dryer/fabric filter systems and effectively forced use of this technology by recommending 90 percent control of HCl emissions, 70 percent control of SO₂, and control of particulate matter emissions to the 0.02-0.07 g/Ncm (0.01-0.03 gr/dscf) range in preliminary guidance provided to States for regulating new municipal solid waste incinerator systems.

Many States are adopting stringent regulations for medical waste incinerators. Without federal guidance on achievable emission performance or beneficial unit operating practices, these new State requirements are widely divergent. The gradual evolution of medical waste incineration technology during the 1970's and early 1980's has greatly accelerated, and the incineration industry is in a major state of flux.

CLASSIFICATIONS OF COMBUSTION EQUIPMENT

Three types of incinerators are generally used to burn medical waste. These are:

- Starved-air modular incinerators
- Excess-air modular incinerators
- Rotary kilns

STARVED-AIR MODULAR INCINERATORS

The major product line of most of the manufacturers contacted consists of "controlled" or "starved"-air incinerators. Figure 13 is a diagram of a typical dual chamber starved-air incinerator.

Waste is fed into the lower combustion chamber which is supplied with only about half of the air theoretically required to stoichiometrically burn the waste. Thus, the lower chamber is operated in a "starved-air" mode. The waste fed to the incinerator contains moisture, volatile matter, fixed carbon, and ash. The distinction between volatile matter and fixed carbon is that upon heating, volatile matter will be released from the solid (not necessarily burned) while fixed carbon is the remaining organic solid. Fixed carbon can burn only when an oxidizer diffuses to the solid's surface.

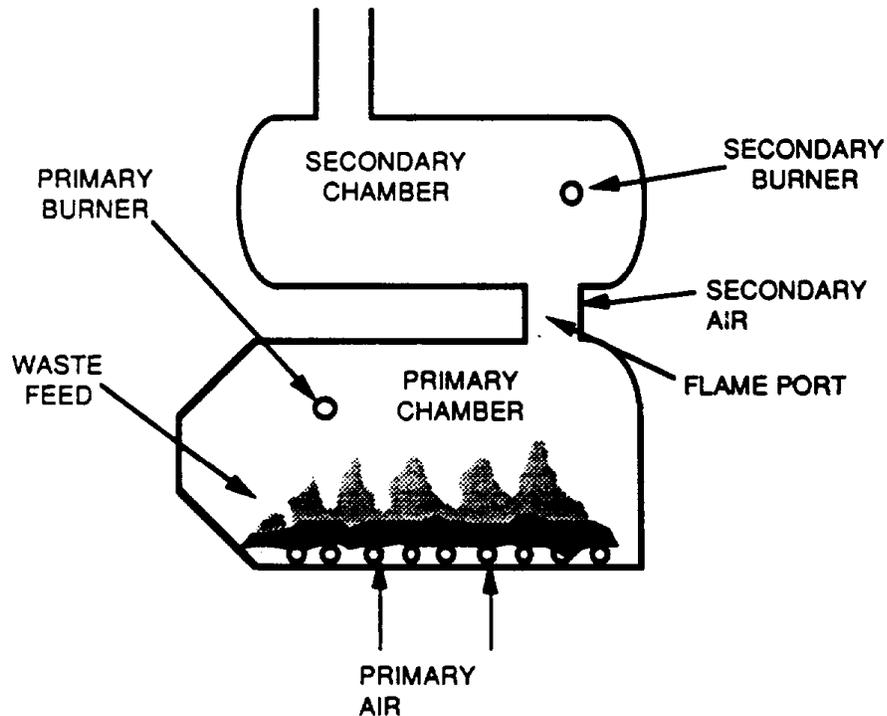


Figure 13. Dual-chamber, starved-air incinerator schematic.

When waste is fed into the lower chamber, moisture and volatile matter are rapidly released and the volatiles will at least partially burn to release heat. The fixed carbon on the incinerator hearth will also burn but only at high temperature when an oxidizer diffuses to the surface. Thus, to provide for char burnout, air enters the primary chamber from beneath the burning bed of waste. This air is often referred to as underfire air. Due to the limited quantity of air admitted to the primary chamber, combustion gases above the bed will not be fully burned and will contain percent level concentrations of CO, H₂, and unburned hydrocarbons.

The partially burned primary gases exit the lower chamber and enter a connecting duct to the second stage. About 75 percent of the total combustion air (three times the underfire air rate) is introduced through ports in this connecting duct. The short connecting duct is often referred to as the flame port and the extra air is called main flame port air. This terminology is derived from the fact that a substantial secondary flame is formed in the flame port when air is added to the fuel-rich gases leaving the primary chamber. The quantity of air added in the flame port is enough to bring the gas mixture in the second stage to excess air conditions. The secondary chamber ideally provides sufficient excess oxidizer, mixing, reaction time, and temperature to complete the combustion of hydrogen and carbonaceous material (CO, hydrocarbon gas and carbonaceous solids) exiting the lower chamber. At the exit of the secondary zone, the flue gas will mainly consist of CO₂, water vapor, oxygen, and nitrogen.

The volume of the primary zone in a controlled-air incinerator is sufficiently large to ensure that the gas velocity is low. By maintaining low velocities, only a small quantity of non-combustible matter is entrained and carried through the remainder of the system. This design feature is the reason controlled-air incinerators can meet a 0.18 g/Ncm (0.08 gr/dscf) exhaust particulate loading limit without use of air pollution control devices.

Both the primary and secondary chambers in controlled-air incinerators consist of a steel shell lined with refractory material to minimize heat losses. Gas temperature at the primary zone exit is typically adjusted to about 1000-1100 K (1400-1600°F) by controlling the amount of underfire air. The upper chamber is designed to provide the residence time and exit temperature specified in local regulations. Typically, the exit gas temperature will be about 1300 K (1800°F) and the gases will have a dwell time of 1 second or more. An auxiliary fuel fired burner is provided in the secondary chamber to deliver supplemental heat if the minimum exit temperature cannot be maintained.

EXCESS-AIR MODULAR INCINERATORS

While these units may be operated continuously, they are usually operated in a batch mode. Thus, they are commonly referred to as batch or retort incinerators. A typical batch incinerator is shown in Figure 14.

Waste is manually placed in the combustion chamber. The charging door is then closed and the afterburner ignited. Once the stack reaches a target temperature, the primary burner is ignited. The primary burner ignites the wastes. Initially, moisture and volatile organic material are vaporized. The volatile gases burn in the primary chamber and the stack. The waste itself then begins to burn. Air is supplied at a constant rate throughout the combustion process. During this initial period, substoichiometric quantities of air are typically supplied. As the organic material is consumed, less air is needed. Eventually, the chamber operates at excess air levels.

Once the wastes are consumed, the primary burner shuts off. After a delay, the afterburner shuts off. When the chamber cools, the ash is manually removed and a second charge placed in the chamber. The cycle may be controlled by a timer only or may involve a more complex control system which uses chamber temperature as a criterion as well.

ROTARY KILNS

A typical rotary kiln incinerator is shown in Figure 15. The systems include a slowly rotating cylinder or kiln. Waste is fed from a hopper into the kiln. The kiln walls are made of acid-resistant refractory brick. The

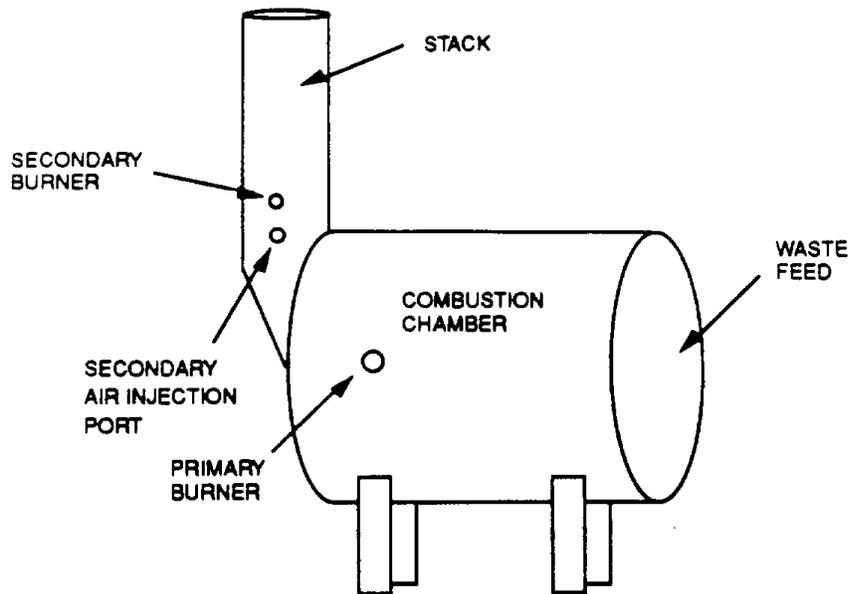


Figure 14. Typical batch incinerator.

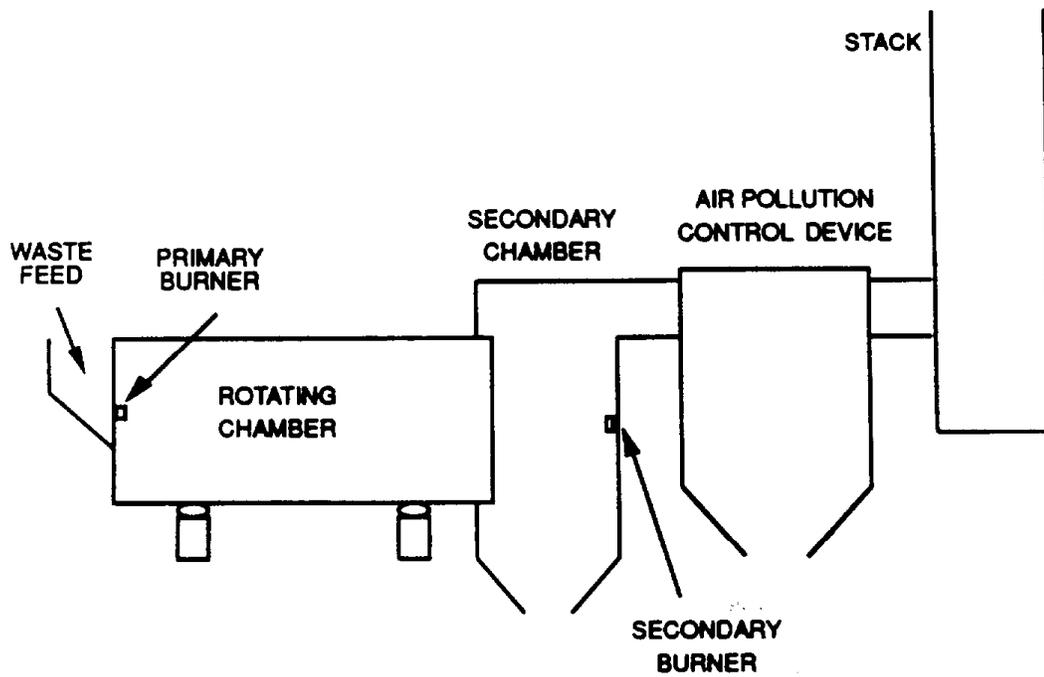


Figure 15. Typical rotary kiln incinerator.

kiln is inclined at a small angle (about 5 degrees). This causes the waste to move slowly from the feed hopper to the discharge end of the kiln. The rotation of the kiln mixes the waste and aids in moving it through the system. Increasing the rotation speed or the angle of inclination will decrease the solids residence time. Both an auxiliary fuel burner and a port opening to admit combustion air are located at the front face of the unit. The auxiliary fuel burner is fired during start-up and intermittently after that based on the measured kiln exit gas temperature. Combustion air is admitted to the kiln through the ports on the front face as well as through seal leakage and is controlled by the kiln operating pressure. Kiln pressure is typically maintained at -12 to -25 Pa gauge (-0.05 to -0.10 in. W.G.).

Ash drops from the kiln onto an overlapping pan conveyor and is transported to a waste hopper. Typical ash carbon contents are almost as high as those observed in starved-air units with continuous ash removal.

Flue gas exits the kiln and goes into a secondary chamber which is equipped with an auxiliary fuel burner and a temperature control system. Secondary air is added to ensure thorough mixing. An auxiliary fuel burner is located in the secondary chamber, but is mainly used for start-up. Typically, the secondary chamber is sized and controlled for 1- or 2-second residence time at 1400 K (2000°F).

CURRENT DESIGN PRACTICE

This section of the report presents a brief review of equipment offerings from major manufacturers of medical waste incineration equipment. The material presented was developed from plant visits or telephone interviews with corporations identified as major system suppliers. The organizations contacted include:

Industrionics*
489 Sullivan Avenue
South Windsor, CT 06074
(203) 289-1588
Mr. Ray Zanni

*Recently purchased by:
Enercon Systems, Inc.
300 Heron Street
Elyria, Ohio 44035-4829
(216) 323-7080
David A. Hoske, President

Joy Energy Systems, Inc.
11900 Westhill Drive
Charlotte, NC 28241-0647
(704) 587-8000
Mr. Steve Shuler

Simonds Manufacturing Corporation
304 Progress Road
Auburndale, FL 33823
(813) 967-8566
C. Michael Booth

**M&S Engineering & Manufacturing
Company, Inc.**
95 Rye Street, Box 445
Broad Brook, CT 06016
(203) 627-9396
Zygmunt J. Przewalski

Basic Environmental Engineering Inc.
21 West 161 Hill
Glen Ellyn, IL 60137
(312) 469-5340
John N. Basic, Sr., P.E.

Cleaver Brooks
P.O. Box 421
Milwaukee, WI 53201
(414) 961-2958
Tom Van Remmen

Vulcan Waste Systems, Inc.
1050 United Penn Bank Bldg.
Wilkes Barre, PA 18701
(717) 822-2161
E. G. Klein

Consumat Systems, Inc.
P.O. Box 9379

International Waste Industries
1777 Walton Road, Suite 216

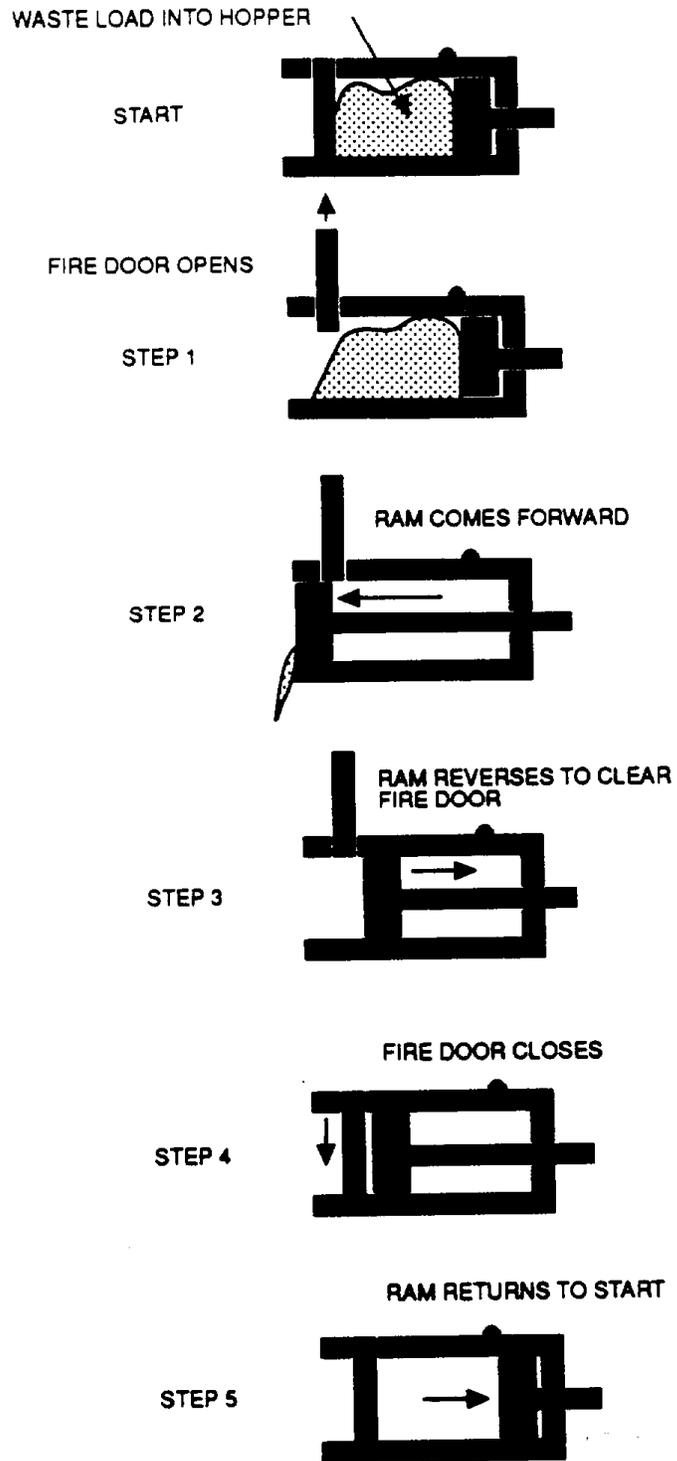


Figure 16. Waste feeding sequence in Joy Systems.

Hearth Systems and Ash Transfer Rams--

Small incinerator systems may have only one hearth and require manual ash removal at the end of the day. Larger systems have several hearth sections with internal rams to move the waste along the hearths. Sequential hearth sections are arranged like a staircase with the face of the ram conforming to the size and shape of the step. Typically, there will be two or three hearth sections.

Underfire Air--

Underfire air is generally added through ports in the floor or side walls of each hearth section. Underfire air is not added to the first hearth in multi-hearth systems built by Joy, but is added nearly uniformly through many ports in later hearth sections. Mechanical fingers are provided to clean material which could clog these ports. The clogging issue can become significant if waste bed temperatures get too high and cause some metals in waste (such as aluminum cans) to melt. Molten metal can flow into the ports and solidify when cooled by the underfire air.

As noted previously, char burning occurs only when an oxidizer reaches the surface. Since a controlled-air incinerator uses substoichiometric air quantities in the primary chamber, a high degree of carbon burnout is difficult to achieve. One of the options offered by Joy involves injecting steam below the waste bed on the rear hearth sections. This promotes the gasification reaction:



Since this reaction is endothermic (absorbs heat instead of releases heat), it helps to cool the ash bed and reduce plugging of the underfire air ports.

Ash Removal--

At the end of the final hearth section, ash is allowed to fall into a water filled pit. This standard arrangement permits continuous ash discharge from the system while providing an air seal for the starved-air primary chamber. A hydraulically operated "ash hoe" digs the quenched ash from the pit and pulls it into an ash cart for eventual disposal.

Temperature Control--

Figure 17 illustrates the variation of combustion gas temperature with percent excess air. Peak flame temperature occurs at stoichiometric conditions. The primary zone of a controlled-air incinerator operates at well below stoichiometric conditions while the upper chamber operates above stoichiometric. Increasing the flow of air to the primary zone increases temperature in that zone in two ways. First, it increases the rate at which the bed of solid waste on the hearth burns. Second, it moves the gas phase mixture closer to stoichiometric conditions. In the secondary chamber, an increase in flame port air makes the combustion gas more fuel-lean and causes the temperature to decrease.

Temperature control in the secondary chamber is straightforward. A thermocouple near the chamber exit senses the temperature and creates a control signal for modulating flame port air. To increase temperature, flame port air is decreased. If the desired temperature cannot be maintained without dropping flame port air below a minimum set point, an auxiliary burner is available to add supplemental heat.

In the primary zone, a similar process is used but the logic is more complex due to phenomena associated with waste charging and waste burnout. Thermocouples near the flame port sense primary zone temperature and are used to control underfire air. On recent advanced models, that same signal is used to control the rate at which waste is added to the system. The primary zone is controlled to operate between upper and lower temperature limits. After a fresh charge of waste begins to burn, the volatile matter is released rapidly and as it burns the gas temperature in the primary chamber rapidly rises to the upper limit. Underfire air modulation is decreased to maintain the temperature below the set point. As the volatiles burn out, air flow can be slowly increased until a maximum air flow limit is reached. The gas temperature then tends to fall slowly

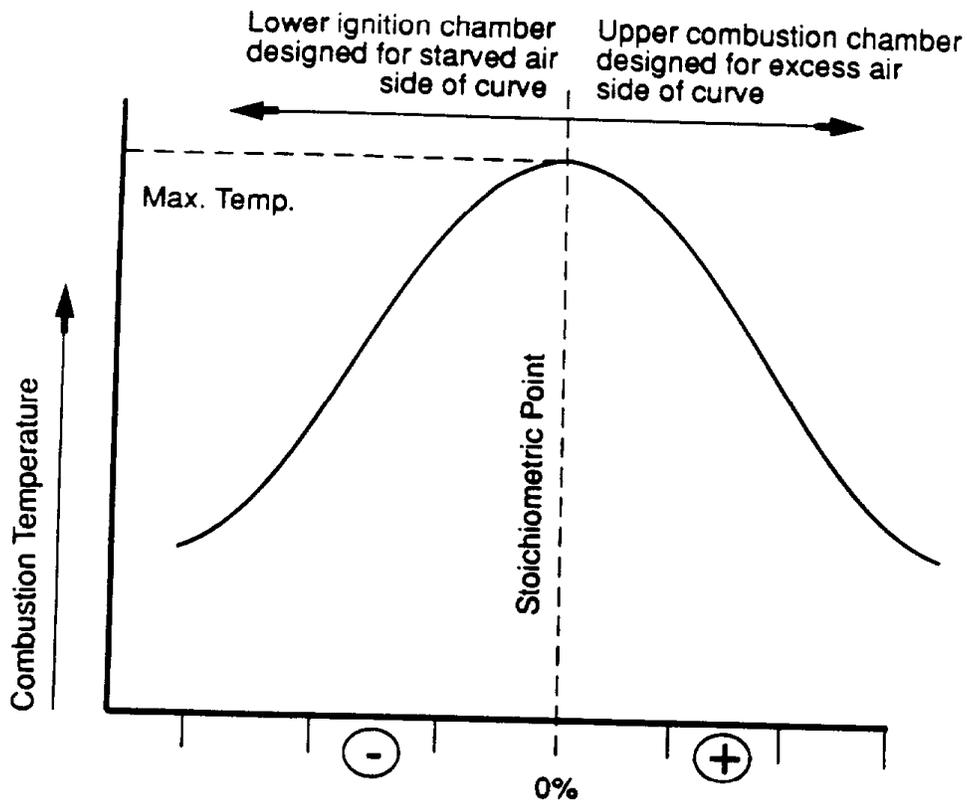


Figure 17. Variations of combustion temperature with excess air.

until the lower temperature set point is reached. This is the time in the process when a fresh charge of waste should be added to the system. This cycle takes about 6 minutes to complete depending on characteristics of the waste.

In older Joy models, waste charging was controlled by the operator allowing the unit to be easily overcharged. In modern designs, the ram feeder will not operate until the automatic control system permits the charging cycle to begin.

Transient Control--

One of the difficult to control features for a "controlled-air" incinerator is that a significant quantity of air leaks into the primary chamber when the fire door is opened for charging. That air causes the primary temperature to rapidly rise and can create an excessively rapid release of volatile matter from the fresh charge. This temporary upset condition increases the quantity of combustible material entering the flame port and may cause the unit to emit a puff of smoke. Joy provides a control system to limit this effect. Shortly before the fire door is opened, the underfire air flow is reduced to its minimum set point and the air flow to the flame port is increased to its maximum condition. Minimizing the underfire air at least partly compensates for the inevitable air in-leakage. It also places the underfire air damper in the proper initial position for temperature control during the normal burning cycle. If a rapid release of volatile matter occurs, the proper combustion control response is to provide enough air in the flame port to burn all the volatiles. By increasing flame port air to its maximum set point, that goal is accomplished.

Waste Heat Boilers--

Combustion gases exiting the secondary chamber contain a significant amount of heat which may be recovered as steam in a waste heat boiler. Inclusion of heat recovery is optional and is dependent upon the need for steam at the facility as well as overall economics. Joy and other similar system manufacturers noted that waste heat recovery is only economically viable for hospitals larger than about 300 beds.

A separate exhaust stack is provided at the exit of the secondary chamber. Without a boiler or air pollution control, this stack provides continuous system exhaust. If downstream equipment is included, this stack is capped and serves as an emergency exhaust. The stack cap automatically opens for a variety of reasons including a boiler failure, loss of water to the air pollution control device, or a power failure.

CONSUMAT SYSTEMS, INC.

There are over 2000 Consumat incineration systems installed for thermal treatment of medical waste. Consumat manufactures an entire line of incinerators with waste throughput rating ranging from about 90 kg/hr (200 lb/hr) to over 90 Mg/day (100 tons/day). There are about 50 Consumat units installed for combustion of municipal solid waste. Consumat controls such a large share of the market that the terms "Consumat" and "two-stage, starved-air, modular incinerator" are often used interchangeably.

Figure 18 illustrates the standard Consumat waste combustion system and the general arrangement of system components for treatment of medical waste. As illustrated, the Consumat system approach is very similar to the two-stage controlled-air concept described previously. In the following description, numbers in parentheses refer to numbered locations in Figure 18. Waste is fed into the system through a hydraulic ram loader (2) with combustion initiated in a multi-hearth lower chamber (3). Internal transfer rams (4) move the waste slowly through the system. The lower chamber is operated in a starved-air mode. Additional air to complete combustion is introduced in the secondary combustion chamber(s) (5). In systems with heat recovery, hot gases pass from the secondary chamber into a waste heat boiler system (6 and 7) and then are routed to flue gas cleaning equipment or to the stack. In non-heat recovery applications, exhaust gas is typically vented through the dump stack (9). Ash from the primary chamber is ejected into the wet sump (1) and conveyed (11) into an ash cart (12) which can be hauled to the local landfill.

There are several system details which distinguish Consumat waste combustors from other controlled-air incineration systems. As shown in Figure 19, ash transfer rams and the underfire air system are integrated. The rams are circular tubes hydraulically activated to move waste across the hearths. Underfire air is used to cool the rams and passes into the primary chamber through a large diameter port on the ram centerline.

Air to the upper combustion chamber is added through a series of ports located around the periphery of the secondary chamber instead of through ports in the primary to secondary transfer duct. These secondary air ports are provided at several axial locations in the secondary chamber. Jet diameter and velocity are designed to assure that secondary air penetrates across the chamber.

As noted earlier, different States have different requirements for the minimum residence time of gases in the secondary chamber. Some require 1 second while others require 2 seconds. The Consumat design response is consistent with modular construction philosophy. The standard secondary chamber has a residence time of 1 second and is equipped with an auxiliary fuel burner. If State or local regulations dictate a 2-second residence time, Consumat provides two standard modules in series including two auxiliary fuel burners.

Consumat provides automatic control systems quite similar in operation to those described previously for Joy. This includes automatic control of primary and secondary temperature, lockout of the charging system until the unit is ready to accept additional waste, and an anticipator cycle to minimize the potential of puffing.

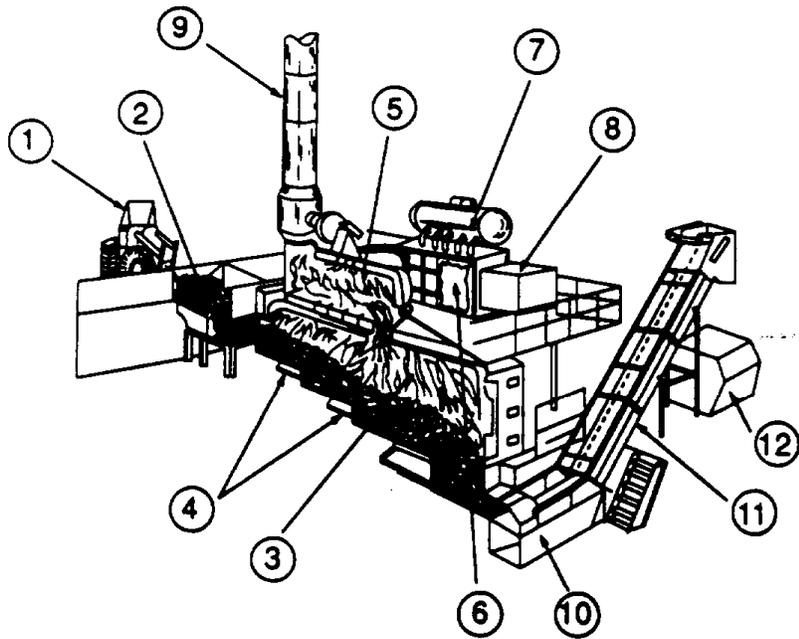
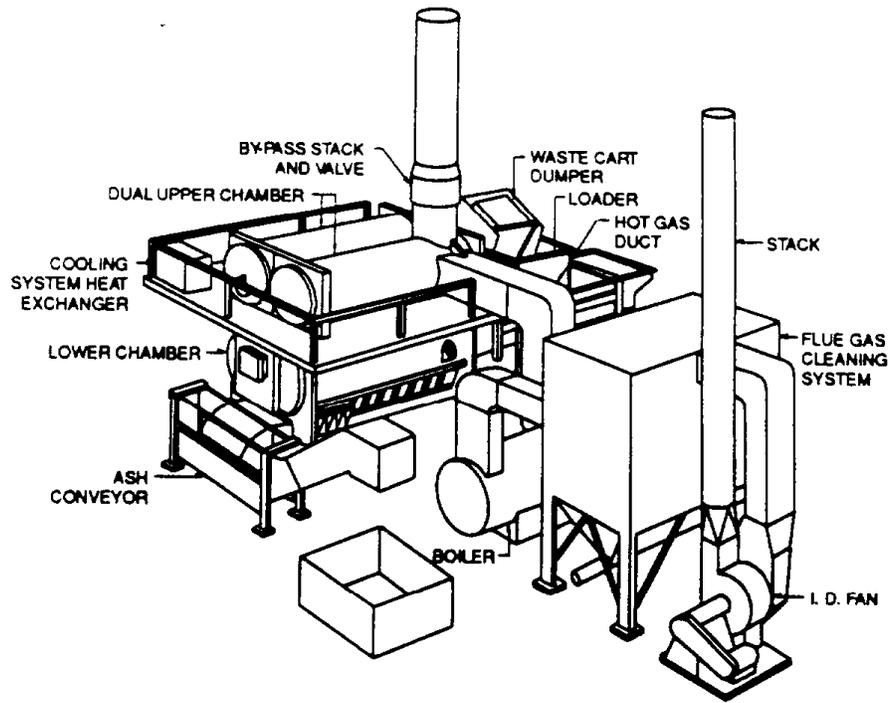


Figure 18. Standard Consumat Systems incinerator configurations for medical waste.

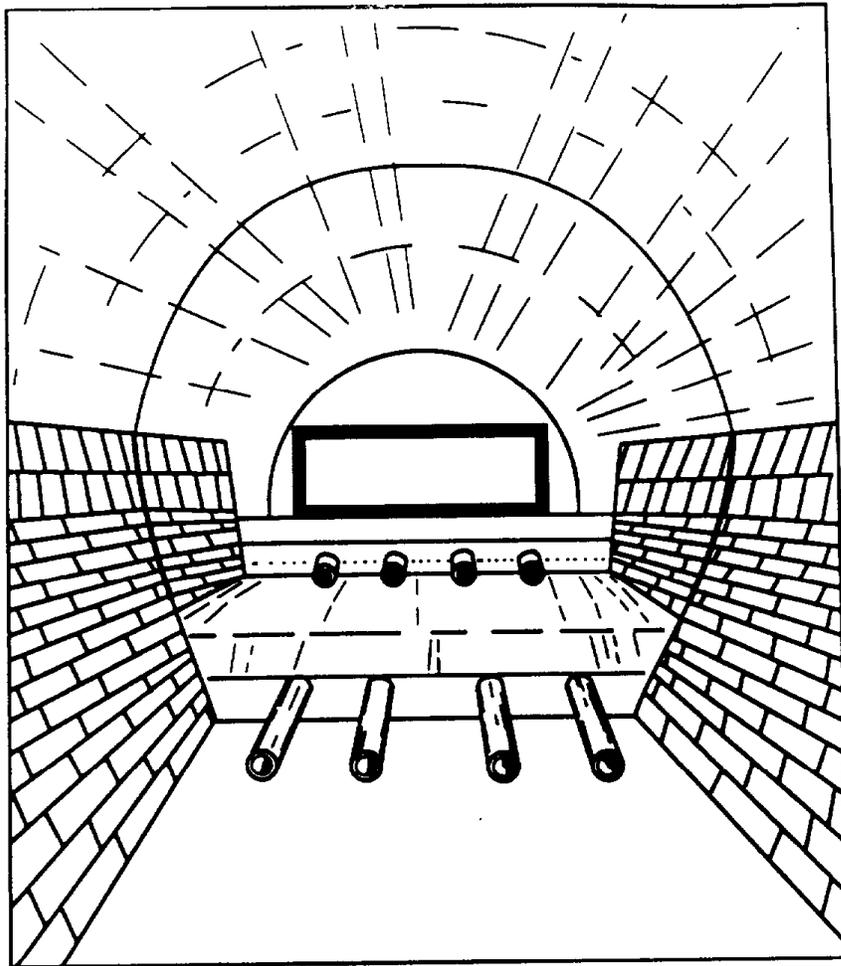


Figure 19. Internal transfer rams in primary chamber of typical Consumat facility.

With few exceptions, new Consumat installations are being equipped with air pollution control systems. They prefer to use dry, hydrated lime injection for acid gas control and a baghouse for particulate matter control. This type of system will be discussed in a later section.

SIMONDS MANUFACTURING.

Simonds Manufacturing, located in Auburndale, Florida, manufactures controlled-air incinerators and has captured a large portion of the medical waste incineration market. The product line is generally divided into automatic feed (AF Series) and batch fed (B Series) units. These two product series will be discussed separately below.

The Simonds AF product line is designed according to the general controlled-air, two-stage combustion philosophy discussed previously. The primary stage is operated under fuel-rich conditions while the

secondary chamber is operated in an excess-air mode. Simonds Manufacturing implements this general controlled-air philosophy using several design features unique among the various manufacturers surveyed in the current study. The large-scale, AF series units are readily distinguishable by the flat chamber walls and the rectangular cross-section. This mechanical design characteristic was adapted from the metallurgical industry and uses external box beams for structural support of the outer steel shell. Refractory is anchored to the flat steel walls.

Waste is fed to the first hearth with an automatic feeder, moved through the system with internal transfer rams and dropped from the incinerator into a water quench pit. Combustion air is supplied to the lower chamber by dampered forced-draft fans as underfire air below the waste bed creating a substoichiometric gaseous environment. The remainder of the combustion air is introduced through ports in the short transition duct connecting the primary and secondary combustion chambers. The Simonds AF Series incinerators use a unique method to distribute underfire air to the second and later hearths. As with most other manufacturers surveyed, little or no underfire air is supplied to the first hearth section. In the second and later hearth steps, air enters the chamber through lateral plenums within trenches located on the floor. These plenums and a large part of the entire last hearth section are covered with a thick layer of crushed stone. This design feature is intended to help distribute the underfire air to the entire waste bed, thereby creating a more uniform burning profile and improving ash burnout.

The semi-continuous feed system of the AF Series incinerators is composed of a 5.7-m³ (200-ft³) storage hopper, hydraulic rams, a guillotine door to the furnace and a water jacketed compaction sleeve. One of the special features of this system is a hydraulic ram to break up waste bridges that may form in the hopper region. In addition, the charging ram is programmed to create a slug of compacted waste in the water jacketed compaction sleeve. The dense slug of waste augments the guillotine door in blocking entry of tramp air into the substoichiometric lower chamber. Flame detectors and water sprays are provided in the compaction sleeve to detect and respond to any active burning that may occur in that region. Once in the primary chamber, the densified slug of waste is in direct contact with burning waste in the lower chamber.

The primary and secondary combustion chambers in Simonds incinerators are connected by one or more short circular ducts with many ports for addition of secondary air. The number of ducts (flame ports) is established by the size of the facility, allowing the partially burned combustion products to be extracted uniformly from the primary chamber and distributed across the width of the secondary chamber. The small cross section of each flame port allows for more efficient mixing of the gases from the primary chamber with the secondary air.

The combustion control scheme used by Simonds for AF Series machines is similar to that described earlier for other manufacturers. The temperature of the primary chamber is monitored with thermocouples. Primary and secondary air injection rates are varied to control the temperatures. Special modulation of primary and secondary air flow is used to compensate for the rapid release of volatile material when a fresh charge of waste is added to the system. Waste feeding is controlled on a timed cycle to maintain desired volumetric heat release rates in the lower chamber. Auxiliary fuel burners are located in both the primary and secondary chambers for unit preheat and to provide additional heat input for unusual operating conditions. A computer based control system has been developed for the incinerators.

Simonds also manufactures batch-fed incinerators. The small, batch-fed product line includes a unique system called the Simonds Superbatch incinerator. Historically the incinerator manufacturers have given little attention to careful control of the combustion process in batch incinerators. The phrase "stuff and burn" is widely used to describe how those small units were designed to operate. Simonds developed the Superbatch line of incinerators to overcome both the real problems and the negative public perception of small systems. Simonds batch incinerator product line includes control feed back loops generally found only on large scale, high cost machines. A schematic of a Superbatch machine designed to burn a 450-kg (1000-lb) charge of waste is presented in Figure 20. Key features include the fact that once the waste is charged, the combustion

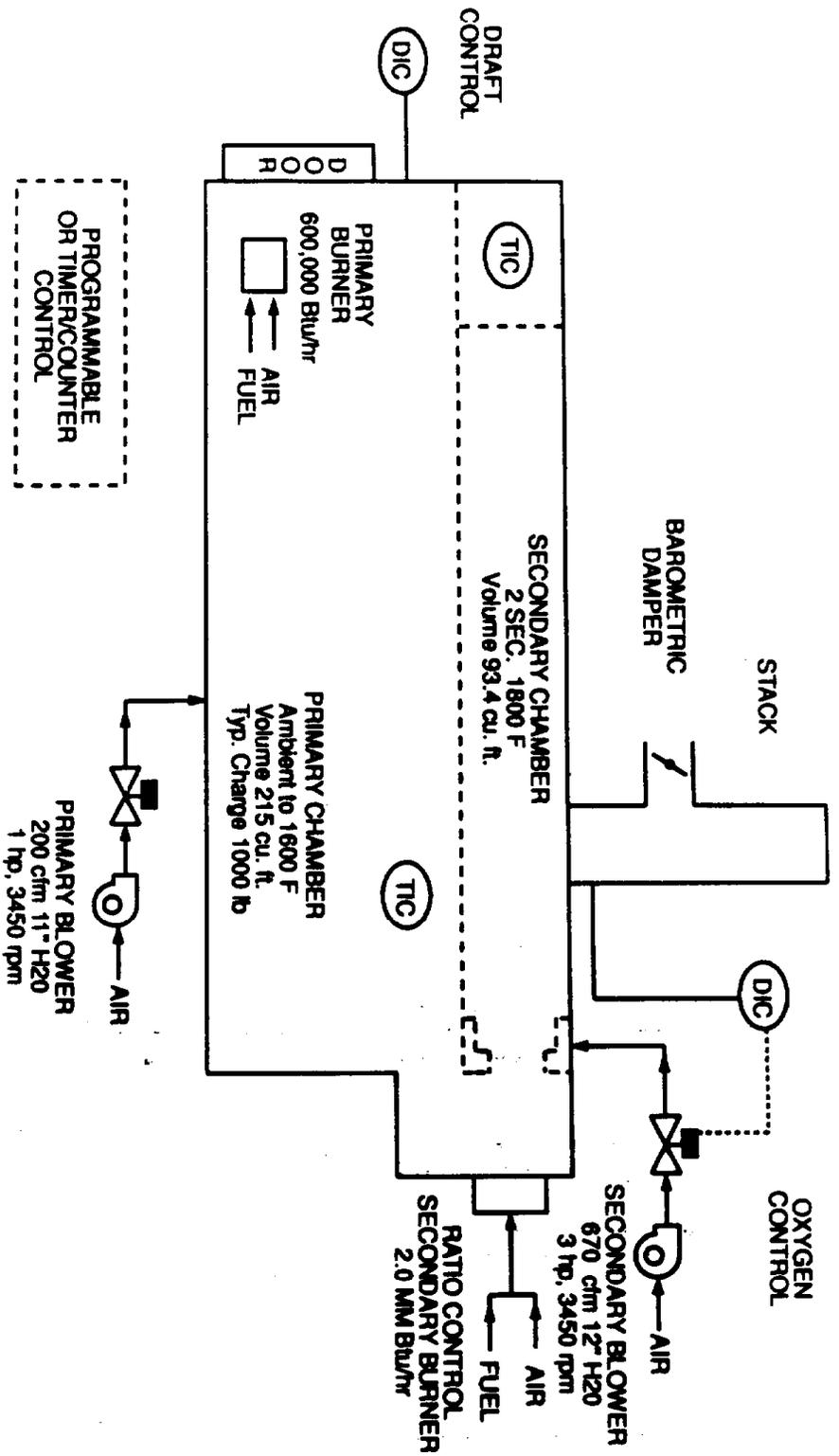


Figure 20. Simonds Model 215158 "Superbatch" incinerator.

chamber is sealed shut allowing no air in-leakage and no operator control of the burning process. Air to the primary zone is supplied by a controlled damper fan as opposed to the traditional practice of air supply by natural draft through holes in the furnace wall. An auxiliary fuel burner in the primary chamber maintains temperature in that zone at required levels and is used to ignite the waste. A large auxiliary fuel burner with fuel/air ratio control is provided at the inlet of the secondary chamber. The secondary chamber is designed for 1250 K (1800°F) operation and 2-seconds residence time. The quantity of excess air in the system exhaust is continuously monitored and provides a feedback control signal to the secondary air fan. These features help to maintain controlled combustion during the entire waste-burning cycle. By allowing the waste to "burn down," it is possible to achieve very low carbon content in the ash. That is a performance characteristic not typically found in continuous duty machines. The main use for this type unit would be at small facilities generating only a limited quantity of waste each day.

Thermtec

Thermtec, Inc., located in Tualatin, Oregon, has been in business for over 20 years and has installed approximately 750 units. They only manufacture multi-chamber, starved air incinerators equipped with ram feeders. For purposes of the current study, the three Thermtec units located in California at Kaiser Hospital, Sutter General Hospital, and American Environmental are notable.

Thermtec's equipment line is quite similar to other controlled-air incinerators. All waste feeding is controlled by a timed cycle or by a temperature measurement. Thermtec attempts to prevent unit overcharging by limiting the size and stroke of the ram. A distinguishing feature of Thermtec's incinerators is a narrow flame port geometry connecting to a long, narrow secondary chamber. The secondary chamber is mounted above and either parallel or perpendicular to the primary chamber. An auxiliary burner is positioned to impinge its flame on the secondary chamber wall. This is intended to cover the narrow secondary chamber cross-section and to promote mixing.

INTERNATIONAL WASTE INDUSTRIES (IWI)

IWI is located in Blue Bell, Pennsylvania, and has been in business for about 10 years having bought rights to their product line from Kellogg-Mann. IWI units have been in operation for decades. The first stack tests on one of these units was performed in New York in 1972. The basic technology is two-stage starved-air incineration. Their product line covers units with a rated capacity as small as 35 kg/hr (75 lb/hr) and as large as 2300 kg/hr (5000 lb/hr). Many of the basic features of this system are very similar to those of controlled-air incinerators discussed earlier, but the IWI personnel stress the importance of process details. Only limited information on those details was provided but for at least two installations, they were able to achieve 0.03 g/Ncm (0.015 gr/dscf) particulate matter emissions without the use of air pollution control devices.

The rationale given for low particulate emission levels was extreme care in waste movement through the lower chamber. IWI uses a multi-step hearth system and will employ one or even two rams per hearth. Bed thicknesses of 20 to 25 cm (8 to 12 in.) are maintained and IWI may provide a refractory hump down the center of the hearth. Underfire air is introduced through the furnace side walls (and through the hump if it is used) and directed into the waste pile (not above the pile). A unique feature is the use of recirculated flue gas for the underfire "air." It is unclear how use of flue gas recirculation enhances particulate emission performance, but certified performance data clearly indicate enhanced performance. It should also be noted that IWI offers (as an option) the use of a mixture of air and steam for injection to the final hearth. The purpose of this approach is to enhance fixed carbon burnout. A further explanation for the particulate matter performance was attentive control of tramp air in-leakage to the primary chamber. For example, the primary zone auxiliary fuel burner is designed and located such that no air is needed to keep it cool when it is not in use.

IWI notes that they use standard modules but adapt the design to meet requirements of each job. Most manufacturers have similar practice but since IWI has been active in foreign and domestic markets, that flexibility has been important. For example, for units installed in Saudi Arabia, the incinerator feeder system had to be designed to accommodate an entire dead camel.

A general concern expressed by IWI senior personnel was that regulatory insistence upon add-on air pollution control devices tend to thwart combustion technology development. Extensive combustion controls to limit particulate matter emissions are not free and if regulatory agencies demand air pollution control devices, those combustion controls will not be price competitive.

BASIC ENVIRONMENTAL ENGINEERING

Basic Environmental Engineering is located in Glen Ellyn, Illinois, and offers a multi-stage incineration technology which has many differences from the "controlled-air" technologies discussed earlier. Incinerators for medical waste were adapted from those developed by Basic for municipal solid waste. Figure 21 illustrates a Basic Environmental Engineering system for municipal solid waste. Key features of the Basic technology include:

- Pulse Hearth™
- Stoichiometric fuel/air ratio in primary chamber
- Endothermic second stage/exothermic third stage
- Excess air added through "thermal exciters"

Each of these features is described in more detail.

The primary chamber contains a series of grates beginning with a fixed drying grate followed by one or more Pulse Hearths. The critical combustion issue is that the hearth itself is pulsed causing the bed of waste to move through the primary chamber. This motion also stirs the bed material, exposing fresh surface for oxidation. As illustrated in Figure 22, each Pulse Hearth is suspended from an external frame, using cables connected to four suspension points. At the forward end of each Pulse Hearth, there are two to four (depending on unit size) air bag/load levelers. (These double-convoluted air bags are adapted from standard load levelers used on transfer trucks). A pulse of air from an accumulator tank causes the bags to expand, pushing the hearth forward a distance of about 10-15 cm (4-6 in). The forward motion is rapidly decelerated, however, when the hearth strikes a 10-cm (4-in.) thick rubber bumper attached to a stationary support. This rapid deceleration causes the waste pile to slide over the hearth, effectively moving the waste down the chamber. The entire hearth then swings back to its original position.

The hearth itself is made of welded steel and is configured as a double-step arrangement. Ports for the primary zone air are located on the riser portion of these steps and spaced at 23-cm (9-in.) intervals axially down the hearth. A separate underfire air fan is supplied for each hearth. A water seal on the side of the hearths prevents tramp air in-leakage to the primary chamber.

The controlled-air combustors discussed previously were typically operated at about 40-50 percent theoretical air in the primary chamber. In the Basic Environmental Engineering unit, this chamber is designed for near stoichiometric operation. Due to the volatile matter/fixed carbon split of the waste, the entrance region of the primary chamber operates fuel-rich, the center is near stoichiometric, and the exit region is fuel-lean.

Units fired with municipal solid waste typically have welded wall, watertube configurations forming the primary zone enclosure. This configuration may also be used for medical waste incineration but an alternative

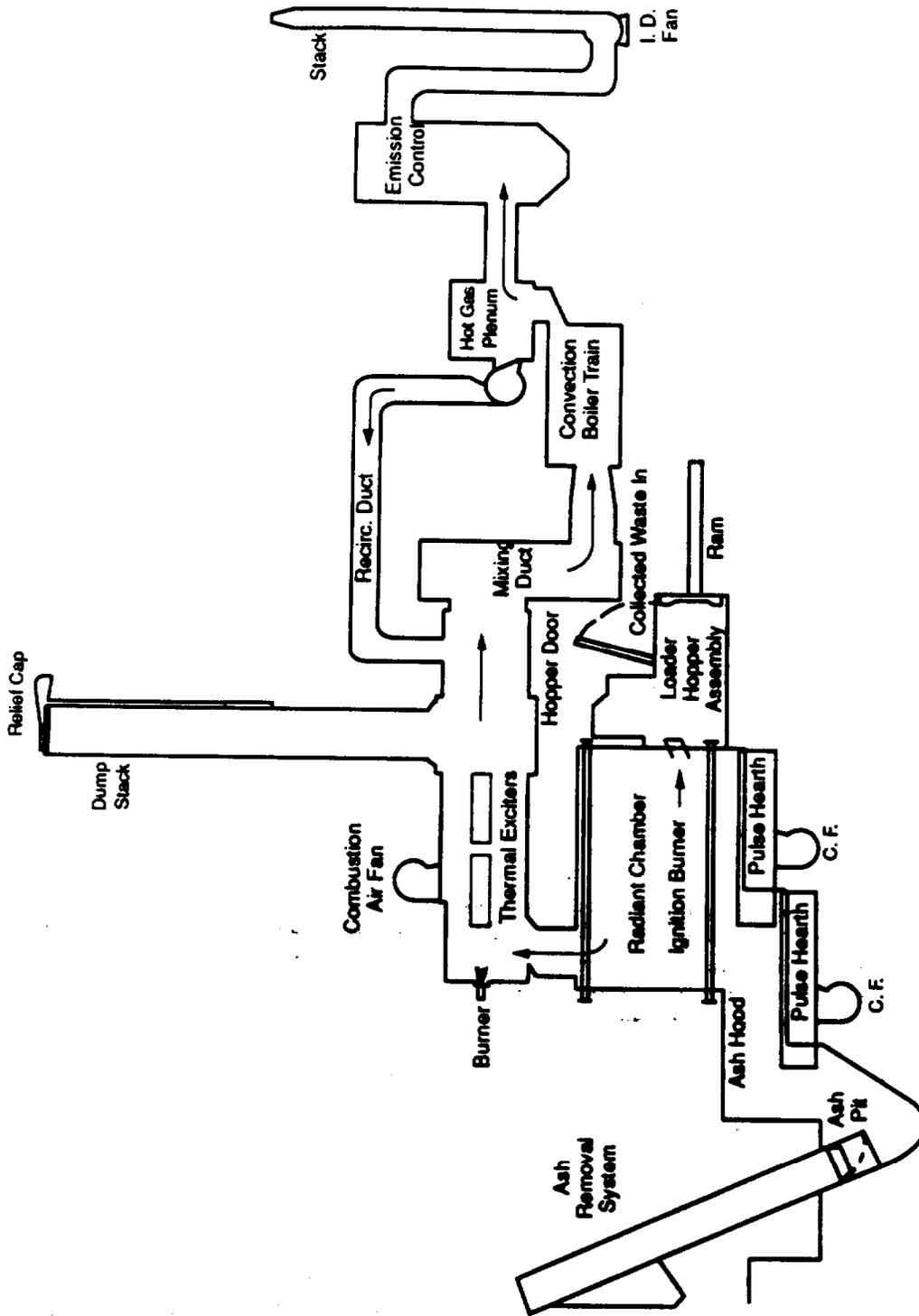


Figure 21. Basic Environmental Engineering system for MSW.

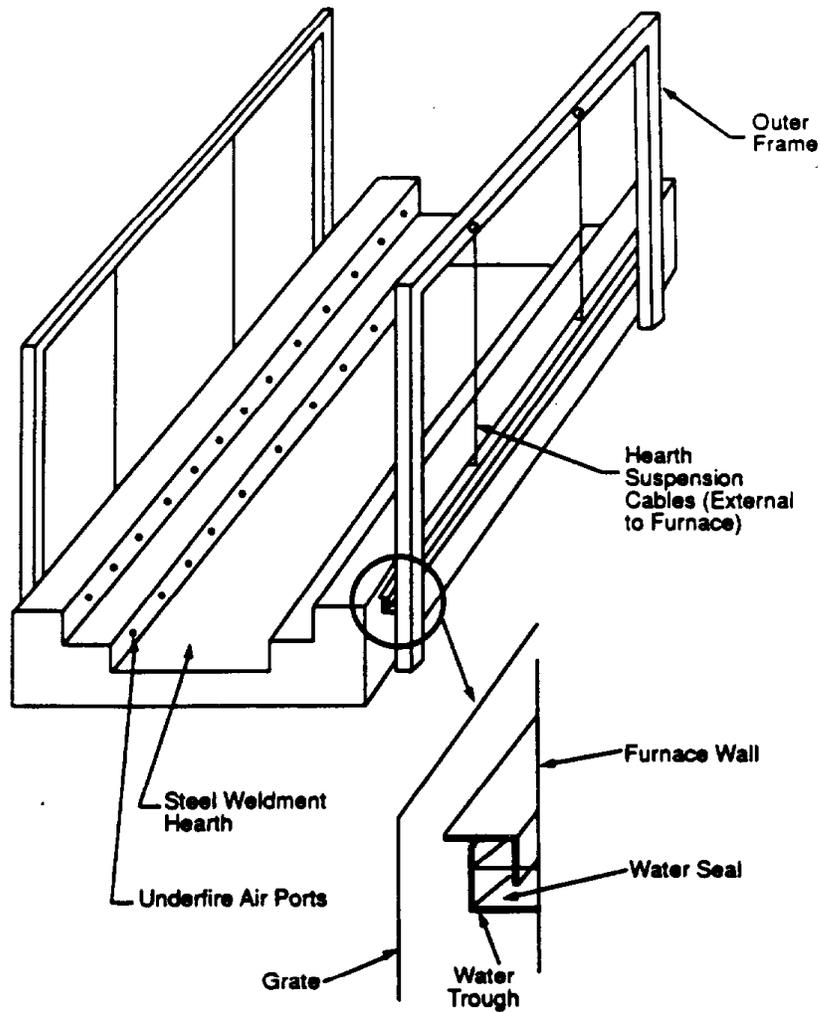


Figure 22. Basic Environmental Engineering Pulsed Hearth™.

configuration for this type of waste is to use a refractory wall with water spray. The size of the primary zone generally corresponds to the following criteria:

Plan area $3.15 \times 10^8 \text{ J/s-m}^2$ (100,000 Btu/hr-ft²) hearth area

Volume $12-15 \times 10^8 \text{ J/s-m}^3$ (12-15,000 Btu/hr-ft³)

Maximum vertical
Gas Velocity 0.46 m/s (1-1/2 ft/sec)

Using these criteria, Basic can achieve particulate emission rates of 0.18-0.23 g/Ncm (0.08-0.10 gr/dscf) without the use of air pollution control devices.

Combustion products from the primary zone enter the second and third stages where excess air is added. The second stage provides only a limited quantity of excess air to maintain high system temperature. As described by Basic, the second stage is included to promote combustion of trace organics which might escape the primary. High temperature, low excess air, and possible use of the auxiliary burner are design features to initiate the endothermic ignition reactions. The third stage provides further excess air addition for the exothermic burnout reactions.

Excess air addition in both the secondary and tertiary zones is done by a flow device called a "thermal exciter." Figure 23 illustrates the triple wall construction. A zone combustion air fan provides 500-2500 Pa gauge (2 to 10 in. W.G.) to force air into the outer annulus, through a connecting leg and into the inner cylinder. Small ports through the walls of the center body allow excess air to penetrate normal to the main combustion flow. One major benefit of this configuration is that the air jets need to penetrate only a short distance to achieve good mixing with the main combustion gas stream. A second advantage is that heat lost from the combustion gases is picked up by combustion air in the outer annulus and returned to the system as sensible heat in the air jets. Lastly, the hot refractory wall configuration allows radiation back to the combustion gas which is believed to increase burnout of combustible particles which might escape the primary zone.

A dump stack is supplied at the exit of the third stage. In systems with heat recovery, Basic feels it is necessary to control the temperature of gases entering the waste heat boiler. As shown in Figure 21, that temperature control is accomplished by recirculating flue gas from the boiler exhaust. Basic refers to the region where hot combustion products are merged with recirculated flue gas as the fourth stage. A mixing zone is also provided so that the convective section of the waste heat boiler receives a uniform temperature gas stream. If required, an air pollution control device and the induced draft fan are provided downstream of the boiler. Other system features, such as continuous ash removal and waste feeding, are as illustrated in Figure 21.

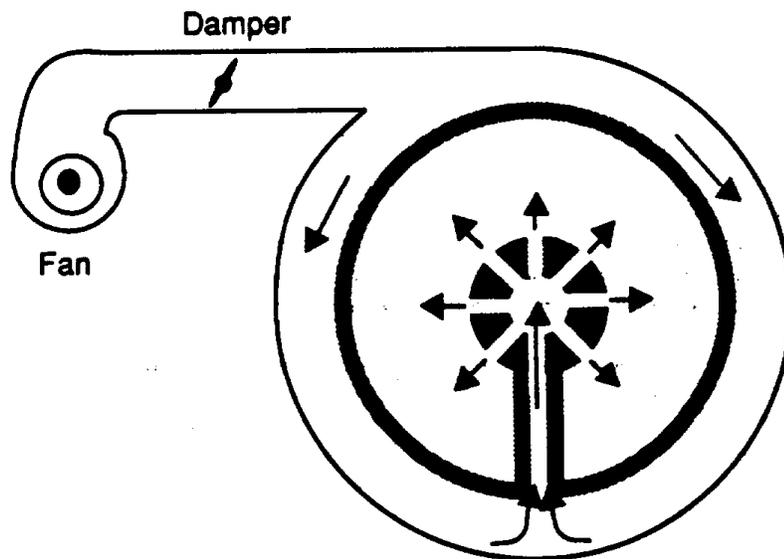


Figure 23. Schematic illustration of Basic Environmental Engineering thermal exciter.

CLEAVER BROOKS

Cleaver Brooks is located in Milwaukee, Wisconsin, and is a division of Aqua-Chem, Inc. There are three main divisions of Cleaver Brooks, covering (1) Water Technologies, (2) Industrial Combustion, and (3) Turbo Refrigeration. The industrial combustion division is one of the major suppliers of package boilers. About 15 years ago, they entered the incineration industry and about 5 years ago purchased Kelly Incineration. The entire Kelly technology line has been renovated to comply with emerging emission regulations and State time/temperature system requirements.

Cleaver Brooks manufactures three types of incinerator systems including vertical units, rotary kilns, and fixed-hearth units. The vertical units are small two-chamber batch- or ram-fed incinerators with capacities between 45 and 230 kg/hr (100 and 500 lb/hr). Sales are typically about 10-20 per year. These are designed to operate up to 8 hr/day and do not provide for continuous ash removal. The secondary chamber is sized for 2-seconds residence time at a temperature of 1370 K (2000°F). This class of equipment is generally sold without flue gas cleaning equipment.

The vertical incinerators are operated in a batch mode. The unit is preheated with an auxiliary fuel burner which heats the secondary chamber and warms the primary chamber. Waste is then fed into the system. Combustion air to the primary zone is introduced through holes in the base of the cast iron hearth. Air is drawn in by natural draft, and there are no provisions for air flow modulation. Generally, however, the primary zone is designed to operate at a fuel-rich stoichiometry. More air must be added in the secondary chamber. That air addition is modulated based on secondary chamber temperature measurement.

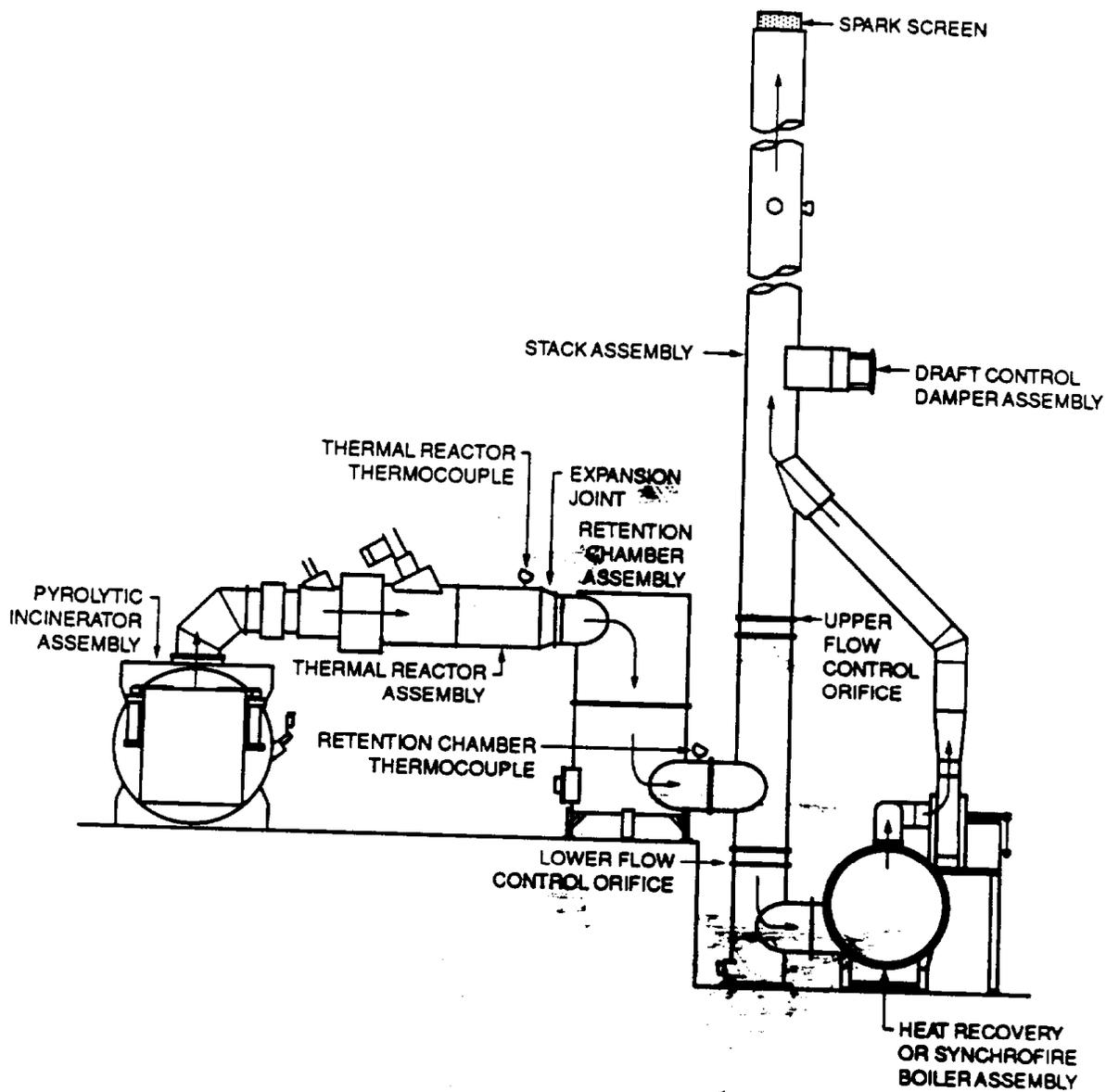
A second class of incinerators offered by Cleaver Brooks is the rotary kiln. These are primarily used in hazardous waste applications, but are making in-roads for regional medical waste incineration application. No detailed information on this product line was obtained during the plant visit.

Fixed hearth incinerators represent the major incineration product line for Cleaver Brooks. They have 600-700 units installed in sizes ranging from 170 to 910 kg/hr (380 lb/hr to 2000 lb/hr) [rated at 19,800 J/g (8500 Btu/lb)]. These units do not provide continuous ash removal and are sized to operate 10 to 18 hr/day. After the daily waste charging activity, a burn-down period is provided to reduce the ash carbon content and assure that none of the ash is recognizable. Cleaver Brooks believes that carbon burnout significantly deteriorates with continuous ash removal and does not provide that feature, even as an option.

Figure 24 illustrates the standard arrangement of the Cleaver Brooks fixed hearth incinerator without heat recovery (top view) and with both a retention chamber and a heat recovery boiler (bottom view). Waste is introduced with an automatic feeder into the lower chamber (referred to by Cleaver Brooks as a pyrolysis chamber) which is operated fuel-rich. The pyrolysis chamber is constructed of castable refractory capable of operation at 1700 K (2550°F) under reducing conditions. The hearth is made of cast iron with many small diameter [0.64 cm (1/4 in.)] holes for introducing underfire air. Underfire air pressure drop is set by maintaining a 1000-1200 Pa gauge (4-5 inch W.G.) pressure in the plenum beneath the hearth. No modulation to the underfire air flow is provided. Instead, Cleaver Brooks attempts to modulate primary chamber temperature by modulating waste feed rate. An ash transfer ram is located beneath the waste feeding system. This ram is used to move ash to the opposite end of the primary zone and to maintain a uniform thickness of ash on the hearth.

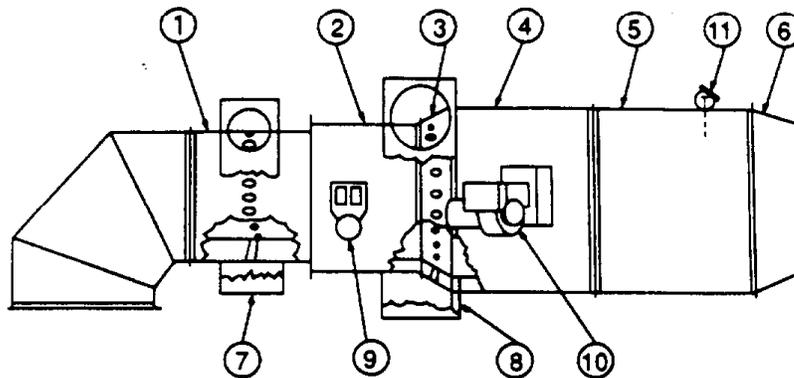
Another operational feature for the Cleaver Brooks system is that either water is sprayed into the primary chamber or steam is added to the underfire air about four hours after the unit is started. Cleaver Brooks indicates that steam tends to depress peak bed temperatures which in turn helps to minimize slagging problems. Steam also causes CO to oxidize to form CO₂ (water-gas shift reaction).

From the pyrolysis chamber, combustion products are routed to a secondary chamber which Cleaver Brooks calls a "thermal reactor." Figure 25 is an expanded view of the thermal reactor section. As indicated,



HEAT RECOVERY CONFIGURATION

Figure 24. Cleaver-Brooks pyrolytic incineration system.



1. Premixer Section
2. Igniter Section
3. Expansion Section
4. Combustion Burner Section
5. Combustion Section
6. Reducer Section
7. Premixer Air Plenum
8. Thermal Reactor Combustion Air Plenum
9. Pilot Burner Assembly
10. Auxiliary Thermal Reactor Burner
11. Thermal Reactor Thermocouple

Figure 25. Expanded view of Cleaver Brooks thermal reactor section.

air is introduced to the thermal reactor in two positions. The first air addition is called pre-mixed air and is supplied by the primary chamber combustion air fan. This air is added at a constant rate (manual damper setting) and imparts a slight spin to the flue gases. Immediately downstream, a pilot burner is used to assure ignition of the primary zone product/pre-mix air combination and to maintain minimum temperature in the thermal reactor. This burner is also used to preheat the thermal reactor during daily start-up. During normal operation, the burner fires any time the indicated temperature falls below a minimum set point.

Downstream of the pilot burner, the main secondary air is added by the thermal reactor combustion air fan. This fan is run continuously during the normal run cycle and burn-down cycle, but is locked out during preheat. A motorized damper modulates this air flow to maintain the required temperature at the thermal reactor exit.

Many States require minimum residence time as well as minimum temperature in the secondary. In response to that requirement, Cleaver Brooks furnishes an additional retention chamber between the thermal reactor and the stack. To assure that minimum gas temperature is achieved at the retention chamber exit, a second auxiliary fuel burner is supplied at the end of the thermal reactor.

The stack arrangement offered by Cleaver Brooks for units with heat recovery is unique. As shown in Figure 24, the normal flue gas path is through the lower portion of the stack, into the heat recovery boiler,

through the induced draft fan and out the upper portion of the stack. Two flow orifices are provided to ensure that this is the actual gas flow pathway and to provide a control signal to the induced draft fan. In actual practice, the ID fan damper is adjusted to ensure there is a slight recirculation of flue gas back to the boiler inlet.

It should also be noted that there is a control loop which maintains primary combustion pressure at -12 to -25 Pa gauge (-0.05 to -0.10 in. W.G.) by adjusting a damper on the stack. This damper influences total stack draft which in turn controls incinerator pressure.

JOHN ZINK COMPANY

John Zink is a multi-faceted energy company located in Tulsa, Oklahoma. For disposal of medical waste, they make a complete line of incinerator equipment ranging in scale from 50 kg/hr to 1400 kg/hr (120 lb/hr to 3000 lb/hr) of 10,000 J/g (8500 Btu/lb) waste. They have located approximately 300 units in hospitals around the country with most of those units rated at about 90 Kg/hr (200 lb/hr). The John Zink technology has undergone substantial development in recent years and only about 20-30 of these 300 installations represent current technology.

The technology offered by John Zink is the basic two-stage, starved-air (controlled-air) system with a substoichiometric primary and an excess air secondary chamber. One of the key design characteristics of John Zink systems is minimization of tramp air in-leakage to the primary chamber. Included are features such as spring-loaded brass seals on the fire door and use of an auxiliary fuel burner which does not need air cooling when it is not firing. Since John Zink modulates primary zone combustion air to maintain desired primary zone combustion conditions, the design philosophy is to assure that air flows are controlled, not disrupted by in-leakage.

Typically, the larger size incineration systems contain two or three hearth/grate sections in the primary chamber with a controlled quantity of underfire air added to all three sections. The hearth is made of firebrick and forms the roof of an underfire air plenum. A small gap [0.16-0.32 cm (1/16-1/8 in.) wide] is provided between two or three sets of adjacent brick rows forming long slots for underfire air flow. This underfire air, therefore, enters beneath the waste. As noted, John Zink provides underfire air to all grate sections and distributes the air flow down the length of the hearth. Most of the underfire air is added to the first hearth, less to the second, and still less to the third (if present). Other manufacturers of controlled-air incinerators report having no air addition to the first hearth, but John Zink adds most of the underfire air to that section. The rationale offered by John Zink personnel is that they want to match the quantity of air flow with the amount of material to be burned. This air distribution approach is designed to maintain uniform stoichiometry on each grate section.

The quantity of underfire air is adjusted to maintain the primary zone temperature at about 980 K (1300°F). The company feels that higher primary zone temperature will lead to increased melting of ash and to increased trace metal emission in the stack. Even at 980 K (1300°F), some melting of aluminum and glass occurs and those molten constituents tend to plug the underfire air ports. John Zink suggests that the hearth be inspected monthly and that any plugging material be removed with a reciprocating power saw. If that cleaning approach is not successful, it is easy to replace a few bricks.

Most of the incinerators being sold by John Zink are for installation at hospitals which typically operate the unit(s) for 8-10 hours per day. Accordingly, most Zink systems are designed to provide for a 2-3 hour burn-down period before the ash is discharged. During burn-down, the underfire air dampers remain open assuring that air is provided to burn all combustibles. To make certain that primary chamber temperature does not get too high, an intermittent water spray is provided above the final hearth. The water spray is typically used only during burn-down.

Waste is fed to the system using essentially the same approach as other manufacturers (Figure 16). As noted earlier, special care was given to sealing the fire door. To move material down the second and third hearths, John Zink provides transfer rams that they refer to as ash plows. Movement of the plows is restricted. They only move far enough to form a gap for material to fall from a higher hearth. After burn-down is complete (at the end of the day or the start of the next day), full translation of the plow can be used to clean the hearth. Very few John Zink units have been sold with continuous ash removal although that feature can be supplied as an option. They do not, however, recommend that option because of the significant improvement in ash quality resulting from burn-down. With the burn-down cycle, John Zink is typically able to achieve ash carbon contents of between 3 and 8 percent.

The duct between primary and secondary combustion chambers is at the far rear of the primary chamber. There are two main reasons for this positioning. First, it represents the longest distance from the fresh waste charge. Thus, any entrained material will experience the longest residence possible. Further, it provides an opportunity for any large particles lifted from the grate to fall to a later grate rather than flow into the secondary chamber. Note that the first grate has the maximum vertical gas velocity since most of the underfire air is added at that position.

The secondary chamber contains an auxiliary fuel burner, two positions for secondary air addition, and generally contains a refractory choke ring. The hardware arrangement is illustrated in Figure 26. The auxiliary fuel burner is located on the centerline of the chamber at the inlet end. Surrounding this burner is a series of secondary air jets directed toward a point on the centerline about 1/3 of the axial distance down the chamber. This point is also the axial position of the refractory choke ring. Additional secondary air is added through a series of wall jets positioned between the head end of the chamber and the refractory choke. These other air jets are also directed toward the choke ring plane but are skewed to give swirl to the flow.

The size of the secondary chamber auxiliary burner varies with the design firing capacity of the incinerator. For a 450-kg/hr (1000-lb/hr) unit, this burner would have a full load rating of about 1.5-1.8 million J/s (5-6 million Btu/hr). This rating is sufficient to preheat the secondary chamber to 1260 K (1800°F) in about 1-2 hours from a cold start. The burner itself is capable of a high degree of turndown and is fired at all times the incinerator is in operation. During normal operation, it is adjusted to a low-fire position which is 1/10 or less of the full load rated capacity.

The secondary air flow entering the system through the back face is equivalent to about 50-60 percent of theoretical air required for the waste. Thus, the combination of this air and primary zone underfire air is almost equivalent to the stoichiometric air requirement. The auxiliary fuel burner is intended as a standing pilot flame for the mixture of fuel fragments coming from the primary zone and this first portion of secondary air. The second allotment of secondary air is called quench air and serves to drop exhaust temperature to the required level. Both sets of secondary chamber air are provided by a single blower with the distribution set with a fixed position damper in the duct-work. An adjustable, motor-driven damper is located on the fan inlet to modulate the total quantity of secondary air.

The refractory choke is provided to increase mixing in the secondary chamber and was adapted from John Zink combustion developments in other fields. They believe that the choke improves burn-out of carbon monoxide. It is sized to provide about 7.6 m/s (25 ft/s) velocity in the choke ring. The size of the secondary chamber is nominally set for a 1-second residence time but that size is adjusted to meet prevailing regulations. John Zink personnel indicate there is no apparent improvement when residence time is increased above about 0.7 second.

Secondary chamber controls are based on regulatory requirements to maintain a prescribed minimum temperature. The first order control sequence is to modulate air flow up or down as dictated by the exhaust temperature measurement. There is, however, a minimum air flow setting, and any additional heat requirement is supplied by modulating the secondary auxiliary fuel burner.

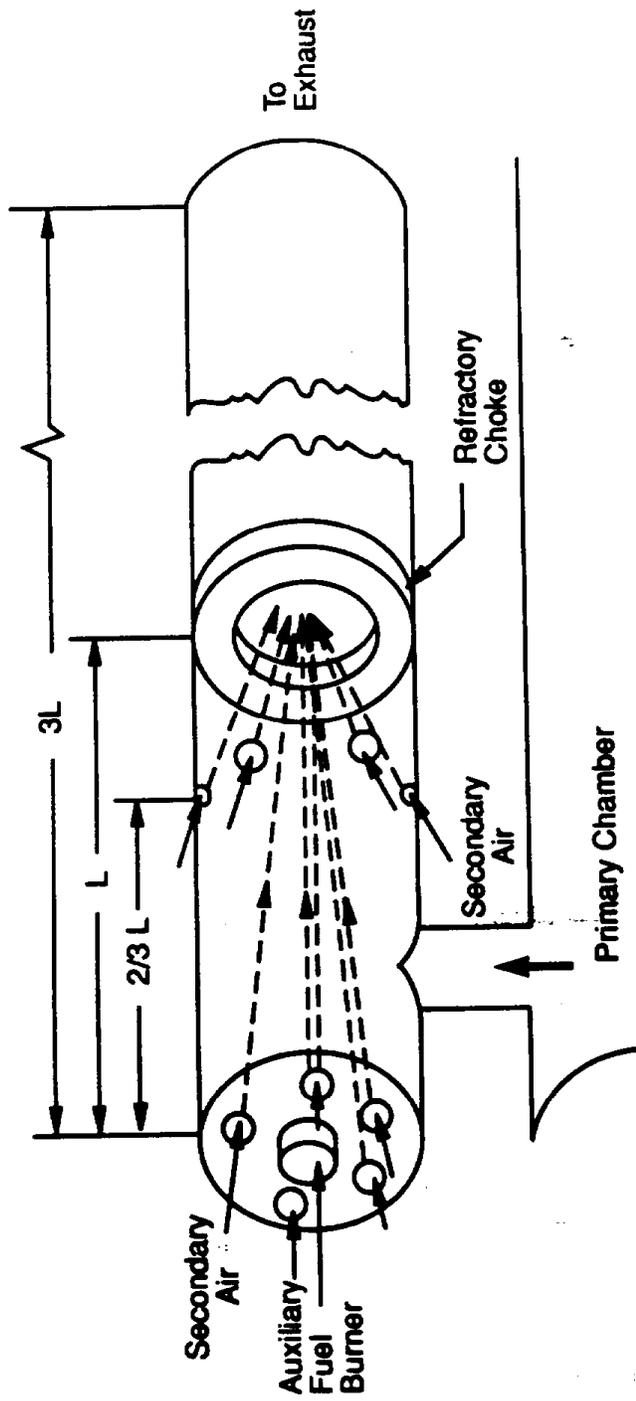


Figure 26. Secondary chamber for John Zirk incineration system.

Control of waste firing rate is set by the capacity of the waste hopper and through lockouts to the charging systems. John Zink prefers to size the feeding hopper as small as practicable with more frequent waste charging. Based on the charging capacity, a maximum charging frequency is established (minimum time between waste additions) and incorporated into the automatic control system. After the unit is charged, the controller prevents actuation of the door opener and charging ram until the minimum time has elapsed. An added lockout feature is provided to assure that no new waste is fed unless the secondary exit temperature is at or above the regulatory limit.

Control of the transient phenomena is generally similar to that used by other manufacturers for the primary zone, but a unique twist is provided in the secondary. Shortly before the charging door is opened, the control system causes the primary chamber auxiliary fuel burner to extinguish (if it is operating) and the underfire air is reduced to a minimum. The secondary chamber temperature controller is overridden and the secondary fan damper is driven fully open. After the charge is added and the fire door closed, the underfire air flow is increased, and the lower chamber is returned to automatic temperature control. The secondary chamber, however, remains on computer control, and the fan damper is modulated at a prescribed rate in an attempt to match air flow to expected release of volatile matter from the fresh charge. This control period extends for about 90 seconds before the system is returned to the mode where the exhaust thermocouple-generated signal is used to modulate the secondary air fan damper.

Since most of the units being sold by John Zink are small scale systems, the coming of State-mandated air pollution control is seen to have a major economic effect. Cost issues are discussed in more detail later but it was noted by John Zink personnel that acid gas control for a 250 lb/hr incinerator would double the facility capital cost.

Most John Zink units are being installed without heat recovery systems. However, one trend that is being observed and strongly supported is use of co-fired boilers. In this configuration, most of the boiler rating is supplied by standard fossil fuel such as natural gas which can easily be regulated to accommodate heat input from hospital waste incineration. Such systems are, however, practical only if the hospital (or other facility) can effectively use the steam on a year-round basis.

CIL INCINERATION SYSTEMS

CIL Incineration Systems is the new name for Atlas Incineration, one of the oldest manufacturers of small waste incinerators in the United States. They are located in Coon Rapids, Minnesota. CIL manufactures two lines of incinerators which they refer to as the CFA and the CA models. Both lines are dual-chamber controlled-air incinerators. The CFA line includes units with ratings between 23 kg/hr and 270 kg/hr (50 lb/hr and 600 lb/hr) [based on 19,750 J/g waste (8500 Btu/lb)] while the CA line covers ratings from 270 to 680 kg/hr (600 to 1500 lb/hr). The smaller units have both the primary chamber and secondary chamber configured as vertically-oriented right circular cylinders. The secondary is directly above the primary. The CA line also has cylindrical configurations but the two chambers are horizontally stacked.

The CA line is configured with an automatic waste feeding ram and two internal hearths. There is a step height of about 0.3-0.6 m (1-2 ft) between hearths and an internal transfer ram to move waste to the ash pit. This configuration is designed for 24 hr/day operation and includes automatic ash removal in either a wet or dry configuration. In the wet systems, ash drops into a water-filled pit and travels by conveyor to an ash cart. In the dry systems, ash falls directly into an ash cart where it is sprayed with water to cool the residue.

The CFA series comes with manual waste feeding as standard, but a hydraulic feeder is available as an option. These smaller-scale units usually do not have internal transfer rams nor do they provide continuous ash removal.

Air addition to the primary chamber is generally set at substoichiometric conditions but with the air addition rate held constant during the operating cycle. No underfire air is supplied to the first hearth. In the

current CA configuration, air is added through several wall ports down the length of the second hearth. A new CA design innovation provides both wall air and true underfire air. The underfire air enters a plenum beneath the second grate/hearth and flows through many small-diameter openings in the stainless steel grate. Wall air and underfire air will be provided by separate primary zone fans.

The primary chamber in a CIL incinerator is designed to maintain temperature less than about 1100-1140 K (1500-1600°F). To accomplish that objective, CIL provides three water-spray nozzles in the primary chamber controlled by a signal from a thermocouple located in the primary chamber exhaust. Primary chamber temperature is also influenced by waste loading rate. Generally, waste addition is permitted every 10 to 20 minutes. There is, however, a lockout that prevents waste addition unless three process parameters are satisfied. First, a timer is used to assure that a minimum time period has passed since the last charging action. Second, the primary chamber temperature must be below a minimum set point (without water spray). Lastly, the secondary chamber exit temperature must be above the limit set by local regulation.

An auxiliary burner is provided in the primary chamber, but its use is generally limited to preheating the refractory from cold starts and for igniting the first load of waste for the day. After the first load begins to burn, the flame is self-sustaining and the primary burner is no longer operated.

Fuel-rich combustion products pass from the primary into the secondary chamber where they encounter more combustion air and an auxiliary fuel burner flame. The general configuration of this section is illustrated in Figure 27. (Note that this Figure was developed based on a description supplied via telephone by CIL personnel.) As shown, secondary air is introduced normal to the flow of gas from the primary chamber through a single large port. This air flow generates a swirling motion to flow in the secondary chamber. The auxiliary fuel burner is located above the secondary air port and increases the swirling gas flow pattern. A thermocouple in the secondary zone exit controls a damper in the air flow system as well as turndown on the auxiliary fuel burner. The temperature set point is nominally 1260 K (1800°F).

The capacity of the auxiliary fuel burner varies with incinerator equipment size. On the CA equipment line, the smallest incinerators (270 kg/hr (600 lb/hr)) have auxiliary burners rated at 6×10^6 J/s (2×10^6 Btu/hr) heat input while the 680 kg/hr (1,500 lb/hr) units have burners rated at 1.2×10^7 J/s (4.2×10^6 Btu/hr). Burners typically have about a 10:1 turndown capability and are fed continuously while the incinerator is being operated.

Excess oxygen levels at the secondary zone exhaust typically range from 4 to 10 percent. The standard unit provides a 1-second residence time in the secondary chamber, but options are available for 1-1/2- and 2-second dwell times to meet local regulations.

Most of CIL's existing units were sold without heat recovery and without flue gas cleaning systems. Recent trends are toward the use of flue gas cleaning systems on larger-scale units. CIL equips their units with wet venturi scrubbers and packed bed absorbers for control of particulate and acid gas emissions--where required by State regulations. Uncontrolled particulate emissions have been measured on several units and some systems could achieve 0.18 g/Ncm (0.08 gr/dscf) (corrected to 12 percent CO₂). Carbon monoxide emissions are typically on the order of 10-20 ppm (dry, corrected to 12 percent CO₂) but peak values may reach as high as 50 ppm. As with other manufacturers of controlled-air incinerators, careful attention was given to the unit charging operation to limit visible smoke emissions. Just before the waste loading door is opened, all air flow to the primary chamber is stopped. After the fresh load is added and the door shut, a timer provides a 1- to 2-minute delay before the primary air fan(s) are restarted. Further, as part of the waste loading procedure, the secondary chamber temperature controller is bypassed and the secondary air fan increases to full flow. These control sequences limit the influence of air leakage to the primary chamber and assure that sufficient heat and oxidizer are available in the secondary chamber to completely burn all combustibles leaving the primary chamber.

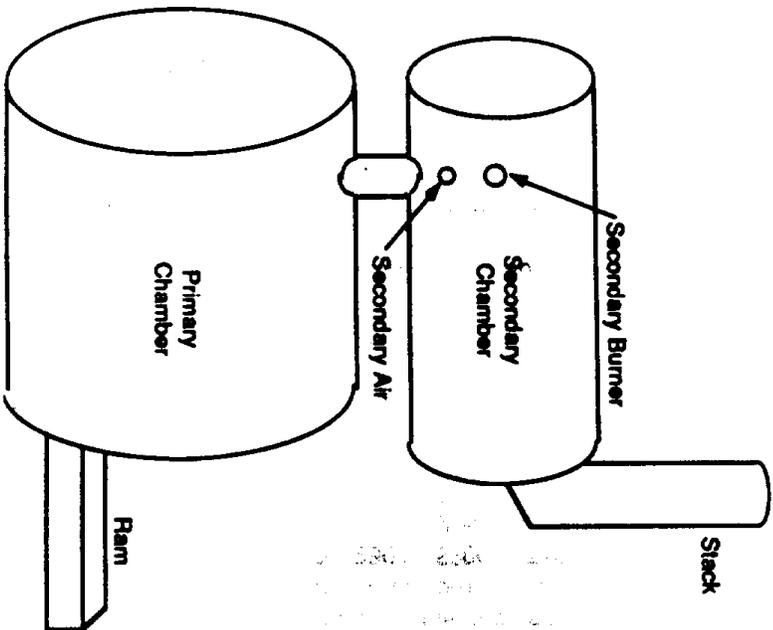
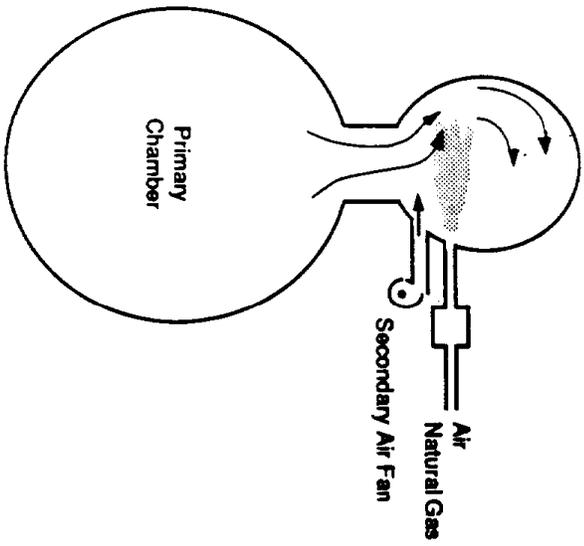


Figure 27. Configuration of CIL secondary combustion chamber.

SHENANDOAH MANUFACTURING

Shenandoah is located in Harrisonburg, Virginia, and is a major manufacturer of very small-scale incinerators. They have been involved in incinerator manufacture and sales since 1962 and have sold several thousand units domestically and abroad. There are two main product lines that Shenandoah refers to as their professional and farm lines. The professional line is marketed to hospitals and veterinarian clinics and has a nominal rating of 45 kg/hr (100 lb/hr) of waste [about 20,000-21,000 J/g waste (8500-9000 Btu/lb)] in non-continuous use. The farm line is used mainly for disposal of dead animals and has a primary combustion chamber volume of only about 0.1 cubic meter (4 cu. ft). Recently 120 of the farm line units were sold to Egypt for incineration of waste products at AIDS clinics. The remainder of this section describes the professional product line.

As noted, the professional line incinerator is rated at 45 kg/hr (100 lb/hr) of waste. It is configured as a two-stage incinerator with the first stage generally configured as a rectangular box. The secondary stage has a cylindrical geometry, is oriented vertically, and is mounted directly above the primary stage. The primary chamber has ceramic grate bars mounted into the walls of the chamber. The ceramic grate bars are about 15 cm x 8 cm (6 in. x 3 in.) in cross-section and extend across the 61-cm (24-in.) width of the furnace. There is about a 6.4 cm (2-1/2 in.) gap between grate bars. The overall furnace inside depth is approximately 1.5 m (5 ft) and the height above the grate is 0.75 m (2.5 ft). Thus, the furnace volume above the grate is 0.71 m³ (25 ft³). Waste is loaded into the primary chamber manually through a door in the furnace front wall. The waste is ignited with an auxiliary fuel burner mounted in the back wall of the primary chamber. This burner is located such that it fires horizontally into an open space between the grate and hearth of the furnace and exhausts upward between the grate bars. After the waste is ignited, the auxiliary fuel flow is stopped but air flow is maintained. That is the only source of primary zone air for the system. The amount of airflow is constant and the primary zone stoichiometry varies throughout the burning cycle. Shenandoah personnel indicate, however, that the nominal condition is such that the primary zone temperature is in the 810-920 K (1000-1200°F) range and under starved-air conditions.

Combustion products flow from the primary zone into the vertically-oriented secondary chamber. This chamber has a 76-cm (30-in) ID and can be supplied with either a 1/2-second or 1-second residence time at 1260 K (1800°F). The 1-second residence time secondary has a length of about 1.5 m (5 ft). The secondary chamber contains both an auxiliary fuel burner and a secondary air blower supplying air through multiple ports. The secondary auxiliary fuel burner is rated at 1.5×10^5 J/s (800,000 Btu/hr) for the 1/2-second residence time configuration and 2.3×10^5 J/s (1.2×10^6 Btu/hr) for the 1-second residence time configuration. This burner is capable of turndown to 1.5×10^4 - 2.9×10^4 J/s (50-100,000 Btu/hr) firing rate and is fired continuously when the incinerator is operated. This secondary burner is located such that it fires tangentially into the side of the upper chamber. Two of the eight overfire air ports are also oriented in a tangential configuration, increasing the swirl imparted by the burner. The remaining six overfire air jets are oriented to inject air radially inward.

Unit operation begins with a preheating cycle during which the secondary auxiliary burner preheats that section and warms the primary chamber. Waste is then added to the system and, after a built-in 6-minute delay, the primary burner is fired. Temperature at the exit of the secondary chamber is sensed by a thermocouple which simultaneously actuates the secondary auxiliary burner firing rate and the rate of secondary air addition. A call for higher exit temperature simultaneously causes the burner firing rate to increase and the excess air level to decrease. Opposite damper/burner adjustments cause exit temperature to increase.

Charging of the unit typically occurs at about 30-40 minute intervals. System options allow the charging door to be locked shut based on either a charging frequency or on a prescribed drop in primary zone temperature. Alternately, for pathological waste incineration, it is usual to load the system fully with several hundred pounds of waste and let the unit operate unattended for up to 8 hours.

The type of batch loading/firing described above has typically raised concerns for regulatory groups. Shenandoah personnel note, however, that particulate emissions are generally less than 0.23 g/Ncm (0.10 gr/dscf) (corrected to 12 percent CO₂) and CO emissions are typically on the order of 10 ppm. A standard Shenandoah incinerator was used for pathological spore testing and the unit was shown to be 100 percent effective for spore destruction. Results have been supplied to the incinerator trade association (WCEI-Waste Combustion Equipment Institute) and to EPA.

Shenandoah is nearing completion of a new incinerator line which has a rating of 79.4 kg/hr (175 lb/hr). Features of this new line include elimination of the grate and addition of an automatic waste loader. A separate fan provides for underfire air which is introduced at substoichiometric conditions. Shenandoah personnel note, however, that primary chamber temperature is expected to be in the 1030-1090 K (1400-1500°F) range which is generally inconsistent with starved-air operation. Further, the secondary chamber is designed to operate at up to 1370 K (2000°F) with 2-seconds residence time. Shenandoah is hopeful that this new design will be consistent with the emerging, more stringent State regulations.

INDUSTRIONICS

The preceding sections have discussed various forms of hearth- or grate-fired incineration systems. Industrionics is one of several organizations who supply small rotary kiln incinerators for treatment of medical waste. Over the past six years, Industrionics has supplied 11 units, ranging from 8.8×10^5 to 3.8×10^6 J/s (3×10^6 to 13×10^6 Btu/hr) heat input for medical waste treatment. As illustrated in Figure 28, the basic configuration consists of continuous auger feeding of waste into a rotary kiln followed by a secondary combustor and waste heat boiler.

Waste is fed from a hopper into the kiln using a screw feeder which has hook-like protrusions to grab the waste. Various kiln sizes are designed to have roughly constant volumetric heat release and are configured to have an L/D of at least 3:1. The kiln walls are made of acid-resistant brick with a 1900 K (3000°F) maximum use temperature. The kiln also features double-wall construction through which air is forced to reduce outer skin temperature. Heated air is vented after passing through this annulus. At the front face of the unit, Industrionics provides both an auxiliary fuel burner and port opening to admit combustion air. The auxiliary fuel burner is fired during start-up and intermittently after that based on measured kiln exit gas temperature. That measurement is done with a type-R thermocouple which protrudes about 0.5 m (1.5 ft) into the kiln exhaust. Combustion air to the kiln is admitted through the port(s) on the front face as well as through seal leakage and is controlled by kiln operating pressure. Kiln pressure is typically maintained at -12 to -25 Pa gauge (-0.05 to -0.10 in. W.G.).

Ash drops from the kiln onto an overlapping pan conveyor and is transported to a waste hopper. The ash is sprayed with water as it drops into the hopper. Typical ash carbon content was noted to be on the order of 30 percent which is almost equal to starved-air units with continuous ash removal.

Flue gas exits the kiln and goes into a secondary chamber which has (1) a flat hearth, (2) an "air wall," (3) an auxiliary fuel burner, and (4) a temperature control system. The flat hearth (or floor region) can be reached for charging through an access door and is used for disposal of carcasses and solid items such as sharps. Secondary air is added through a dampered slot opening in the floor of the secondary. The configuration is very much like an inverted T with dampers on each of the air inlets. Air enters by induced draft and forms the "air wall" between the kiln and the hearth. An auxiliary fuel burner is located in the secondary chamber but is mainly used for start-up. Typically, the secondary chamber is sized and controlled for a 1- or 2-second residence time at 1370 K (2000°F) but can go up to 1530 or 1590 K (2300 or 2400°F). The control system is very simple, consisting of an type-R thermocouple located in the breaching to the stack. The thermocouple signal is used to drive the dampers in the "air wall" assembly. If the required temperature is not maintained, with the dampers fully closed, the auxiliary fuel burner is actuated.

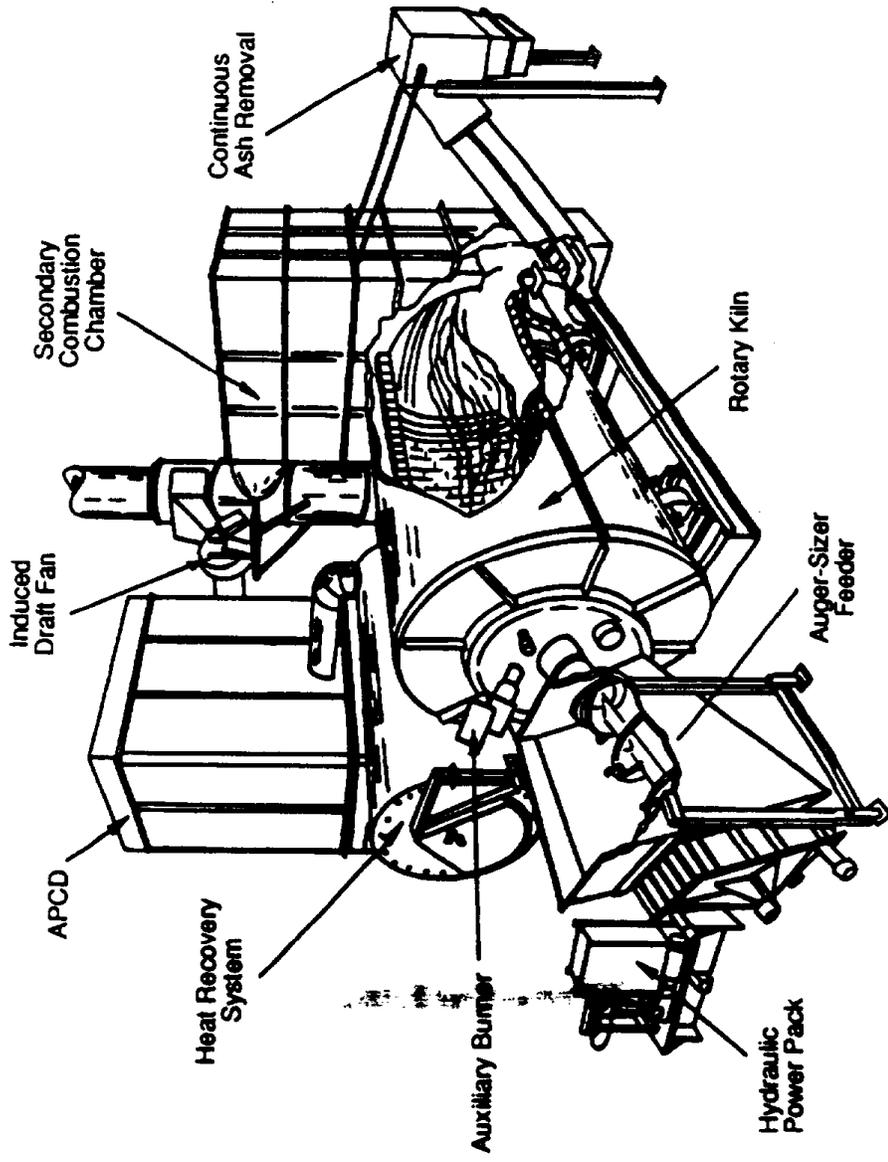


Figure 28. Industrious's Consertherm™ rotary kiln incineration system.

The gases exit the secondary chamber through a breaching which contains a diverter damper. This damper normally directs hot gases to a waste heat boiler but in an emergency divert gas to the dump stack. All systems sold to date have been equipped with waste heat boilers. From the boiler, the gases go to the induced draft fan, through an optional flue gas cleaning system and out the stack.

During the plant visit, several practical issues were discussed with Industrionics personnel. The operation of the screw feeder tends to break open bagged material which can help expose waste surface to the combustion environment. There may be concern, however, if the waste feed contains liquids such as blood or body fluids. Industrionics indicates that this has not posed any reported problems to date.

Waste motion in the kiln is described as both tumbling and sliding. This implies that typically waste feed materials have a wide range of particle sizes. Industrionics is concerned about overfeeding the kiln. Overfeeding results in strong smoking from the unit.

Oxygen levels in the system exhaust are typically about 11 percent and CO emissions are typically less than 50 ppm. No continuous monitors are supplied with those systems but that would present no problem to Industrionics (at least for O₂) if required by regulation. The issue of the stringent performance regulations in New York are pertinent to Industrionics since 2 of their 11 existing units are in that State. They are generally comfortable with the NY requirements stating that their current technology can meet those regulations by incorporating off-the-shelf air pollution control equipment. That is an attitude not shared by most other manufacturers.

M&S ENGINEERING AND MANUFACTURING COMPANY

M&S is located in Broad Brook, Connecticut and is a small corporation specializing in rotary kiln technology for waste incineration. They are best-known for their small hazardous waste incineration systems including the rotary kiln system installed at EPA's Incineration Research Facility in Pine Bluff, Arkansas. To date, M&S has supplied only two kiln systems for incineration of medical waste in the United States. Both units are rated at 27 kg/hr (600 lb/hr) waste feed rate and are direct adaptations of the hazardous waste incineration equipment line.

The feeding system is an important component for any rotary kiln. M&S has chosen to use a ram feeder. They rejected auger feeding because they did not want to break bags or packaging which might expose operators to airborne infectious agents. M&S indicated that continuous feeding through a chute might also be possible for large-scale systems.

The M&S kilns have the typical 3-4:1 L/D ratio but are generally designed to give about 470,000 J/s-m² (150,000 Btu/hr-ft²) of equivalent "grate area." They want to keep very slow heating of waste in the kiln to prevent slagging. That slow heating is augmented by counter-flow configuration. The kilns are designed to operate with about 20-40 percent excess air in the kiln. Feeding is typically done on 3-minute cycles. The air flow is uncontrolled, being added by induced draft through holes in the front face plus tramp air. Substantial heat loss is indicated since the kiln temperature is typically 1030-1140 K (1400-1600°F). Solids residence time in the kiln (adjusted by rotation speed) is nominally 45 minutes. M&S claims that ash carbon content is below 3 percent and never more than 5 percent.

The afterburners are typically operated at 1260-1370 K (1800-2000°F) with 2-seconds residence time. Auxiliary burners are supplied in both the primary and secondary chambers but are generally used only for start-up. When the secondary burner is not firing, it is an additional source (major) of tramp air. Baseline CO emissions from their units are claimed to be well below 50 ppmv. Uncontrolled particulate matter emissions are in the 0.2 to 0.5 g/Ncm (0.1 to 0.2 gr/dscf) range. There are no data on PCDD/PCDF emissions.

SYSTEM OPERATION

A two-phase program was undertaken to assess the operation of medical waste incinerators. The first phase involved visiting the sites of medical waste incinerators and interviewing the personnel responsible for operation of the facility. This phase of the program focussed on obtaining detailed information on the way in which incinerators are operated. The second phase of the program was a broad survey in which incinerator operators were contacted by telephone and asked a limited number of specific questions about their incinerator. The focus of this phase of the program was to determine the frequency at which incineration is used to treat medical wastes and to identify the general practices used.

SITE VISITS

The following five facilities were visited:

- Kaiser Foundation Hospital - San Diego, Ca
- Cedars-Sinai Medical Center - Los Angeles, Ca
- American Environmental - Rancho Cordova, Ca.
- University of Florida's Jackson Medical Center - Miami, Fl
- Baptist Hospital of Miami - Miami, Fl

The facilities operate a range of incinerators. The Kaiser Medical Center in San Diego, California, owns a modular starved-air incinerator designed and installed by Thermtec of Tualatin, Oregon. The unit has a capacity of approximately 360 kg/hr (800 lb/hr). A diagram of the facility is shown in Figure 29. The scrubber is a spray chamber with a capacity of 2 Vs (33 gpm). A magnesium hydroxide solution is used in the scrubber to control HCl emissions.

Cedars-Sinai Medical Center is located in metropolitan Los Angeles. The hospital owns a large starved-air incinerator system designed by Joy/Ecolaire. The system was purchased and installed in 1986 but, according to Joy/Ecolaire representatives, makes use of 10-year-old technology. A diagram of the facility is shown in Figure 30. The unit was used to process 454 kg/hr (1000 lb/hr). The system is unique because it is equipped with a fabric filter to control particulate emissions.

American Environmental is a private waste management company located outside Sacramento, California. The company operates a large ram-fed, starved-air incinerator which is not located at a hospital. The system was manufactured and installed by Thermtec. The facility has a capacity of 360 kg/hr (800 lb/hr). The emissions can be passed through an extensive quench/wet scrubbing system or through a fabric filter.

The Jackson Medical Center is equipped with Joy's most recent incinerator design. The unit is a large ram-fed, starved-air incinerator equipped with heat recovery equipment. No air pollution control equipment is used. An extensive control system is installed on the incinerator which allows the operator only limited control of the unit. The facility is operated at about 940 kg/hr (2080 lb/hr). A diagram of the unit is shown in Figure 31.

Baptist Hospital operates two incinerators. Both are ram-fed, modular starved-air units. One was manufactured and installed by Simonds in 1983, the other is a newer Joy/Ecolaire incinerator. The Simonds unit is equipped with heat recovery equipment and has a capacity of 760 kg/hr (1600 lb/hr). The Joy/Ecolaire unit has a capacity of 356 kg/hr (785 lb/hr).

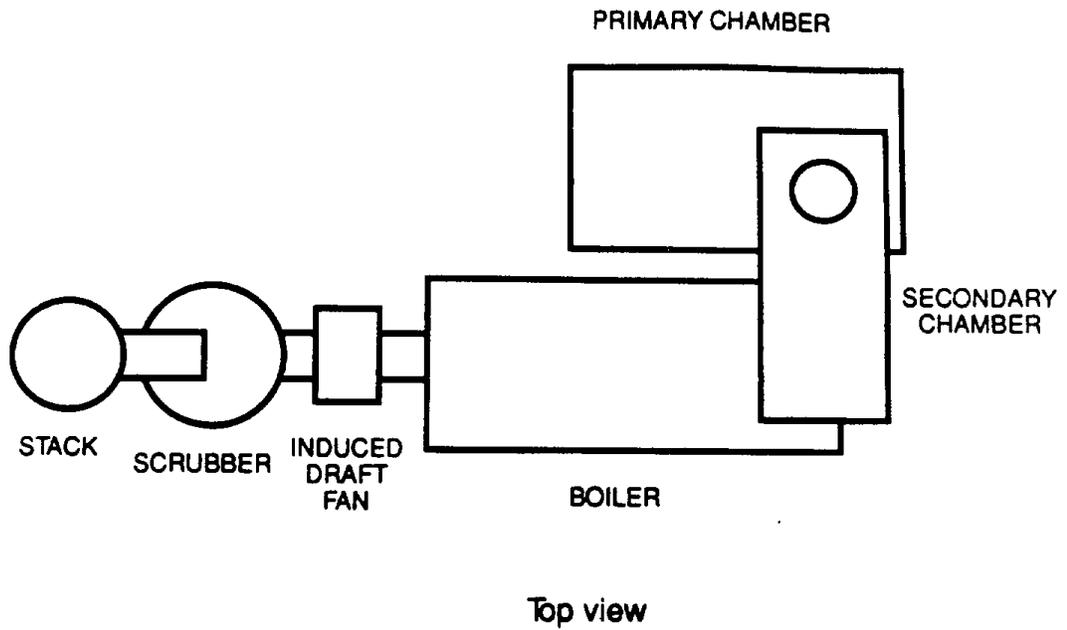


Figure 29. Schematic diagram of incinerator at Kaiser Medical Center (San Diego).

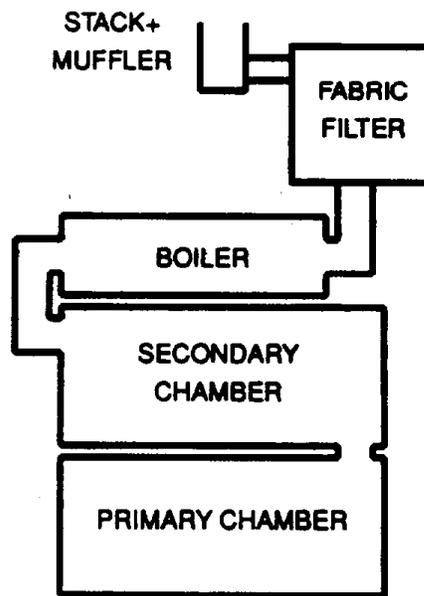


Figure 30. Schematic diagram of incinerator at Cedars-Sinai Medical Center (Los Angeles).

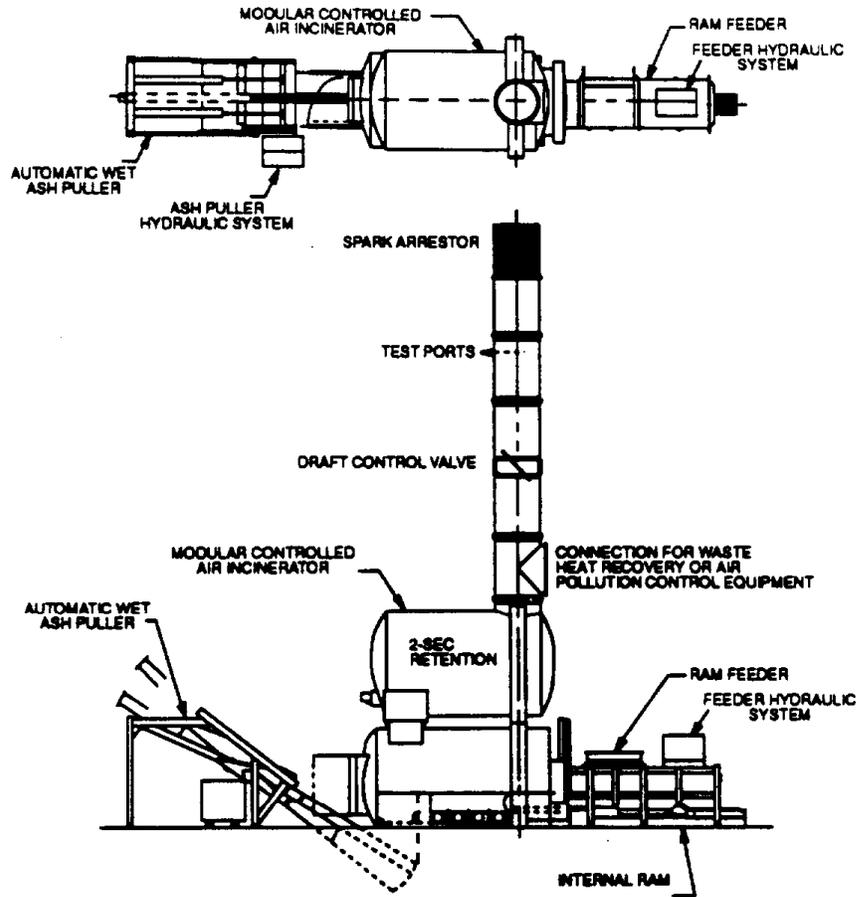


Figure 31. Schematic diagram of incinerator at the University of Florida's Jackson Medical Center (Miami).

Both Kaiser and Cedars-Sinai were not operating their incinerators at the time of the site visit. Kaiser was in the midst of negotiations with the San Diego Air Quality Management District over their operating permit. Cedars-Sinai's incinerator had been shut down by the hospital administration due to concerns the administration had about HCl emissions from the unit. The commercial facility in California and the hospital units in Florida were operating. Baptist was forced to overcharge both of their incinerators to process all the waste produced by the hospital and an adjoining medical office building.

None of the facilities provided special training for the operating personnel. At Kaiser, machinists operated the incinerator, however at all the other hospitals, janitorial staff operated the units. General labor personnel operated the American Environmental unit. Cedars-Sinai used licensed boiler operators to oversee the operation of their facility because of the attached heat recovery boiler. The person ultimately responsible for operation and maintenance of the incinerators at the hospitals also had little specific training, however, the commercial facility was operated by an engineer with combustion training. The incinerator supervisor at the hospitals often had been involved in the start-up training provided by the incinerator's manufacturer, but had received no further training. Because of the maintenance requirements of the equipment, the incinerator supervisor was often intimately familiar with the mechanical requirements of operating the system. This gives them the ability to bypass or circumvent manufacturer-installed control systems. This type of circumvention was not uncommon when the operator felt that the incinerator was not performing as he would like.

All the hospitals used their incinerators to dispose of all waste generated at the hospital. The commercial facility incinerated infectious waste only. The feeding practices varied widely. One facility weighed each charge before placing it in the feed chamber and made sure every fourth load was infectious waste. At the other extreme, one of the hospitals simply placed wastes in the feed chamber until it was full.

Feed rate is the only variable that the operators have control over in most of the incinerator systems. In the newest units, even the ability to control the feed rate is severely limited by the automatic control system as described in the previous section. Most manufacturers view automatic controls as an effective way to compensate for the lack of operator knowledge. In all except one unit, the feed rate was reduced when temperatures exceeded the design levels. One unit only curtailed feed rate when refractory damage was imminent.

The regulations that each facility had to comply with varied immensely. The Florida units were not required to install air pollution control devices or to monitor air emissions. At times, county officials would inspect the unit to ensure that no visible emissions occurred. Strict controls, however, were placed on the ash. The California units met varying regulatory restrictions. The San Diego Air Quality Management District (the body responsible for regulating air emissions from the Kaiser unit) appeared to be the most restrictive local authority. San Diego Air Quality Management District regulations were focused on specifying the technology to be used rather than on allowable emissions.

The cost for operating the units varied from \$0.13/kg to \$0.40/kg (\$0.06/lb to \$0.18/lb). The larger units were the least costly to operate. These numbers do not include capital costs or depreciation. The incinerator at Cedars-Sinai cost around \$1.5 million to construct and permit, whereas Kaiser's incinerator only cost \$0.6 million.

All the facilities plan to continue using their incinerators if possible. Some facilities are not optimistic that the regulatory environment will remain conducive to the incineration of medical wastes. All plan on installing or have installed a wet scrubber to control acid gas and particulate emissions.

Generally, operation of medical waste incinerators has not proven especially difficult. The major hurdles that must be overcome are regulatory restrictions and control of emissions. HCl and particles are the pollutants of principal concern. The major goal of the incinerator operators is smooth operation of the unit.

When this conflicts with good combustion practices or with the built-in control system, the system maintenance crew makes a concerted effort to achieve smooth operation even if this means circumventing the control system or using poor combustion practices.

SURVEY

A telephone survey was conducted to determine how many California hospitals incinerate all or some of their waste. The survey targeted general acute-care hospitals of all sizes representing every county in California. Over two hundred (205) hospitals were contacted. Five of these were psychiatric hospitals, none of which operated an incinerator. No information could be obtained from 36 hospitals, because either the appropriate person could not be reached or information about the hospital's waste handling would not be divulged. Responses were obtained from hospitals in 47 of the 57 counties in California. The hospitals ranged in size from 18 to 1457 beds.

Of the 169 hospitals that offered a response, 34 (20 percent) are operating a waste incinerator. This proportion is decreasing as more hospitals find that their usually old incinerator cannot meet the increasingly stringent regulations imposed by the local authorities, especially in the more populous regions. These hospitals choose to obtain the services of hazardous waste haulers. Of those hospitals not incinerating their waste, at least 8 percent were incinerating four years ago.

Figure 32 presents the results of the survey in terms of percent of responding hospitals that incinerate versus county population (estimated for 1985). It should be stressed that Figure 32 does not represent every hospital in each county. Only one hospital out of 46 contacted in Los Angeles County, which has the highest population, had an operating incinerator, and that single hospital is planning to stop incinerating. Problems related to HCl emissions were indicated for this voluntary action. Rural hospitals tend to incinerate their waste because their local emissions regulations are not as strict, and they cannot afford to have their wastes hauled long distances to landfills that will accept infectious waste. However, the survey indicated the some rural regions are becoming more strictly regulated. Consequently, the waste disposal options for the rural hospitals are decreasing.

Operating regulations vary from minimum combustion chamber or stack temperature limits in rural areas to emission limits on several pollutants and temperature restrictions in populous areas. Recently set particulate emission limits have the greatest impact on existing hospital incinerator operations since most operating units have no device for catching fly ash.

Wastes definitions can have as much effect on incinerator operation as the emissions regulations. When the ash that is produced from incineration of infectious waste is considered to be hazardous, the treatment costs increase dramatically. Ash treatment varies significantly. At one facility the ash is placed in sealed containers and hauled away by specialists; at another the waste is simply being landfilled in bulk with general refuse.

Of the hospitals that identified the wastes they incinerate, about half incinerate only infectious waste. There are apparently differing views on whether pathological waste should be incinerated. About 8 percent of the hospitals incinerate infectious waste excluding pathological waste, while about 16 percent incinerate exclusively pathological waste. Hospitals that burn other wastes in addition to infectious waste have varying protocols for how the added wastes are included in the incineration process. Some incinerator operators are careful to load the incinerator with a certain proportion of paper waste to infectious waste to maintain a constant heat load in the system. However, some incinerator operators simply load the infectious waste first, then, if the incinerator is not loaded to capacity, load general refuse until capacity is reached.

The character of medical wastes may be changing. Many hospitals are discontinuing the use of aerosol cans. This action benefits the incineration process in two ways. First, safety is increased for the workers who must handle the waste and operate the incinerator. Second, the heavy particulate emissions associated with exploding aerosol cans in the incinerator are eliminated.

Incinerator operators agree that infectious wastes should be incinerated or sterilized before landfilling. Many operators feel that their governing regulations are too restrictive and cannot be met. Regulations for incinerator ash is a prevalent concern. Some operators are unhappy because their ash is considered hazardous when they do not see why it is any more hazardous than the ash that other industries produce.

Most incinerator operators think that regional incineration is a good idea while the costs of hauling the waste to the regional facility are reasonable. Hauling costs would be especially important to rural hospitals.

OPERATOR TRAINING

Currently, incinerator operators receive only cursory training. Three types of training are available:

- Manufacturer-sponsored instruction
- Facility-sponsored instruction
- EPA Control Technology Center instruction program

MANUFACTURE-SPONSORED INSTRUCTION

When a system is installed, the manufacturer often conducts an initial training session. The content and format of these sessions can vary widely. Some manufacturers simply discuss maintenance procedures and briefly familiarize the operating personnel with the system. Other manufacturers provide several days of sessions and video tapes of basic procedures. However, these sessions usually contain two common elements:

- System maintenance
- Basic system operation

System maintenance instruction generally touches on routine maintenance and general troubleshooting. Session attendees include the person responsible for the incinerator's operation and various maintenance personnel. The sessions are usually strongly oriented to the basic mechanical details of the incinerator and do not include any of the rationale behind the system design or operation.

The second area generally covered in manufacturer-sponsored training sessions is basic system operation. These sessions focus on what buttons to push and when to push them. Since many parameters on modern incinerators are automatically controlled, there is little for the operators to learn. Thus, these sessions can be brief.

FACILITY-SPONSORED INSTRUCTION

When new employees begin operating the incinerator, they receive basic operating instructions. Since the incinerators are generally operated by the hospitals' janitorial staff, there is a high rate of turnover of incinerator operators. Often there is no link between the initial sessions conducted by the manufacturer and the personnel operating the incinerator at some later time. It is generally quite easy to train a person to operate a typical incinerator. Operator instruction can take anywhere from 15 minutes to an hour.

PILOT PROGRAMS

While no operator training and certification program has been enacted nationally, there have been pilot programs. The most recent of these was conducted by MRI for the EPA and the State of Maryland (26). The

training course is targeted for incinerator operators and is limited in scope. However, it does identify the key parameters for operating medical waste incinerators to minimize pollutant emissions and key maintenance items.

The course is organized into 11 sessions as follows:

- Protecting the Environment - Your Responsibility
- Basic Combustion Principles
- Basic Incinerator Design
- Air Pollution Control Equipment and Functions
- Monitoring and Automatic Control Systems
- Incinerator Operation
- Air Pollution Control Systems Operation
- Maintenance Inspection - A Necessary Part of Your Job
- Typical Problems
- State Regulations
- Safety: An Important Part of Your Job

Each session briefly covers its topic. The course is designed to be taken by a person who has no technical background and who may not have finished high school. Because of this, there are necessarily simplifications and omissions. Materials that have been developed for the course include a student handbook, presentation slides, worksheets, and an instructor's handbook. The course has only recently been developed (Spring 1989) and has not yet been used much. Thus, the effectiveness of this program and of operator training programs generally have not been thoroughly assessed.

SECTION 5

FLUE GAS CLEANING EQUIPMENT

Many States (Pennsylvania and New York for example) have recently imposed strict emission standards for acid gases and particulate matter. These standards require the use of air pollution control devices on both new and existing medical waste incinerators. Several other regulatory bodies in the U.S. are considering similar regulations. There are two basic types of air pollution control systems that have been designed to control particulate and acid gas emissions. The system types are:

- Venturi scrubber/acid gas absorber
- Sorbent injection/fabric filter

By a wide margin, current practice is to use venturi scrubber technology to control acid gas and particulate emissions from small-scale systems [less than 1360 kg/hr (3000 lb/hr) waste feed rate]. The primary driving forces for technology selection include:

- Initial capital cost
- Ease of operation
- Control effectiveness (acid gases and particulate matter)

While venturi scrubbers can be very efficient at removing acid gases, there are apparent limits to the particulate control which is economically achievable with this technology. Where extremely tight particulate emissions standards apply, manufacturers are developing and applying fabric filtration. However, fabric filters must be combined with some type of acid gas scrubbing to attain low acid gas emissions. The following sections present general descriptions of how these technologies are designed and operated. The general rationale for the current design practice is also discussed.

MANUFACTURERS SURVEYED

To identify current flue gas cleaning equipment design practice, several medical waste incinerator manufacturers were asked to identify major air pollution control device vendors for this class of incineration equipment. Based on the resulting list, plant visits or telephone interviews were conducted with the following air pollution control device suppliers:

Advanced Concepts, Inc.
6370 Nancy Ridge Drive, Suite 110
San Diego, CA 92121
Alfred R. Dozier

Emcotek Corporation
8220 Doe Avenue
Visalia, CA 93291
Herbert W. Spencer

AirPol Inc.
 32 Henry Street
 Teterboro, NJ 07607
 (201) 288-7070
 James Gross

United McGill Corporation
 2400 Farwood Avenue, Box 820
 Columbus, OH 43216
 (614) 433-0192
 Richard P. Bundy

Andersen 2000 Inc.
 306 Dividend Drive
 Peachtree City, GA 30269
 (404) 997-2000
 Dwayne L. Sanders

There are many other manufacturers of flue gas cleaning equipment who could have provided significant insights and professional opinions on appropriate equipment design but it was felt that the above sampling was sufficient to provide an assessment of current design practice.

Several types of air pollution control devices are being used with different classes of waste combustors. Proper selection of flue gas cleaning equipment must consider a variety of factors including:

- Regulatory emission limits
- Operating requirements
- Operating personnel requirements
- Space availability
- Capital and operating cost

After considering each of these factors, most air pollution control device-equipped medical waste incinerators use a venturi scrubber combined with an acid gas absorber (Figure 33).

DESIGN SELECTION CRITERIA

Until recently, the only environmental regulations imposed on medical waste incinerators were that they comply with a liberal particulate emission standard (and occasionally an incinerator operating temperature limit). The controlled-air incinerator was developed and applied as a technology which could achieve typical particulate emission limits [e.g. 0.18 g/Ncm (0.08 gr/dscf)] without use of an add-on control device. This situation has changed dramatically in recent years. In July 1987, the U.S. EPA issued interim permitting guidance for municipal waste combustors and recommended the use of spray dryers and fabric filters to control acid gas and particulate matter emissions (27). This guidance is being used by some States in the development of medical waste incineration regulations. Sedman and Brna (28) note that spray dryer/fabric filter manufacturers are willing to guarantee the following performance levels when their technology is used on municipal waste combustors.

<u>Flue Gas Component</u>	<u>Outlet Concentration (dry at 7% O₂)</u>	<u>Removal Efficiency (Percent)</u>
HCl	20-60 ppmv	88-89
HF	2-5 ppmv	50-80
SO ₂	20-70 ppmv	67-90
Particulate Matter	0.03-0.05 g/Ncm (0.013-0.02 gr/dscf)	

In December 1988, New York issued regulations for infectious waste incinerators limiting particulate matter emissions to 0.07 g/Ncm (0.03 gr/dscf) (at 7 percent O₂) for existing on-site units and 0.034 g/Ncm (0.015 gr/dscf) for existing off-site units and all new units. Hydrogen chloride emissions (3-hour average) must be reduced by 90 percent unless the exhaust concentration is less than 50 ppmv (dry at 7 percent O₂) or less than 1.8 kg/hr (4 lb/hr) for a unit with less than a 230 kg/hr (500 lb/hr) charging rate. Other States are considering similar performance requirements including SO₂ emission limits similar to the performance level of spray dryer/fabric filters on municipal waste combustors.

On-site medical waste incinerators typically are not operated continuously. Even large hospitals tend to operate their incinerators for only one or two shifts per day and generally do not operate the equipment on weekends. To be consistent with this operating schedule, the air pollution control system ideally needs little or no special attention (such as long warm up periods) during start-up or shut-down. A short start-up period is not an essential APCD selection feature, but it may be critical at small on-site facilities where the incineration system operators have received little or no training. These practical considerations tend to favor venturi scrubbers for particulate matter collection since they need no preheating. Fabric filters must be preheated above the acid gas dewpoint to prevent acid attacking the bags and bag blinding.

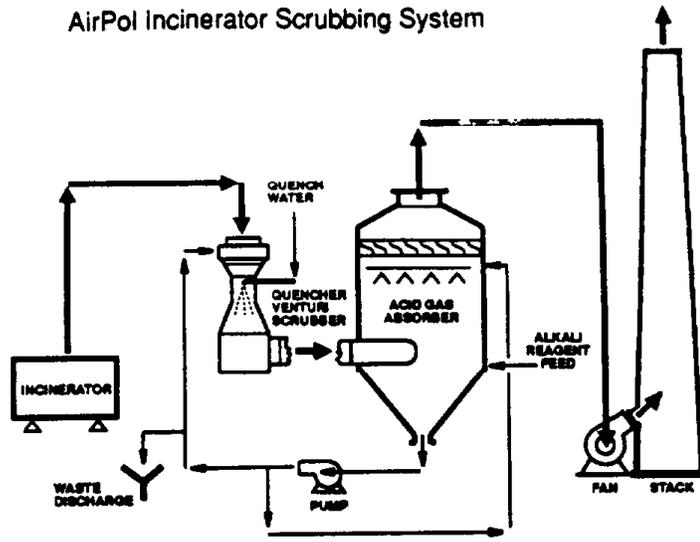
Most medical waste incinerator flue gas cleaning systems are being added to existing incinerators or included with new incinerator applications at hospitals. In most of these cases, space is at a premium. Air pollution control systems requiring extensive room for operation (such as those requiring reagent storage or reagent preparation) are often at a disadvantage. Thus, there is often an advantage for systems using liquid reagents such as NaOH as opposed to lime-based systems.

Assuming alternative air pollution control device selections meet minimum regulatory requirements, the deciding factor in system selection is generally system cost. For a "typical" hospital waste incinerator installation [rated at 450 kg/hr (1000 lb/hr)], there is a clear cost advantage for the wet venturi/acid gas system. For this size installation, designed to achieve 0.07 g/Ncm (0.03 gr/dscf) particulate loading, typical turnkey installed cost for a venturi scrubber/acid gas absorber is about \$250,000. This approximate cost was cited by each of the manufacturers and verified by examining several firm price quotes to different hospitals. In comparison, a spray dryer/fabric filter (SD/FF) system designed to achieve the same acid gas and particulate control for the same size incinerator costs approximately \$750,000. A large portion of the SD/FF system costs are associated with equipment to store and slake the lime reagent. As will be discussed later, lime is less costly than sodium-based reagents. As incineration system size increases, the capital cost advantage of the venturi scrubber system rapidly disappears with the SD/FF having a lower capital cost for units with capacities larger than about 1100 to 1400 kg/hr (2500 to 3000 lb/hr). For a 450 kg/hr (1000 lb/hr) incinerator, dry sorbent injection coupled with a baghouse will have a cost intermediate between the venturi scrubber/acid gas absorber and the spray dryer/fabric filter. Several vendors believe that this option has an advantage for regions with 0.03 g/Ncm (0.015 gr/dscf) particulate limits.

VENTURI SCRUBBER/ACID GAS ABSORBER

The system configurations for venturi particulate scrubbers/acid gas absorbers supplied by AirPol, Inc. and Andersen 2000 are illustrated schematically in Figure 33. These basic configurations, with modifications, are used by other vendors as well. As illustrated, hot flue gas from the incinerator or waste heat boiler is directed to the venturi scrubber which both quenches the hot gas and removes particulate matter. The venturi scrubber also provides partial collection of acid gases and other condensable flue gas constituents. Particulate collection occurs through a variety of fundamental mechanisms but the predominant phenomena is inertial impaction of particulate matter with water droplets sprayed into the venturi inlet. High collection efficiency of particles smaller than 1 micrometer requires that the flue gas and particulate be accelerated to high velocity in the venturi throat region. The basic venturi configuration will minimize pressure loss associated with flow acceleration, but a venturi pressure drop (ΔP) of about 7500 Pa gauge (30 in. W.G.) is needed to achieve 0.07 g/Ncm (0.03 gr/dscf) particulate matter control, and an even higher ΔP is needed to achieve a 0.03 g/Ncm (0.015 gr/dscf) limit. This will be discussed in more detail in a later section.

AirPol Incinerator Scrubbing System



Andersen 2000

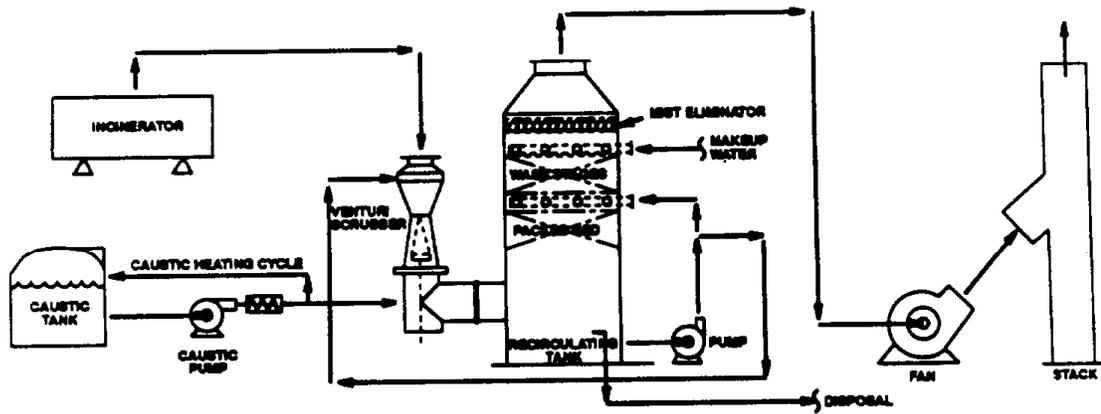
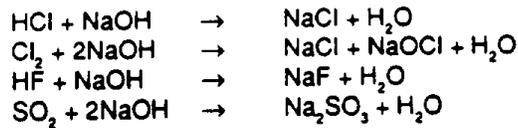
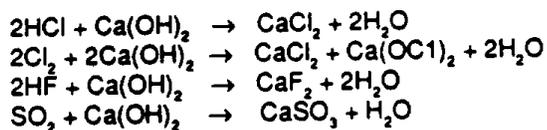


Figure 33. System configurations for venturi scrubbers/acid gas absorbers supplied by Airpol, Inc. and Andersen 2000.

Acid gases such as HCl and SO₂ are only partly absorbed by the water spray in the venturi scrubber. High-level acid gas control is achieved in a counterflow acid gas absorber downstream of the venturi. As shown in Figure 33, AirPol, Inc. uses an open spray tower while Andersen 2000 uses a packed tower absorber. Collection of acid gas tends to drop the pH of the scrubber liquor. An alkaline buffering reagent is supplied for pH control. Either lime or sodium hydroxide may be used for this purpose with NaOH being the typical choice since it can be purchased and stored as a liquid. Common neutralization chemical reactions for sodium hydroxide and absorbed acid gases include:



For lime-based systems, the neutralization reactions include:



The rate of buffer reagent addition is controlled to maintain the scrubber liquor pH between 6.5 and 7.0. This is essentially stoichiometric for the above reactions. For sodium-based buffering, the resultant salts are water soluble, and in many areas, scrubber blowdown can be discharged directly to the facility sewer system. This blowdown will, however, also contain insoluble material including particulate matter captured in the venturi scrubber.

Since particulate matter is captured in the venturi by impaction with water droplets, any liquid escaping from the absorption tower contributes particulate to the facility exhaust. For this reason, one or more stages of mist elimination are included at the top of the absorption tower. As illustrated in Figure 33, Andersen 2000 provides make-up water in a final wash stage in the packed tower just below the mist eliminators.

Total pressure drop across the absorption tower is typically small [1000-1500 Pa gauge (4 to 6 in. W.G.)] in comparison with ΔP across the venturi scrubber. The total head loss across the pollution control system plus that of the incinerator is provided by the induced draft fan. Flue gases enter the fan saturated but are reheated by the fan losses before exiting through the stack.

VENTURI SCRUBBER DESIGN/OPERATION

There are two basic types of venturi scrubber used for hospital waste incinerator application: the "wetted approach" type and the "non-wetted approach" type. The scrubbers are primarily designed to control particulate emissions. Further, these two venturi types may be supplied in either a fixed or variable throat configuration. The wetted approach is used for applications where there is no waste heat boiler and flue gas temperature may reach 1370 K (2000°F) or higher. Figure 34 illustrates the wetted approach, variable throat venturi scrubber manufactured by Andersen 2000. The hot flue gas enters the approach section of the venturi where it is cooled to near saturation. Buffered water is added through tangential inlets supplying a protective film of liquid on the convergent portion of the venturi. The hot gas is rapidly cooled by evaporation and reaches the throat at near saturation conditions. More scrubber liquid is added through a solid cone spray nozzle in either the adjustable throat insert (as shown in Figure 34), in the side wall of the throat region (see Figure 35) or through a nozzle in the approach region directed toward the throat (see Figure 36).

Figure 36 illustrates the "non-wetted approach" fixed throat configuration. As implied by the name, the walls of the convergent region are not wetted and thus, the configuration is restricted to situations with lower

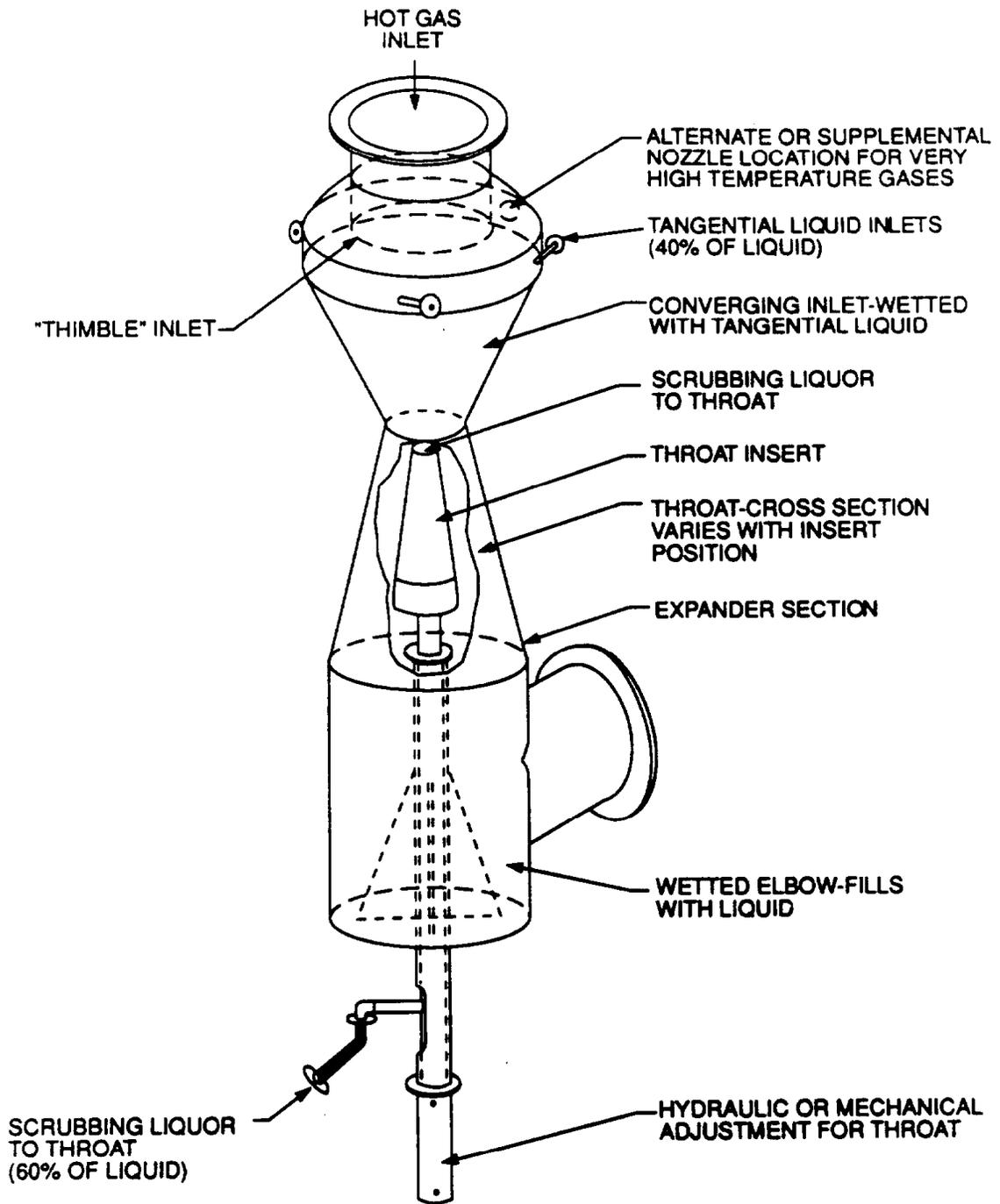


Figure 34. Variable venturi scrubber with wetted elbow

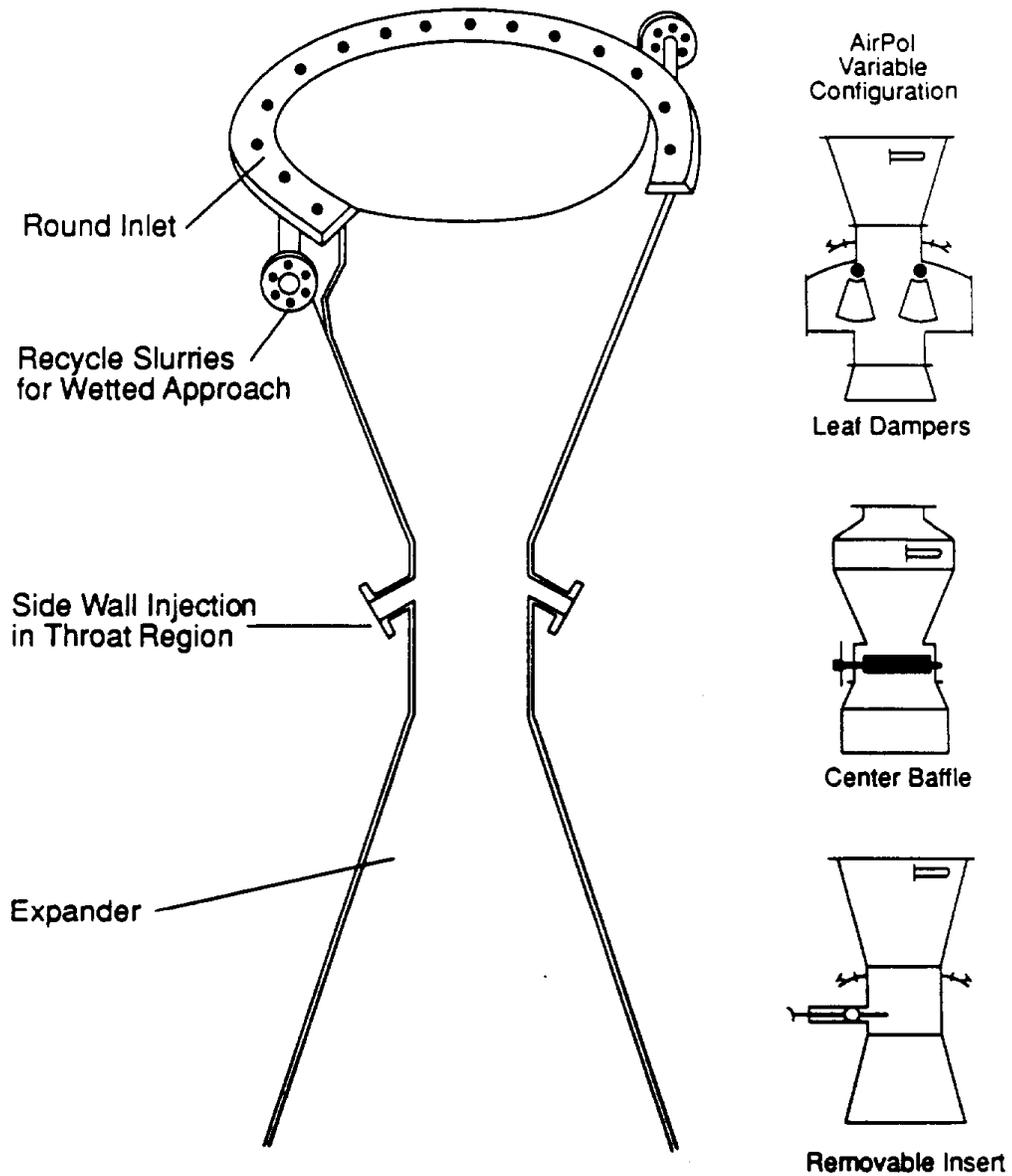


Figure 35. AirPol basic venturi configuration.

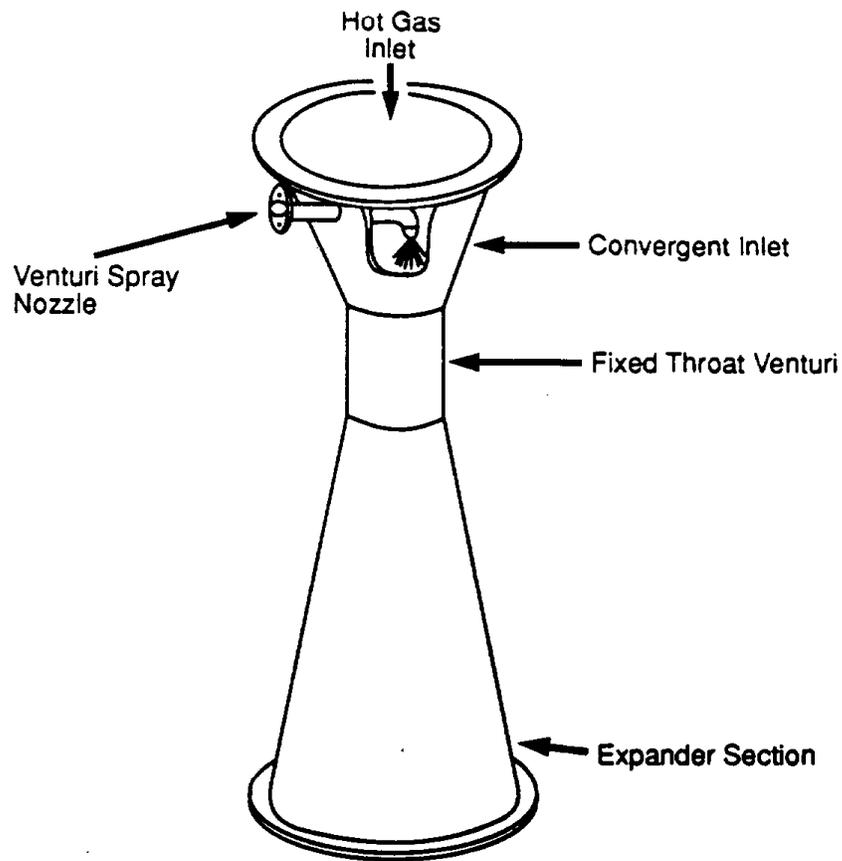


Figure 36. Anderson 2000, Inc. - nonwetted approach, fixed throat venturi.

temperature gases entering the venturi. If hot gases enter the throat of the venturi, they will vaporize the water droplets and reduce the device's ability to capture particles.

Before discussing fixed versus variable throat venturi configurations, it is useful to briefly describe the basic processes involved in venturi scrubber particulate capture. As noted earlier, the dominant capture process is inertial impaction of the particulate matter on water droplets. This process is described in several air pollution control texts (29). It can be shown that the capture efficiency of collisions between particles and droplets is directly related to a parameter known as the impaction number, N_i . The functional dependence of this parameter is given by:

$$N_i = \frac{d_p^2 r_p U}{18 \mu_g d_d} \quad (1)$$

where U is relative velocity between the particle and droplet, r_p is particle density, d_p is the particle diameter, μ_g is the gas viscosity and d_d is the droplet diameter. Figure 37 shows the theoretical and experimental

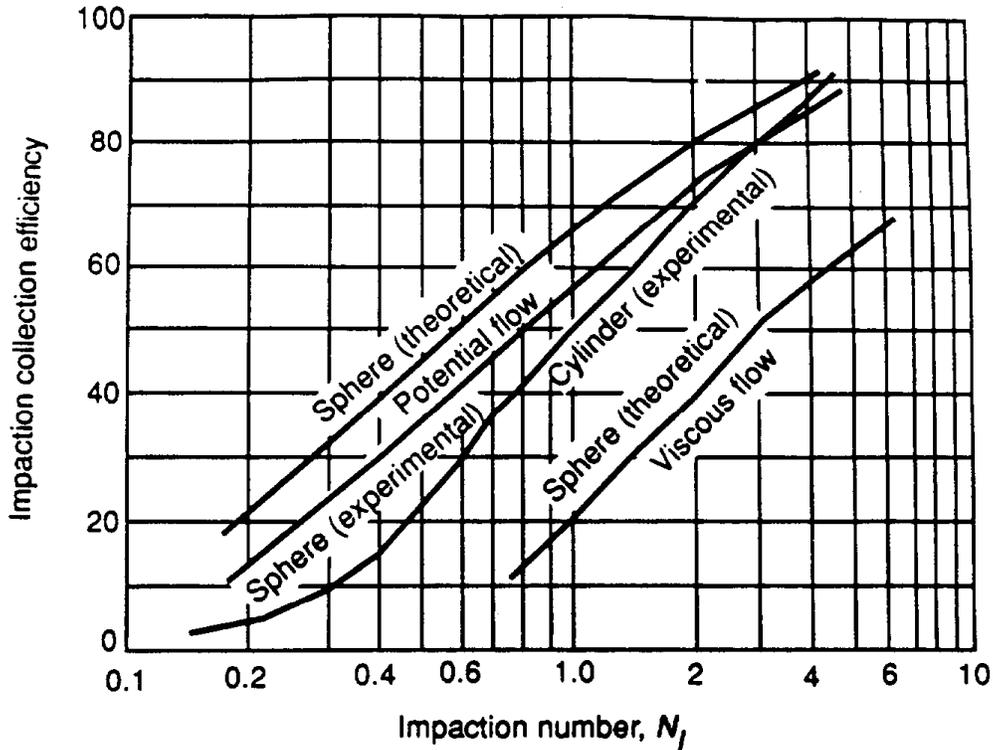


Figure 37. Theoretical and experimental impaction collection efficiencies for spheres and cylinders

relationship between N_i and impaction collection efficiency. For particles less than several microns in diameter, N_i should be multiplied by the Cunningham correction factor (K_c) to account for direct interaction of the particle with air molecules.

$$K_c = 1 + 0.16 \times 10^{-4}/d_p \quad (2)$$

As shown, efficiency of particle capture increases with increasing N_i . For a given particle size and density, collection is improved by providing high relative velocity between the solid and liquid phases and by decreasing the diameter of the liquid droplets.

As shown in Figure 38, gases and entrained particles accelerate in the converging region of the venturi. Immediately after spray injection, the axial velocity of the scrubbing media is nearly zero. Thus, U , the relative velocity between the solid particles and the liquid droplets is very close to the velocity of the solid particles. This produces a high impaction number and high collection efficiency. As the droplets move away from the throat, they will accelerate to the gas velocity causing U to decrease and N_i to drop. When the liquid spray is added in the converging region (as in Figure 36), both the liquid droplets and the solid particles are accelerated as they move toward the throat. U is very small in these scrubbers and collection efficiency is relatively low.

The design gas velocity in the venturi throat will depend on a variety of parameters including the particulate matter size distribution and the needed particulate removal efficiency. N_i varies with the square

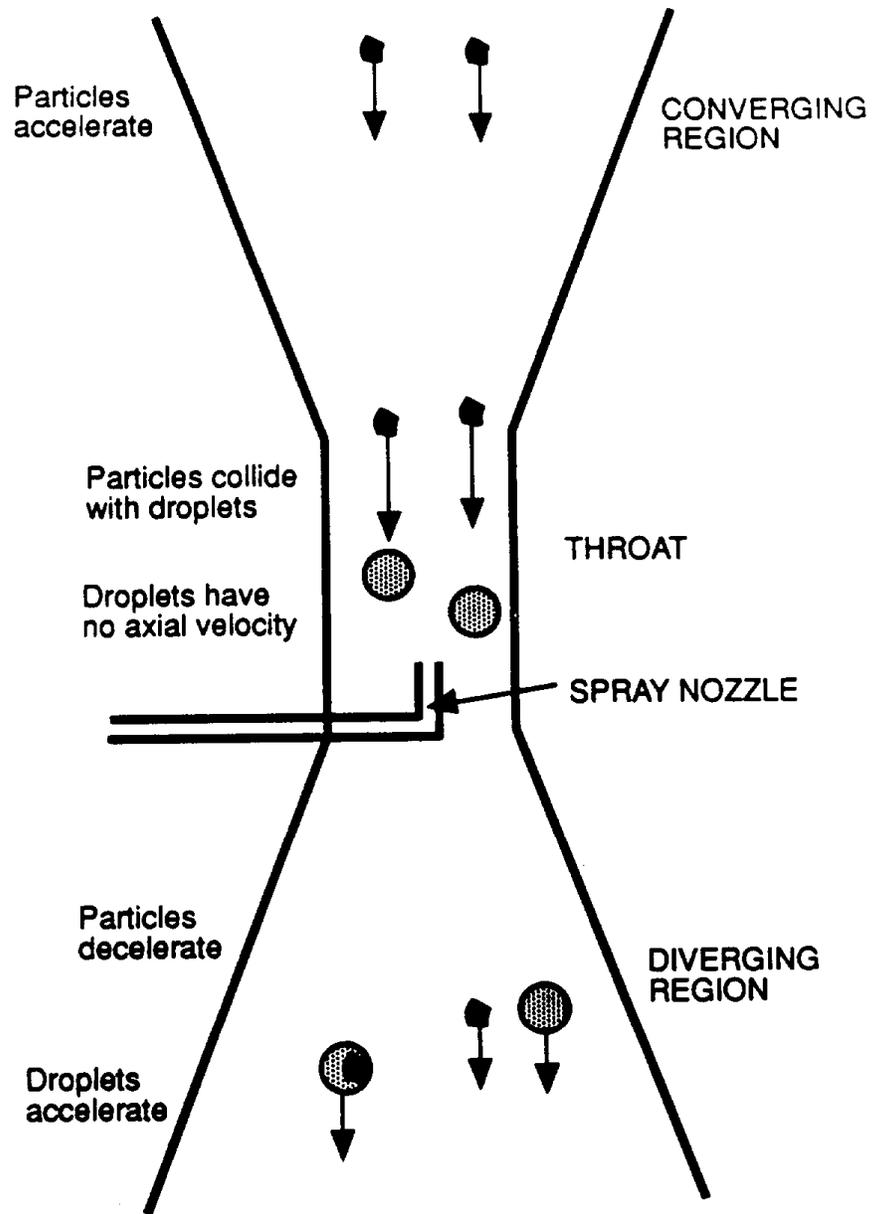


Figure 38. The behavior of solid particles and liquid droplets in a venturi scrubber.

of particle diameter and thus, the collection efficiency falls off rapidly for small particulate. This effect is illustrated in Figure 39 which shows fractional collection efficiency versus particle diameter for several relative velocities (expressed in terms of pressure drop across the venturi). When the allowable particle concentration in incinerator's exhaust is decreased, increased capture efficiency of the small diameter particles is required. This is achieved by increasing the velocity at the venturi throat.

The inability of venturi scrubbers to efficiently capture particles smaller than 1 micrometer has an important implication. As will be discussed later, volatile metals may vaporize in the incinerator. These metals subsequently condense. The condensation occurs evenly on all available surface areas. Particles smaller than 1 micrometer contribute most of the available surface area. As a result, the particles smaller than 1 micrometer have very high concentrations of volatile metals. Many toxic metals are volatile including lead, arsenic, mercury, and cadmium.

Venturi scrubber particulate collection efficiency is generally correlated with the pressure drop across the entire venturi instead of with throat velocity. The pressure drop is relatively easy to measure and has a direct affect on the required size of the induced draft (ID) fan. Figure 40 shows a typical pressure profile for a venturi scrubber. From the inlet of the venturi (Point A), to the throat entrance (Point B), the static pressure drops as the gases (and particles) are accelerated. The pressure is constant through the throat region (Point B to C) and then rises again as the flow is decelerated in the diverging region (Point C to D). The pressure drop between points A and D represent the overall pressure drop for the venturi which must be supplied by the ID fan.

A widely used expression for predicting the pressure drop (ΔP) across a venturi scrubber is the Calvert equation

$$\Delta P = (5 \times 10^{-5}) V^2 L \quad (3)$$

where L is the liquid feed rate (gallon of liquid per thousand cubic feet of gas at saturated conditions) and V is the gas throat velocity (ft/s). ΔP in this equation is predicted in inches of water gauge. The equation is based on the observation that the energy required to pull gas through the venturi scrubber is proportional to that required to accelerate the liquid droplets to a velocity equal to the throat gas velocity. Figure 42 shows a typical plot of venturi scrubber ΔP versus particulate removal efficiency and illustrates the exponential increase in needed ΔP as required removal efficiency increases.

The venturi throat area (A) is established to provide the required velocity (V) with the design point flow rate (Q):

$$A = Q/V \quad (4)$$

As illustrated earlier in Figure 41, the pressure drop across a venturi scrubber increases exponentially with increase in needed particulate removal level. The first increments of particulate removal are easily accomplished by the capture of large-diameter particles. More stringent particulate limits require increased collection of smaller particles which are more difficult to capture (see Equation 1). Figure 42 illustrates the impact of venturi scrubber ΔP on outlet particle loading for a typical medical waste incinerator. The initial particle loading is 0.70 g/Ncm (0.3 gr/dscf) @ 12 percent CO₂. As the venturi scrubber ΔP increases, the outlet particle loading decreases. A ΔP of about 1.7×10^4 Pa (70 in. W.G.) is needed to reduce the particle loading to 0.03 g/Ncm (0.015 gr/dscf) @ 12 percent CO₂. A pressure drop of this size is costly to generate. Most manufacturers do not design venturi scrubbers with a ΔP of greater than 1.5×10^4 Pa gauge (60 in. W.G.). To date, venturi scrubbers have successfully reduced particulate emissions to 0.07 g/Ncm (0.03 gr/dscf). However, systems such as those described previously have not yet demonstrated an ability to achieve 0.03 g/Ncm (0.015 gr/dscf). The major venturi scrubber manufacturers indicate that they can meet this performance level but with difficulty. As will be discussed later, Andersen 2000 plans to include special particulate control features in the acid gas absorber sections. One organization (John Zink Company) reports

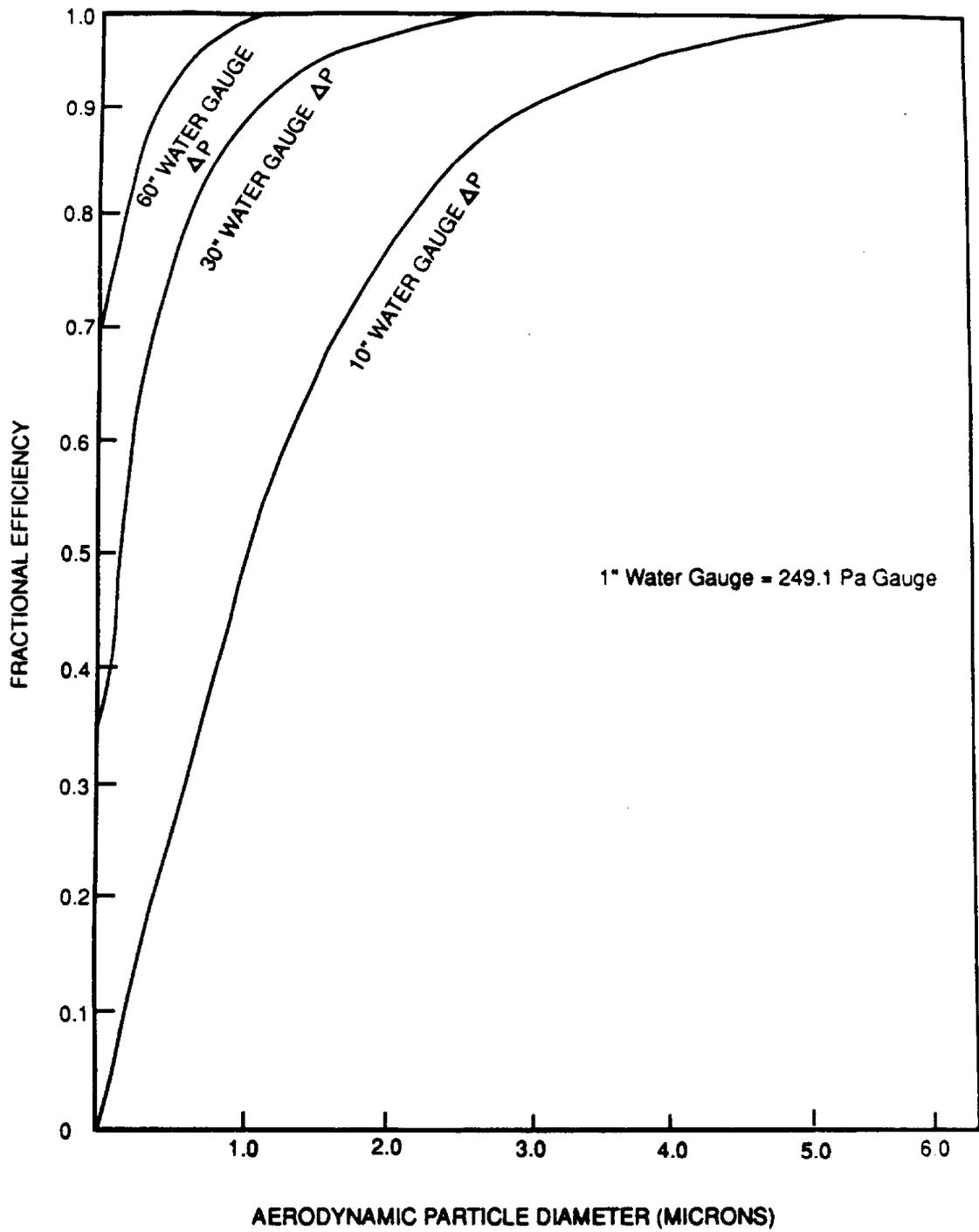


Figure 39. Venturi scrubber fractional efficiency characteristics.

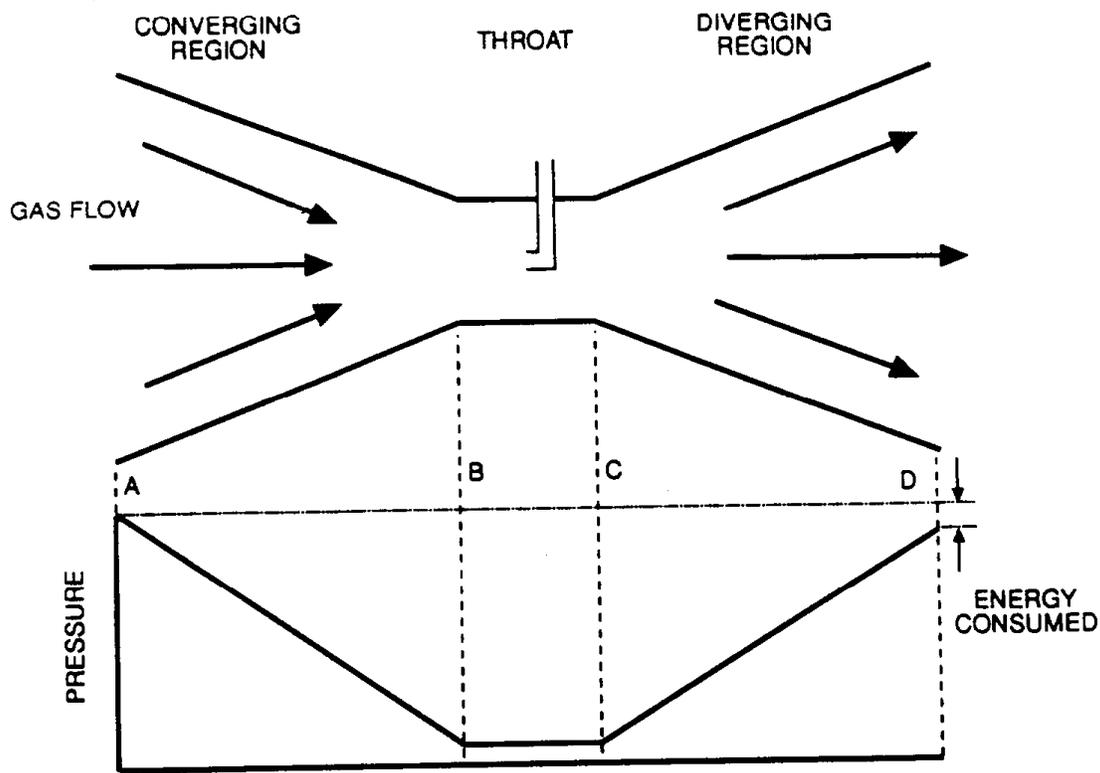


Figure 40. Pressure profile in a venturi scrubber.

that they have achieved 0.03 g/Ncm (0.015 gr/dscf) using a dual venturi system while other incinerator manufacturers are seriously examining fabric filter-based systems for locations requiring 0.03 g/Ncm (0.015 gr/dscf).

For incineration systems which operate at the design point (waste feed rate, waste composition and excess air) almost constantly, it is possible to achieve the required particulate matter control with a fixed throat geometry. Most medical waste incinerators, however, are operated over a wide range of conditions. Waste feed rate is particularly variable. To account for the resultant variation in flue gas flow rate, most venturi scrubber manufacturers provide model lines with variable throat areas. As shown in Figure 34, the system offered by Andersen 2000 uses an inverted cone in the expander portion of the venturi. The actual throat area for this design is the annular region between the cone and the venturi wall. By adjusting the vertical position of the center body, the effective throat area can be controlled to give nearly constant velocity over a wide range of exhaust gas flow rates. AirPol controls gas velocity with an adjustable butterfly valve in the venturi throat region. Other manufacturers diverted variable amounts of flue gas back to the incineration chamber to maintain a constant venturi throat gas velocity.

Several manufacturers are offering alternatives to venturi scrubbers. Like venturi scrubbers, these alternative technologies capture particles and acid gases in a liquid media. The main variation between these technologies is the method used to achieve a high relative velocity between the solid particles and the liquid droplets. Emcotek accelerates the liquid droplets with a rapidly spinning atomizing disk. Another manufacturer splits the gas stream into two separate streams which are subsequently collided. These technologies

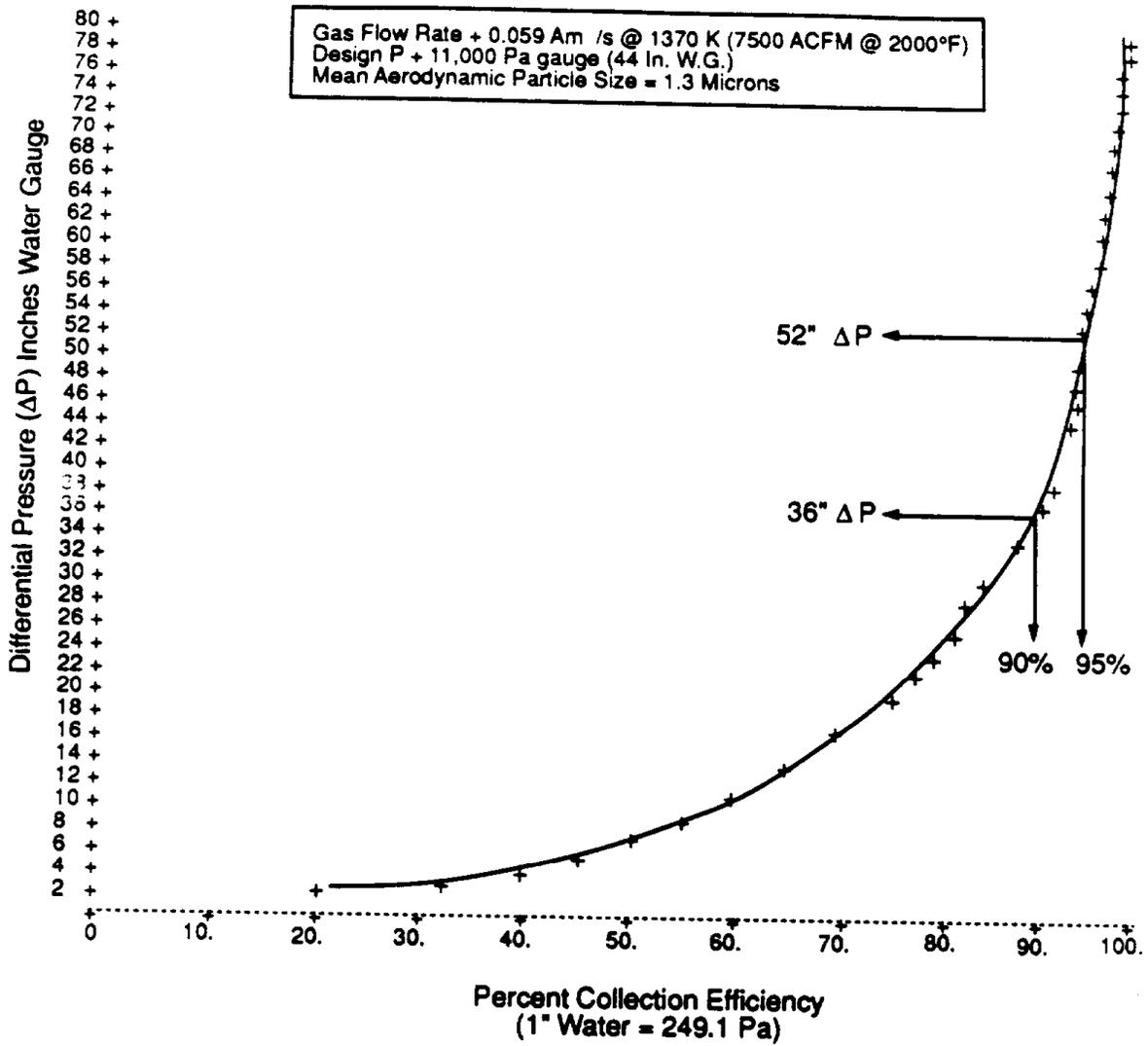


Figure 41. Venturi scrubber collection efficiency versus differential pressure.

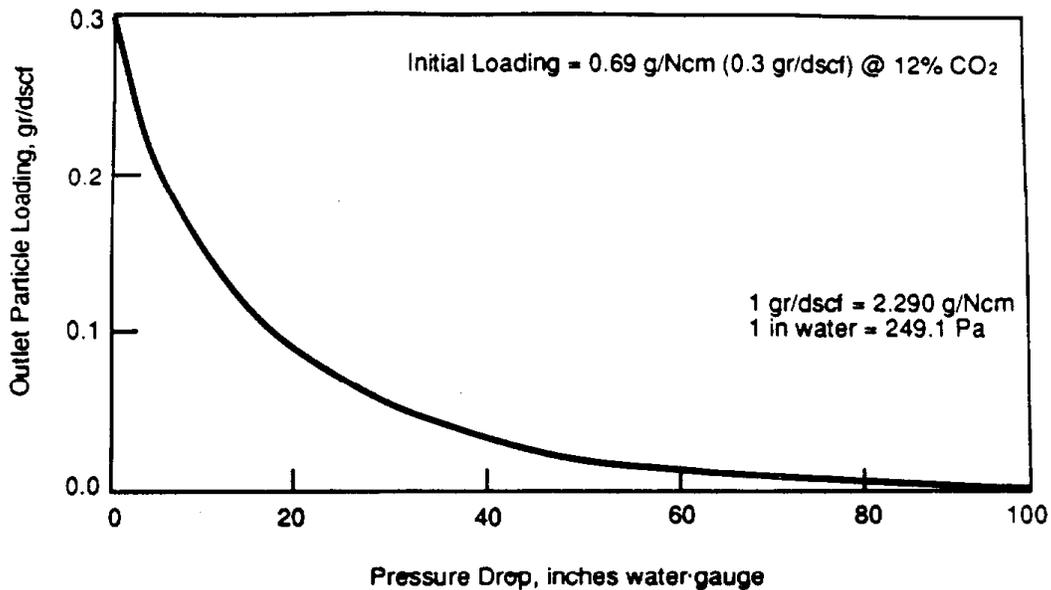


Figure 42. The impact of venturi scrubber pressure drop on the concentration of particles emitted from a typical medical waste incinerator.

reduce the pressure drop needed to achieve a given particle capture efficiency. However, the equipment has not been extensively tested on a range of incinerators.

ACID GAS ABSORBER

As indicated earlier, acid gas capture begins in the venturi scrubber and is completed in the absorption tower. Both packed tower and spray tower configurations are used. Sodium hydroxide or calcium hydroxide are used to control scrubber liquid pH. Sodium hydroxide produces soluble salts of chlorine (NaCl , NaOCl) and sulfur (Na_2SO_3) while calcium salts are insoluble. The open spray tower configuration used by AirPol can operate with either type of alkali reagent. The packed tower configuration preferred by Andersen 2000 is suitable only for sodium buffering since the insoluble salts create plugging problems in packed regions. For calcium-based systems, Andersen 2000 provides a "disk-and-donut"-type acid gas absorber (Figure 43).

Most medical waste incinerator flue gas cleaning systems use sodium hydroxide buffering. The primary reasons for this choice include the simplicity of the design, the compactness of the hardware, and the ease of operation. Sodium hydroxide may be purchased as a 50 percent concentration liquid and stored in a polyethylene storage tank sized for about a 2-week supply of solution. The liquid is pumped from the tank through a heater, to assure that the caustic solution remains liquid [freezing point = 283 K (50°F)]. The pumped caustic solution is then added to the scrubber liquid or recirculated back to the caustic storage tank. The caustic control system is driven by a pH meter which monitors scrubber liquid pH. Solenoid valves control flow of caustic solution, maintaining scrubber liquid pH in the 6.5-7.0 range. The caustic buffering equipment, including the storage tank, can be configured to need little floor space. The entire system can be efficiently operated with little operator intervention. Several systems have been installed on oil-field steam generators in Kern County, California and operated remotely.

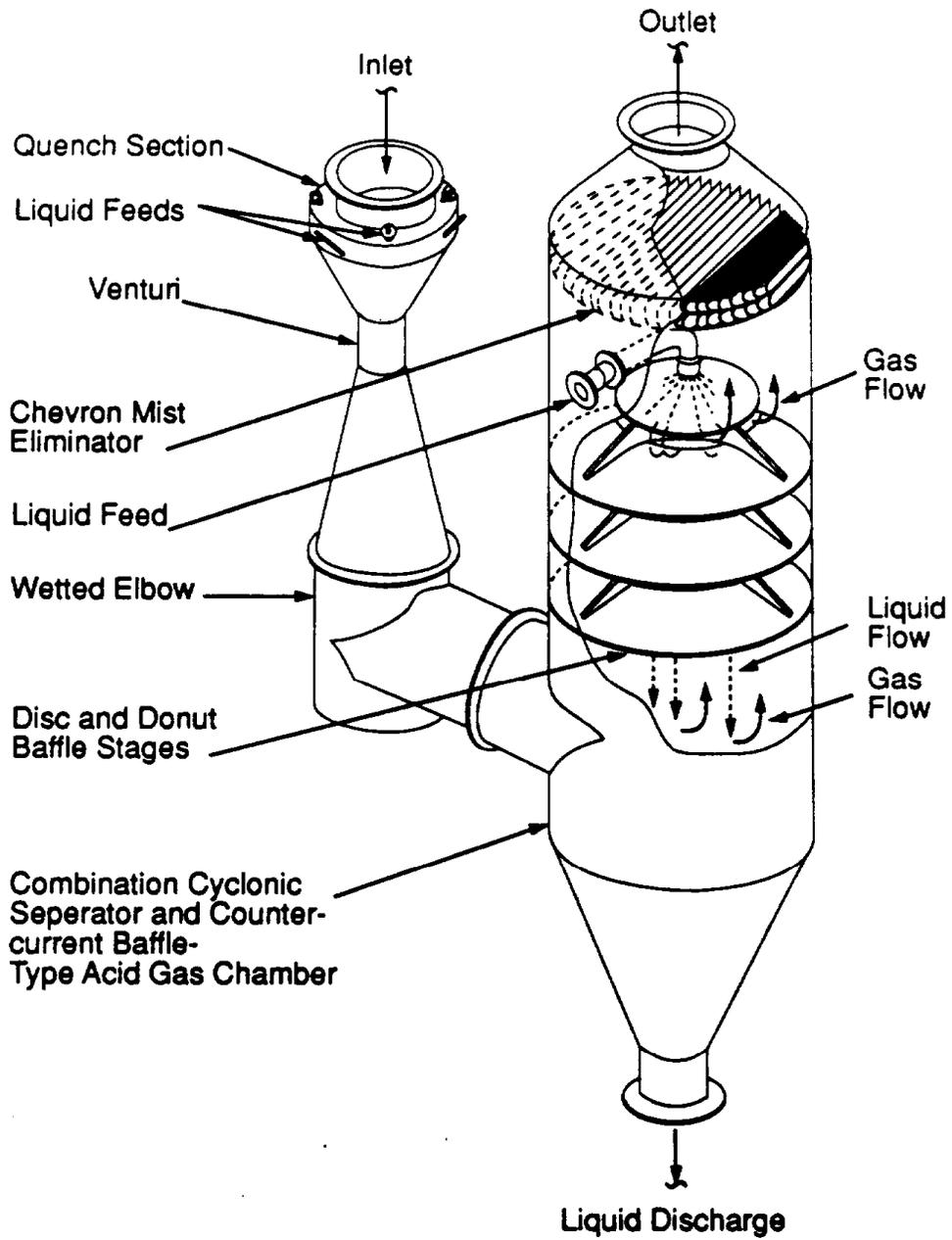


Figure 43. Andersen 2000 scrubbing and HCl absorption system using calcium-based alkali for waste emissions.

In contrast to sodium systems, equipment requirements for traditional lime (CaO)-based scrubbing can be complex. Calcium oxide is purchased as a dry powder and stored in a covered silo. The solid is fed to a slaker where it is mixed with water and then passed to a storage tank which is stirred to maintain the slurry. The lime slurry is then pumped to the scrubber system. This type of system requires a large amount of space, must be carefully controlled by a trained operator, and has a high capital cost (relative to sodium-based systems) for small-scale operation. In addition, calcium may react with the CO₂ in the flue gas to form solid calcium carbonate deposits. Lime-based systems are discussed in more detail in a later section. AirPol, Inc., has suggested, however, that dry lime could be directly added to the scrubber liquid in the absorber tower sump. This would eliminate the need for a slaker, slurry storage tank, and slurry pump. They have not installed such a system on a medical waste incinerator although the approach has been included in several bids as an option.

Neutralization of the scrubbing liquid with caustic maintains the pH near 7.0 but the reactions produce chlorides in the liquid. Generally, as the chloride concentration increases, greater care must be taken in choosing materials of construction. Two different system approaches are in use. AirPol, Inc., constructs their venturi scrubber and acid gas absorber using 316L stainless steel. That material selection requires that chloride levels in the scrubber liquid be maintained at very low levels. AirPol personnel indicate that the ideal situation would be a once-through system. In keeping with this ideal, a large percentage of the liquid pumped from the acid gas absorber is usually diverted to the waste discharge. The discharge fraction is controlled through continuous monitoring of the scrubber liquid density (density is increased by the dissolved chlorides). This approach allows the use of inexpensive construction materials at the expense of high wastewater discharge rates. It should be noted, however, that the total mass of chlorides being dumped to the sewer is not affected by the high water discharge rate.

An alternative approach has been adopted by Andersen 2000 who simply have a liquid overflow in the sump portion of the packed tower. With this configuration, scrubber blowdown directly responds to the excess makeup water addition. To account for high chloride content in the scrubber liquid, they build the venturi scrubber from Hastelloy alloy C-276 or C-22. The acid gas absorber is built of fiberglass-reinforced vinylester with a chemically resistant resin. The resin also contains a fire retardant. Safe continuous operation of fiberglass-reinforced plastic (FRP) is restricted to temperatures below about 370 K (200°F). A potential difficulty for this approach is that failure of the liquid circulation could cause the plastic to overheat and the packed tower components to melt or burn. However, such a system failure should cause the emergency dump stack of the incinerator to open, diverting hot gas flow from the flue gas cleaning equipment.

AirPol, Inc., Andersen 2000 and the various incinerator manufacturers questioned all indicate that the venturi scrubber/acid gas absorber achieves needed acid gas control with relative ease. This includes 90 percent HCl control and SO_x emissions below 30 ppm.

Particulate matter is captured by the caustic/water solution injected into the venturi scrubber. This particulate-laden fluid becomes the scrubber liquid at the base of the acid gas absorber and is sprayed into the scrubber for acid gas control. Care must be exercised in the absorber design to minimize water droplets escaping from the tower. Insoluble material in escaping droplets (incinerator particulate matter as well as insoluble salts) contributes to particulate matter emissions from the air pollution control equipment. Further, California considers condensable solid material collected in the back half of an EPA modified Method 5 train to be emitted particulate matter. Thus, in California, soluble chlorides in the scrubber liquid which escape the absorber tower would contribute to particulate matter emissions. (The U.S. EPA and most other States do not consider the back-half catch of a modified Method-5 train to be particulate.)

To achieve an 0.07 g/Ncm (0.03 gr/dscf) particulate emission limits, control device vendors typically provide a mist eliminator as part of the absorber tower system and may use make-up water in a second stage of washing in the absorption tower. The system offered by Andersen 2000 to achieve 0.03 g/Ncm (0.015 gr/dscf) particulate emission limits includes washing the gases with make-up water, a traditional chevron-type

mist eliminator and a diffusion-controlled mist eliminator they refer to as CHEAF[®] (Cleanable High Efficiency Air Filtration) systems. The CHEAF[®] system is reported to be particularly effective collecting water-soluble particles smaller than 1 micrometer and aerosols of insoluble particles smaller than 1 micrometer particulate. CHEAF[®] systems have been used to control ammonium nitrate and metallurgical fumes. As noted earlier, however, this system's ability to achieve 0.03 g/Ncm (0.015 gr/dscf) has not yet been demonstrated on an operating medical waste incinerator.

ZERO LIQUID-DISCHARGE SYSTEMS

Several different wet air pollution control system designs for application to medical waste incinerators have been developed which produce a dry waste stream. These developments are largely in response to State regulations limiting wastewater discharge. Suppliers of this equipment who were contacted during the current study include Advanced Concepts Incorporated (ACI) and AirPol, Inc. Zero liquid-discharge scrubbers appear to be the main product line for ACI. In addition, for larger, regional medical waste incinerator installations, dry scrubber/fabric filter applications become feasible. Each of these system configurations are briefly described below.

ADVANCED CONCEPTS INCORPORATED

The flue gas cleaning system supplied by ACI is illustrated in Figure 44. Hot combustion gases [at temperatures to 1370 K (2000°F)] are introduced to a submerged combustion-type sparger. The function of the sparger is to break the combustion gases into small bubbles which are forced through a scrubbing solution. This process removes acid gases and much of the particulate matter from the combustion gases. It also reduces the gas temperature to the wet-bulb level.

Cooled and neutralized combustion gases pass through a gas/liquid separator into a venturi scrubber and demister. ACI uses a venturi which separates the flue gas to be scrubbed into multiple small streams. ACI claims that multiple small streams require less energy to accomplish particle capture than one large stream and that capture efficiency is superior. Liquid from the venturi and mist eliminator are collected in a sump and pumped back into the sparger. Downstream of the mist eliminator, combustion gases pass through an induced draft fan [with up to 1.2×10^4 Pa gauge (50 in. W.G.) pressure drop] and out the exhaust stack.

Substantial evaporation of water occurs in the sparger section as the hot gases are quenched. This results in increased concentration of dissolved salts and suspended solids in the sparger liquid. This liquid is controlled to a pH of about 7.0 using caustic buffering. When the salt concentration exceeds the solubility level, the salts precipitate from the liquid. Zero liquid discharge is achieved by filtering precipitated salts and suspended solids from the scrubber liquid.

Figure 45 illustrates the continuous media filter used by ACI. Sludge from the bottom of the sparger is pumped to the filter. Filtrate is pumped from the clean liquid reservoir back to the sparger. The disposal filter media is moved by a positive-drive polypropylene conveyor which is sealed along the periphery by two rotating seal disks. Liquid passes through the media while the contaminants are collected on the filter. Depth of the liquid pool above the filter is controlled by advancing the media. Fresh media passes liquid more easily allowing the pool level to drop. Spent media (contaminated with precipitated salts and particulate matter) is collected and disposed of as a solid waste.

AIRPOL INCORPORATED

The zero liquid-discharge technology offered by AirPol is a direct adaptation of their venturi scrubber/acid gas absorber system discussed earlier. The hardware configuration is illustrated schematically in Figure 46. As shown, a spray dryer is added upstream of the venturi scrubber. Spent liquid from the absorber is sprayed into the dryer at a controlled rate. The water evaporates leaving a solid consisting of previously

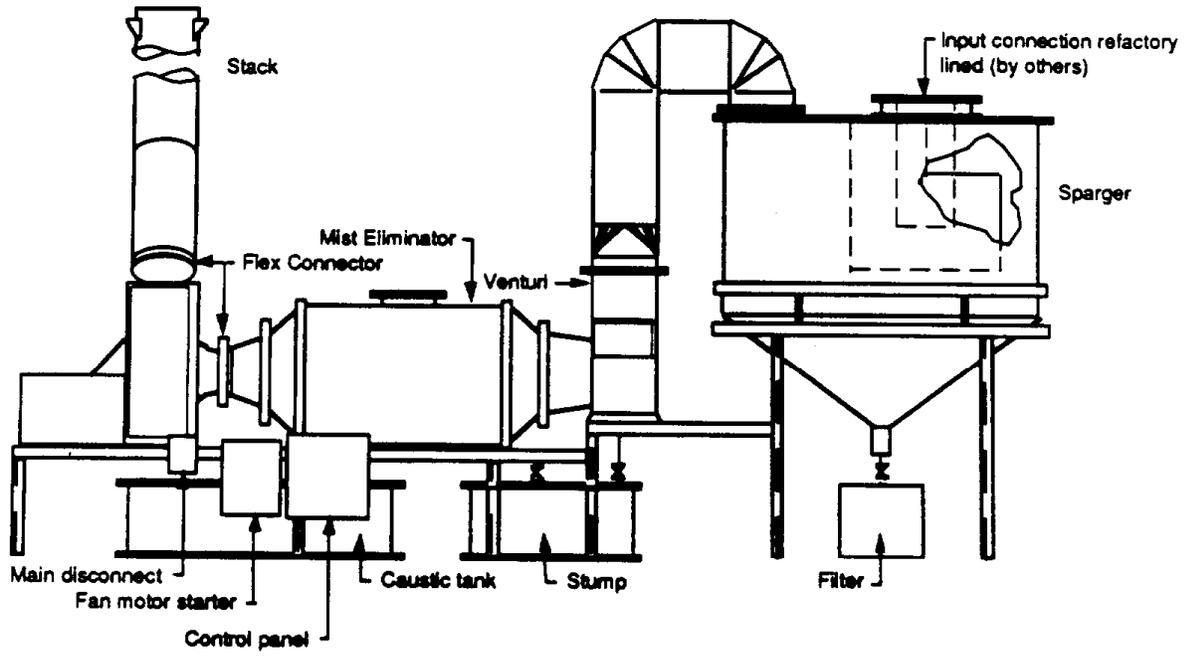
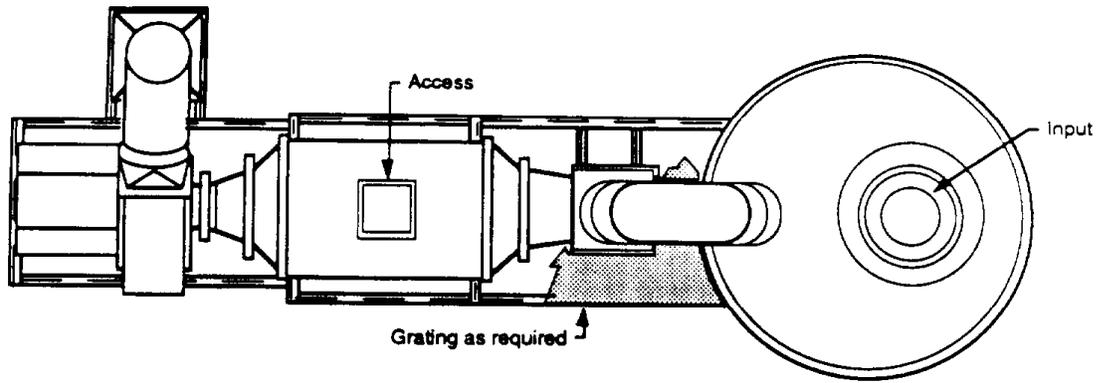


Figure 44. Zero discharge fume scrubber.

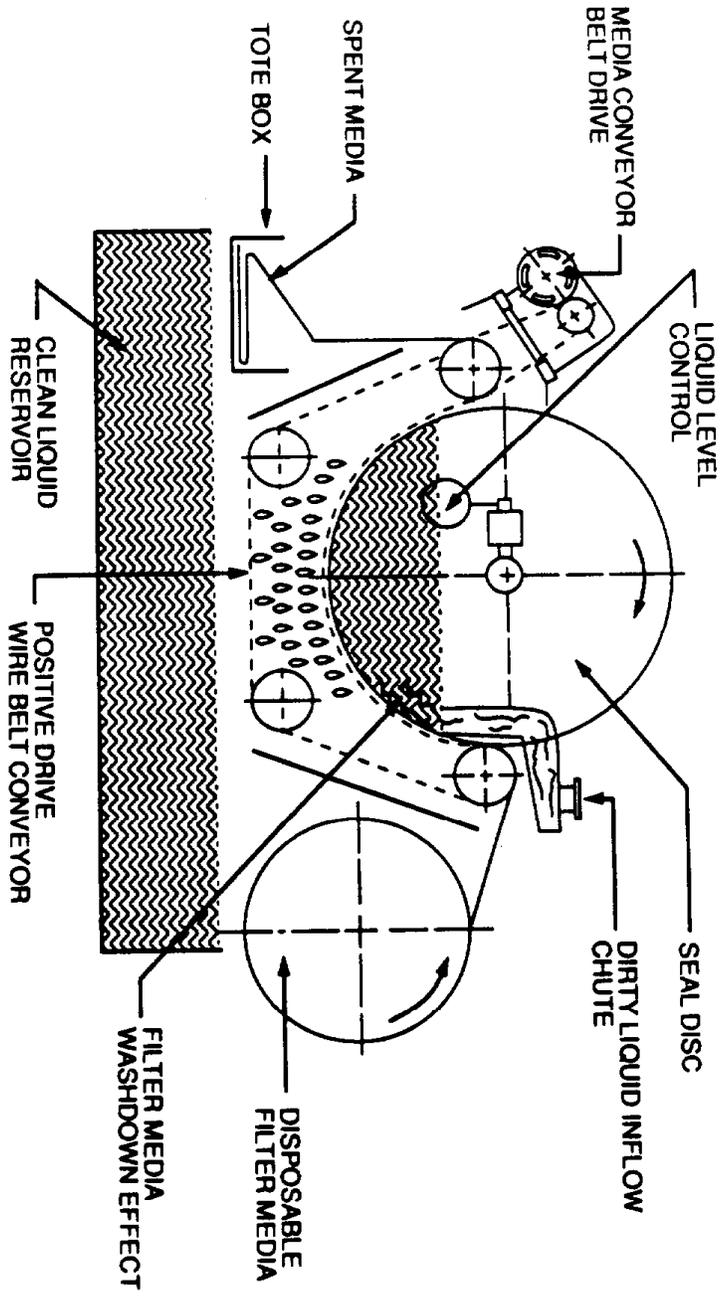


Figure 45. Continuous media filter used by ACI.

This wet system will operate with a spray dryer which precedes the venturi scrubber, to provide for dry disposal of the effluent from the scrubber system.

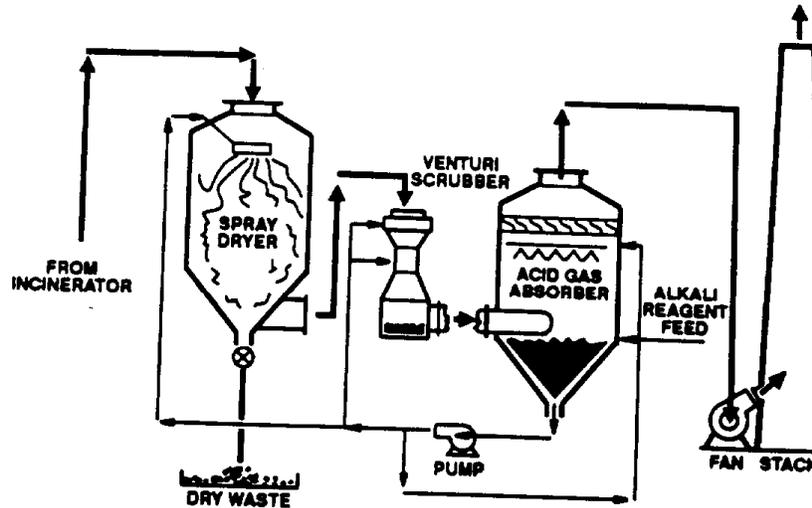


Figure 46. Wet scrubber system/dry disposal.

captured particulate and precipitated salts from the absorber. The solid material falls to the bottom of the spray dryer, is collected and disposed of as dry waste. Uncollected solids are entrained in the flue gas and flow to the venturi scrubber where they are captured. The particle laden liquid is circulated back to the spray dryer. Either sodium- or lime-buffering can be used with this scrubbing technique. AirPol, Inc. is yet to install this type of dry disposal system on a medical waste incinerator in the U.S.

SPRAY DRYER/FABRIC FILTER

In recent years, a significant body of literature and much practical experience has accrued for operation of spray dryer/fabric filter (SD/FF) flue gas cleaning systems on waste-fired combustors. That experience base is generally restricted to large-scale incinerators but recently a system has been designed for a regional medical waste incineration facility. The following paragraphs provide a very brief overview of SD/FF operation. Several detailed descriptions of this technology are available [e.g. the report by Sedman and Brna (28) and the recent journal article by Frame (30)].

Figure 47 provides a schematic diagram of a typical SD/FF system. Lime (CaO) is stored as a dry powder in a silo. Before use, it is slaked and fed into a storage tank. The lime slurry is then pumped into the spray absorber, typically with a rotary atomizer. The heat from the flue gases entering the absorber is enough to evaporate the water in the slurry leaving a dry powder in the gases exiting the absorber. By controlling the amount of water in the slurry, the temperature of flue gas leaving the spray absorber can be controlled to a desired range between 380 and 430 K (230 and 320°F). Some of the powder drops to the bottom of the spray absorber but the majority passes to the fabric filter. The fabric filter provides for excellent particulate matter

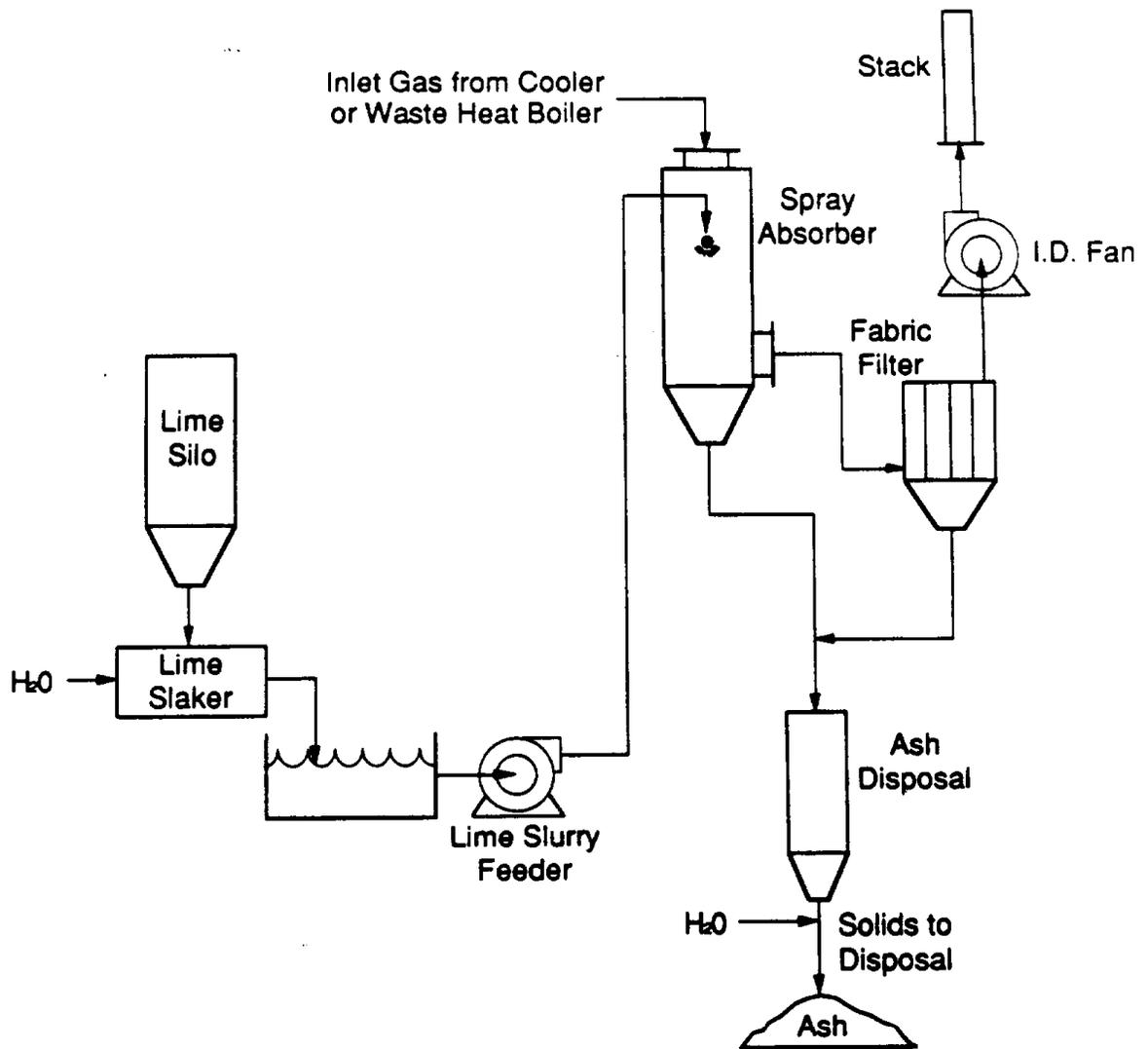


Figure 47. Spray dryer/fabric filter.

collection at low pressure loss [1500-2500 Pa gauge (6-10 in. W.G.)]. Solid material collected by the fabric filter consists of combustor particulate matter, calcium salts, and unreacted lime. This material is typically disposed of as dry solid waste.

UNITED MCGILL CORPORATION

United McGill Corporation is a major manufacturer of SD/FF systems. For a variety of reasons, they find the SD/FF technology to be non-competitive in the current medical waste incineration market. Fabric filtration systems can achieve high levels of particulate control at reasonable pressure drop, relative to venturi scrubbers, but the resultant cost savings in fan power is more than offset by the high cost of lime storage, slaking and slurry pumping as well as the increased complexity of the operation. Further, fabric filter technology has been optimized for larger-scale operations such as industrial or utility boilers, and for small dust collection applications. Medical waste incineration typically presents a set of system conditions which do not match up well with existing fabric filter technology. Fabric filter technology modifications are needed in several areas including the bag cleaning system, system maintenance, reliability and unit cost.

In response to the perceived limitations of SD/FF described above, United McGill developed and is marketing a new system which includes dry injection of lime and a redesigned line of fabric filters. The first part of the system reduces the flue gas temperature to about 390 K (250°F). For incinerators with heat recovery boilers, temperature control is with either an economizer or a gas-to-air heat exchanger. For systems without heat recovery, they provide an evaporative cooler. Downstream of the temperature control section, United McGill provides for dry injection of the lime. The lime is injected as an opposed jet into the incoming flow with the lime jet in the converging region of an adjustable-throat venturi. About 2 to 3 times the lime needed to stoichiometrically react with all the acid gases is added. The variable venturi assures good mixing of solid and gas phases over the broad range of operating conditions expected from the incinerator. Figure 48 schematically illustrates the sorbent injection system and the fabric filtration system. As shown, bag cleaning is accomplished by shooting a jet of compressed air down the center of each bag (pulse jet). Due to system size, a single compartment baghouse configuration is used and bag cleaning is performed on-line. To minimize re-entrainment, bags are cleaned more often. This shortens bag life, but cost associated with more frequent bag replacement is less than the 30-50 percent higher capital cost of a multi-compartment system. For systems with gas volumes above about 0.24 m³/s (30,000 acfm), multiple compartments are justifiable.

Typical systems are designed with air-to-cloth ratios on the order of 1.1-1.5 m/s (3.5-5.0 ft/s). Based on typical bag sizes, baghouse designs with 40 to 180 bags are needed for average medical waste incinerators. Bag replacement will probably be needed about every three years. Replacing all the bags should take less than about 40 hours and can be done over a weekend. United McGill expects general system maintenance to be about 40 hours per year.

The dry injection/fabric filter system has several major potential advantages. First, it can achieve 0.03 g/Ncm (0.015 gr/dscf) or even lower particulate emission limits. Second, it does not have liquid discharge and it should have no visible plume. Third, it can effectively capture particles smaller than 1 micrometer. As was discussed previously, particles smaller than 1 micrometer contain high concentrations of volatile metals. Disadvantages include the fact that reagent costs are two to three times that of a wet control system due to the inefficiency of acid gas capture by dry particles. Further, since continuous HCl monitoring is not available, the rate of sorbent injection must be set at a sufficiently high level to reach 90 percent capture at the maximum expected acid gas level (90 percent capture is required by some States and will probably be required by many more). For small-scale systems, careful modulation of solid sorbent flow is difficult to achieve and would add needlessly to system cost and complexity.

United McGill readily admits that this system is not the best answer for every infectious waste incinerator application. For those States which impose extremely stringent particulate limits, this basic technology approach may prove to be the only choice. Over the next several years, a clearer definition of best technology selections will emerge.

ECONOMIZER OR
GAS-TO-AIR
HEAT EXCHANGER

LIME INJECTION

FABRIC FILTER

STACK

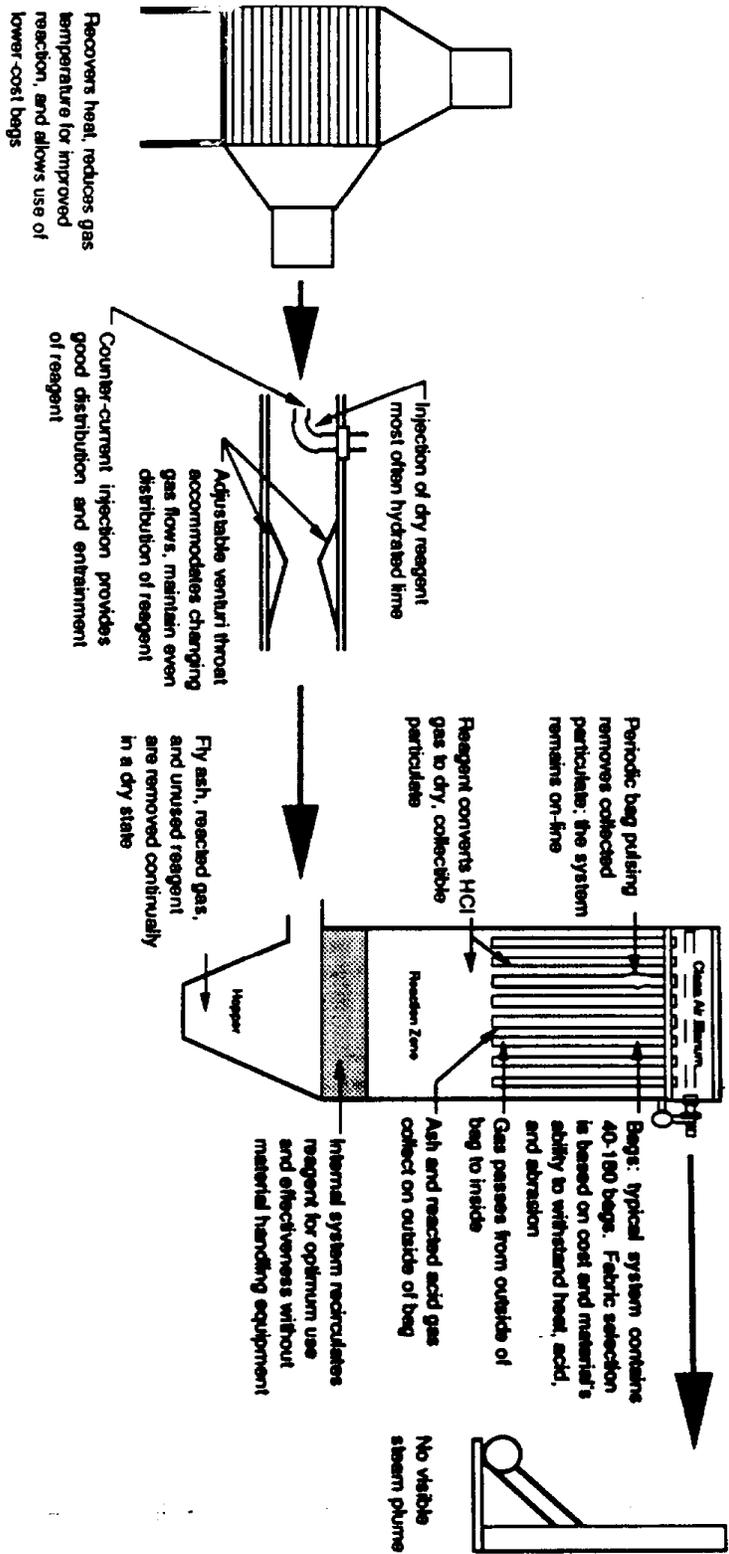


Figure 48. United McGill's DI/FF system (The "DEPARTURE" system).

SECTION 6

ECONOMIC ANALYSIS

This section presents generalized information on the cost of medical waste thermal treatment equipment and the cost of associated monitoring and air pollution control devices. The information included in this section was gathered from the various manufacturers interviewed during the study.

INCINERATOR SYSTEM COSTS

Previously information on current design practices for 12 manufacturers of medical waste incineration equipment was presented. It was noted that there are at least eight other vendors active in this market. The majority of the vendors supply two-stage, controlled-air incinerators while a few vendors supply rotary kiln units. With such a large number of vendors supplying a similar product line to a given market, major differences in equipment cost between vendors was not expected or observed. Indeed, costs for similar equipment from different manufacturers varied by less than 30 percent.

Figure 50 presents the equipment cost for controlled-air incinerators as a function of unit size. These cost data are a composite of information supplied by the various equipment vendors for incinerators meeting the following general criteria:

- Current pricing practice quoted F.O.B. factory (not installed)
- Automatic ram feeding of waste
- Automatic ash removal
- 8-16 hour daily operation
- 1 second residence time secondary chamber
- No heat recovery
- No continuous emissions monitors
- No add-on APCD

Unit sizing was based on incineration of general medical waste with an average heating value of 20,000 J/g (8500 Btu/lb). As shown, over the size range typically provided to hospitals (230-1140 kg/hr (500-2500 lb/hr)), capital costs range from about \$150,000 to a little more than \$500,000 and vary essentially linearly with size.

Small batch-fed incinerators typically do not have automatic waste feeding or automatic ash removal, nor do they have sophisticated combustion control systems. Accordingly, the small systems can be purchased for a lower initial cost and are shown separately in Figure 49.

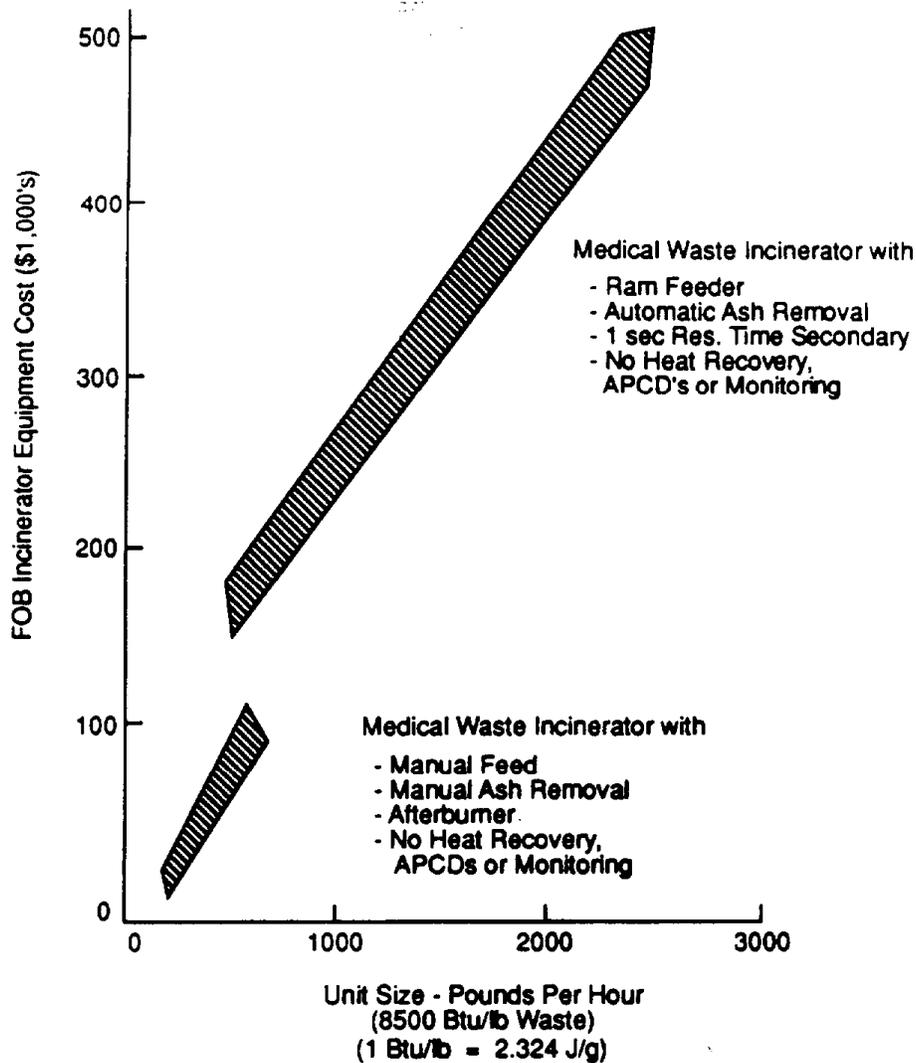


Figure 49. Equipment cost for controlled air incinerators as a function of unit scale.

It should be emphasized that the above incinerator costing information was provided on an F.O.B. factory basis and does not include installation charges. Costs were presented on this basis because installation charges are very site-specific. Many new incinerator installations are integrated into existing hospital buildings. As a rule of thumb, however, installation costs are typically 15-25 percent of the base equipment cost. This is a relatively low installation cost factor reflecting the fact that medical waste incinerator equipment is factory-assembled and generally shipped to the site as a skid-mounted module. For larger systems, the unit may be shipped as several modules which must be mated together in the field.

The various manufacturers were unanimous in their assessment that heat recovery was unattractive for hospitals smaller than about 500 beds. In general, medical waste incinerator vendors do not manufacture waste heat boilers. Cost for the waste heat boiler depends on a wide range of parameters including:

- Type of boiler
- Temperature and pressure of required steam
- Availability of boiler water treatment equipment
- Whether co-firing is to be employed

Clearly a broad range of heat recovery system costs are possible. However, for a 450 kg/hr (1000 lb/hr) incinerator equipped with a low steam pressure fire-tube boiler, heat recovery costs are on the order of \$80,000-100,000. For an incinerator rated at 1140 kg/hr (2500 lb/hr), boiler costs (on the same basis) are about \$180,000-200,000. These waste heat boiler cost estimates were provided through telephone conversations with personnel at Cleaver Brooks, Inc. and Consumat Systems, Inc.

It was anticipated that small-scale rotary kiln incinerators would have higher initial costs than similarly-sized controlled-air units. As described previously, the two rotary kiln vendors interviewed as part of this study have installed few units. The cost estimates provided by these vendors included the kiln, an afterburner, a waste heat boiler and an air pollution control system to meet New York State requirements. Costs were also quoted on an installed basis since at least one manufacturer prefers to complete bricking of the kiln in the field. On this basis, a very small kiln system [160 kg/hr (350 lb/hr)] would cost \$800,000-900,000 while a 680 kg/hr (1500 lb/hr) unit would cost \$1.9-2.0 million. It is very important to note that the basis for these costs is very different from those used earlier to develop Figure 50. The cost data gathered to produce this Figure included information provided by Cleaver Brooks who manufactures kilns as well as controlled-air incinerators. Cleaver Brooks noted that for their unit designs, rotary kilns are cost competitive with controlled-air units at scales above about 910 kg/hr (2000 lb/hr) of waste.

POLLUTION CONTROL DEVICE COSTS - LARGE SYSTEMS

The cost of air pollution control equipment depends upon the type of system used, the level of emission control required and the size of the incineration system. The costs of each of the major equipment classes discussed previously are briefly described below. The emphasis in this section will be applications to medical waste incinerators rated above 90 kg/hr (200 lb/hr).

VENTURI SCRUBBER/ACID GAS ABSORBER

Tables 12 and 13 were included in a recent paper by Jack D. Brady of Andersen 2000 (31) which defines the capital and operating costs of a venturi scrubber/acid gas absorber designed to achieve 0.07 g/Ncm (0.03 gr/dscf) and 90 percent HCl control efficiency for a 450 kg/hr (1000 lb/hr) medical waste incinerator. As shown, the total installed cost is about \$200,000 as compared to an incinerator cost (from Figure 49) of about \$250,000. In addition to the capital cost, there is a substantial operating and maintenance cost associated with the venturi scrubber/acid gas absorber. As shown in Table 13, first-year operating costs are estimated to be \$87,776 plus \$40,541 for a 5-year amortization of the control equipment capital cost, yielding a total first-year air pollution control system cost of \$128,317. Thus, the annual cost of operating the air pollution control system (~\$88K) is on the same order as the first-year amortization cost of the incinerator (\$50K) plus the air pollution control system (~\$40K). However, from an alternate perspective, the normalized cost of this air pollution control system for a 450 kg/hr (1000 lb/hr) incinerator operating 7500 hours per year is less than 1.75 cents per pound of waste treated.

The cost of a venturi scrubber/acid gas absorber changes with the volume of gas to be treated. Table 14 was presented by Shuler (32) based on annual operating cost data supplied by Andersen 2000. As shown, the presence of a waste heat boiler in the incinerator system allows for about a 15-30 percent decrease in the

TABLE 12. CAPITAL COST FOR SCRUBBING SYSTEM ON 1000 LB/HR
INFECTIOUS WASTE INCINERATOR

ANDERSEN 2000 INC. MODEL 480 SCRUBBING SYSTEM		
Component	Description	Price
1. Scrubber	Venturi and packed tower	\$ 55,745
2. Induced draft fan	60 hp, Hastelloy wheel, rubber-lined housing	28,215
3. Exhaust stack	30' tall, FRP	9,410
4. Liquid system	All non-metallic with pump	15,755
5. Chemical neutralization system	Caustic tank, pump, secondary containment	6,930
6. Instrumentation, controls, starters	Includes all safeties and interlocks	30,800
7. Misc. platforms, supports, etc.	Painted with corrosion inhibitor paint	6,350
8. Freight	Average haul	4,500
9. Installation	Utilities, ducts, foundations and all labor	45,000
TOTAL		\$202,705

TABLE 13. OPERATING COST FOR SCRUBBING SYSTEM ON 1000 LB/HR
INFECTIOUS WASTE INCINERATOR

ANDERSEN 2000 INC. MODEL 480 SCRUBBING SYSTEM, 7500 HRS/YR		
Component	Quantity	Annual Cost
1. Electrical Power	42.3 Kwh/h @ 40.06 Kwh	\$ 19,035
2. Make-Up Water	732 gph @ \$0.03/100 gal	1,645
3. Sewer Charge	85.2 gph @ \$0.20/100 gal	1,278
4. Chemicals (NaOH)	24.38 lb/hr @ \$400/ton	36,570
5. Maintenance	2% of equipment capital/yr	3,154
6. Operators	1/2 hr/8 hr shift @ \$45/hr	21,094
7. Testing & Permitting	One test per year	5,000
	SUBTOTAL	\$ 82,781
8. Amortize Capital	5-yr straight line	40,541
	TOTAL	\$128,317

Equals \$0.0171/lb of waste or \$34.22/ton of waste

overall air pollution control device annual cost. This decrease is driven by the fact that less liquid must be pumped into the venturi since the gases are pre-cooled. This decreases the flow rate of saturated gases through the venturi allowing for a smaller venturi (at the same velocity level) and reduce fan size and energy requirements.

The cost of a venturi scrubber/acid gas absorber system is affected by the required level of particulate matter removal. The system cited in Table 12 for a 450 kg/hr (1000 lb/hr) incinerator with ability to meet 0.07 g/Ncm (0.03 gr/dscf) emissions limits was fitted with a 45 kW (60 hp) motor to provide 8.7×10^3 Pa gauge (35 in. W.G.) static pressure. If the air pollution control device was required to meet 0.03 g/Ncm (0.015 gr/dscf).

TABLE 14. VENTURI SCRUBBER/ACID GAS ABSORBER TOTAL ANNUAL COST VERSUS SIZE OF INCINERATOR

Incinerator Waste Burn Rate (lb/hr)	Flue Gas (scfm)	Scrubber Without Boiler (\$)	Scrubber With Boiler (\$)	Percent Reduction Due to Boiler (%)
415	1,500	60,000	50,000	17
550	2,000	85,000	60,000	29
695	2,500	98,000	73,000	26
835	3,000	113,000	85,000	25
1,110	4,000	128,000	97,000	24
1,395	5,000	145,000	112,000	23
1,675	6,000	170,000	128,000	25
2,230	8,000	195,000	150,000	23
2,790	10,000	235,000	190,000	19
3,350	11,000	280,000	230,000	18

the required velocity in the venturi would greatly increase. This would require the use of a much larger pressure drop and a more powerful fan. AirPol, Inc., indicated that a 56 kW (75 hp) fan motor would be required to provide 1×10^4 - 1.1×10^4 Pa gauge (40-45 in. W.G.) for a 450 kg/hr (1000 lb/hr) incinerator meeting 0.03 g/Ncm (0.015 gr/dscf). They also indicated that the capital cost for such a high-performance system would be approximately \$250,000.

System size has an important impact on the relative cost of venturi scrubber/acid gas absorbers. As shown in Table 13, the electrical power costs to operate the venturi scrubber are estimated to be \$19,000 per year for a 450 kg/hr (1000 lb/hr) system which is about 15 percent of the air pollution control device total annual cost (including amortized capital). Fan power required increases linearly with volumetric flow rate and thus electrical costs for the fan scale linearly with incinerator rating (assuming constant fan efficiency and head requirement). On this basis, a 1140 kg/hr (2500 lb/hr) incinerator would have annual electricity cost of \$47,500 (i.e., $\$19,000 \times 2500/1000$). According to the data in Table 14, this would represent more than 20 percent of the total annual cost. If a 1140 kg/hr (2500 lb/hr) incinerator were required to achieve 0.03 g/Ncm (0.015 gr/dscf), the fan head requirement would increase to at least 1.1×10^4 Pa gauge (45 in. W.G.) and the fan electricity costs would exceed \$60,000 per year.

The costs of reagents are a substantial component of the annual operating cost identified in Table 13. The basis of this cost component estimate is that the rate of buffering agent addition is just sufficient to maintain the scrubber pH in the desired range (6.5-7.0). The major acid gas being absorbed is HCl and neutralization with NaOH proceeds according to the reaction



Scrubber liquid pH is maintained if one mole of NaOH [(18 kg (40 lb))] is added for each mole of HCl absorbed [17 kg (36.5 lb)]. The cost estimate in Table 13 is based on chlorine in the waste feed being converted at 100 percent efficiency to HCl in the incinerator exhaust. A slight excess of NaOH is provided to account for the trace quantity of SO₂ in the flue gas.

Since NaOH addition is at a 1-to-1 molar ratio with absorbed HCl, annual costs for chemicals will scale directly with the chlorine content in the waste and the mass of waste treated annually. Since most hospital incinerators are operated substantially less than 7500 hrs/yr, the relative cost of chemicals indicated by Table 13 should be taken as an upper limit.

SPRAY DRYER/FABRIC FILTER (SD/FF)

As illustrated above, initial fan costs and the electricity represent a large portion of the total operating cost for wet scrubber/acid gas absorption systems. Both AirPol, Inc. and Andersen 2000 indicate that for incineration units rated at about 1140 kg/hr (2500 lb/hr), spray dryer/fabric filter systems are competitive in terms of capital cost. Several recent EPA studies have been conducted examining cost of spray dryer/fabric filters for municipal waste incinerator systems. These studies indicate that the total capital cost for a spray dryer/fabric filter applied to a municipal waste incineration unit rated at 45 Mg/day (50 ton/day) is approximately \$1 million. An air pollution control system is sized based on the volumetric flow rate from the incinerator. Due to the difference in heating value of general medical waste [2.0×10^4 - 2.1×10^4 J/g (8500-9000 Btu/lb)] and municipal solid waste [1.0×10^4 - 1.2×10^4 J/g (4500-5000 Btu/lb)], a 45 Mg/day (50 ton/day) municipal waste incineration unit has approximately the same peak flue gas output of a 140 kg/hr (2000 lb/hr) medical waste incinerator.

Little reduction in SD/FF system cost accrues from reducing the equipment size for use with a 450 kg/hr (1000 lb/hr) incinerator. Several vendors indicate that the capital cost for such a system might be around \$800,000. There is no field data available from operating medical waste incinerators equipped with SD/FF equipment. No medical waste incinerator in the U.S. is known to use this equipment.

DRY SORBENT INJECTION/FABRIC FILTRATION (DI/FF)

All available information indicates that a SD/FF system is not cost competitive with venturi scrubber/acid gas absorber systems for the incineration equipment sizes used for treatment of medical waste unless high efficiency dioxin removal is required. The previously noted EPA studies on air pollution control systems for municipal waste combustion applications reach the conclusion that alternate technologies such as DI/FF are preferable for small-scale incinerators. Little direct information was gathered as part of the current study on the cost of DI/FF as applied to medical waste incinerators. United McGill estimated the capital cost of their system. As applied to a 450 kg/hr (1000 lb/hr) incinerator [0.08 m³/s at 390 K (10,000 acfm at 250°F)] costs approximately \$600,000 on a turnkey basis. Unlike the venturi scrubber system discussed earlier, a substantial portion (one-third) of the turnkey cost is associated with equipment installation. Fan power requirements are relatively low since the pressure drop across the venturi and fabric filter are on the order of 2.4×10^3 to 3.0×10^3 Pa gauge (10-12 in. W.G.). Sorbent costs for a Ca(OH)₂-based DI/FF system should be significantly less than for a NaOH-based venturi scrubber/acid gas absorber. The DI/FF system probably operates at 2-3 times stoichiometric requirements to achieve required HCl and SO₂ capture efficiency while the venturi scrubber/acid gas absorber system operates nearly stoichiometrically. The sorbent use efficiency disadvantage of the DI/FF is more than offset by the lower unit cost of calcium hydroxide [\$88/Mg = \$5.02/kg-mole (\$80/ton = \$2.88/lb-mole)] versus sodium hydroxide \$4440/Mg = \$17.60/kg-mole (\$400/ton = \$8/lb-mole)] and the fact that one mole of sodium captures 1 mole of HCl while a mole of calcium captures 2 moles of HCl. This is illustrated in Table 15.

Based on the above reactions in Table 15, the approximate reagent cost for a NaOH-based venturi scrubber/acid gas absorber is on the order of 22 cents/lb of HCl removed. A DI/FF system using Ca(OH)₂

TABLE 15. COMPARISON OF SORBENT COSTS FOR NaOH- AND LIME-BASED ACID GAS SCRUBBING SYSTEMS

	$\text{HCl} + \text{NaOH} \rightarrow \text{NaCl} + \text{H}_2\text{O}$			
molecular wt	36.5	40	58.5	18
per lb HCl	1.00	1.09	1.80	0.49
price per lb HCl		21.8¢		
	$\text{SO}_2 + 2\text{NaOH} \rightarrow \text{Na}_2\text{SO}_3 + \text{H}_2\text{O}$			
molecular wt	64	80	126	18
per lb SO ₂	1.00	1.25	1.97	0.28
price per lb SO ₂		25¢		
	$2\text{HCl} + \text{Ca}(\text{OH})_2 \rightarrow \text{CaCl}_2 + 2\text{H}_2\text{O}$			
molecular wt	73	74	111	36
per lb HCl	1.00	1.01	1.52	0.49
price per lb HCl		4.04¢		
	$\text{SO}_2 + \text{Ca}(\text{OH})_2 \rightarrow \text{CaSO}_3 + \text{H}_2\text{O}$			
molecular wt	64	74	120	18
per lb SO ₂	1.00	1.18	1.88	0.28
price per lb SO ₂		4.72¢		

(Note: 1 lb = 454 g)

injection at 2 times stoichiometry will have a reagent-use operating cost of about 8 cents/lb of HCl removed. A sodium-based DI/FF system would have sorbent-use costs several times that of a venturi scrubber/fabric filter.

The other key operating cost items include bag replacement costs and operating labor. For the 0.08 m³/s (10,000 acfm) system noted earlier, the fabric filter will have about 280 m² (3000 ft²) of total cloth area provided by about 100-150 bags [1.9 to 2.8 m² per bag (20-30 ft² per bag)]. The cost of each bag is about \$50 and they must be replaced approximately every three years. United McGill indicates that maintenance labor for the DI/FF system should be very low but more extensive operating experience is required to firmly establish both the quantity of labor and required experience level for that labor.

DI/FF systems require no water. This eliminates the need for some equipment and simplifies the system. DI/FF produce a dry waste. This simplifies waste handling considerations.

POLLUTION CONTROL DEVICE COST ESTIMATES — SMALL-SCALE SYSTEM APPLICATIONS

The cost of applying alternative types of flue gas cleaning systems to small-scale [<227 kg/hr (<500 lb/hr rating)] medical waste incinerators was studied. However, information is available only for venturi scrubber/acid gas absorber costs. No data could be located on the costs of alternate technologies such as duct injection/fabric filtration. For a variety of reasons, largely alluded to in the previous section, it is anticipated that the majority of small systems required to use air pollution control devices will attempt to use venturi scrubber/acid gas absorbers. Critical issues include:

- Compatibility of air pollution control device operation with incinerator operating cycle

- Relative variation in air pollution control device cost with scale
- Device control capabilities
- Regulatory requirement

Some of these issues are addressed in more detail below.

Small-scale incinerators are usually designed to operate a few hours per day, do not have sophisticated combustion controls, and are not equipped with heat recovery systems. These system characteristics make application of a fabric filter system difficult, particularly when solid sorbent injection is used to achieve acid gas control.

Since the incinerator is only operated for a few hours each day, it will be necessary to provide for daily cold start-up of the air pollution control system. This is a particularly sensitive operation for a fabric filter since it can only accept flue gas in a relatively narrow temperature range. Upper temperature limits are set by materials of construction. Baghouses are not typically able to tolerate temperature levels associated with direct exhaust from an incinerator. Lower temperature limits are set by the flue gas dewpoint. Wetting of the bags can cause bag blinding. In fact, calcium-based sorbents turn to a cement-like material when exposed to water. Any condensate will be highly acidic and attack the bag material. This severely reduces bag life. Since small-scale incinerators will probably not have heat recovery boilers, the flue gas cleaning system must include a quenching system which automatically adjusts the scrubbing media flow rate to achieve the desired temperature. A very careful start-up process is required including a bypass around the fabric filter or exhaust through the dump stack until the flue gas is well above the dewpoint. When the flue gas is directed to this baghouse, a significant increase in system pressure drop occurs.

All of the above start-up features can be accommodated in a fabric filter system design but a sophisticated control system is required. These types of control systems are a feature not typically associated with small-scale operations. At least two baghouse-based air pollution control systems have been installed on small-scale waste incinerators in California. Both have experienced significant operational difficulty. Based on these considerations, it is tentatively concluded that fabric filter-based APCDs are not a demonstrated technology for control of particulate and acid gases on small-scale medical waste incinerators.

In direct counterpoint to the fabric filtration systems, venturi scrubber/acid gas absorbers should be relatively easy to use with small-scale incinerators. By using a wetted-approach venturi, the air pollution control device can accept flue gas directly from the incinerator. These systems are designed to operate under saturated flow conditions. Start-up presents no unusual difficulties and, in fact, the water sprays can be operated independent of the incinerator operation.

Performance data and operational experience is available for at least one venturi scrubber/acid gas absorber system applied to a small-scale incinerator. This air pollution control device, installed at Stanford University, experienced some difficulty but subsequently has provided satisfactory performance. The scrubber installed at Stanford was required primarily for acid gas control and is not designed for stringent particulate control.

As shown in Table 14, venturi scrubber costs are strongly dependent on system size. Comparison of the data in this Table with the incinerator cost in Figure 12 shows that air pollution control devices become relatively more expensive as the system scale drops. The annual operating cost for an air pollution control device applied to a 188 kg/hr (415 lb/hr) incinerator is about \$60,000 which is approximately equal to the purchase cost of the incinerator. An air pollution control device on small systems represents a major cost impact for the owner.

SECTION 7

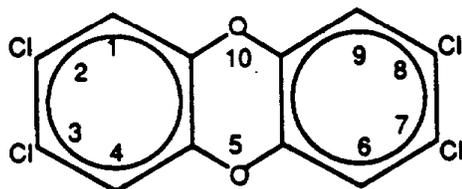
TRACE ORGANIC EMISSIONS

Several organic compounds have been found in air emissions from medical waste incinerators. These compounds include a wide range of potentially harmful aromatic and chlorinated organics. One of the greatest challenges that remains for the disposal of medical wastes by incineration is the control of the emissions of these trace organic compounds.

POLLUTANT CHARACTERISTICS

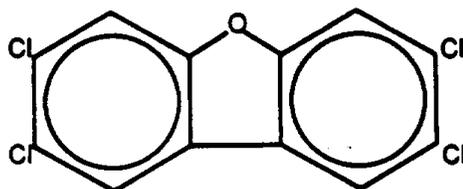
The current emphasis is on the chlorinated congeners of polychlorinated dibenzo-p-dioxin (PCDD) and dibenzofuran (PCDF). However, PCDD/PCDF comprise only two of many types of trace organic compounds that could be emitted from medical waste incinerators. Many other organic compounds may eventually be of concern. For this reason, data on trace organic compounds other than just PCDD/PCDF were gathered during this study. However, the emphasis is on PCDD/PCDF due to the substantial available database on formation and control of these compounds and public concern over their potential health effects.

PCDD/PCDF are organic compounds consisting of two chlorinated benzene rings linked by either one (for furans) or two (for dioxins) oxygen atoms. Diagrams of typical dioxin and furan molecules are shown in Figure 50 and 51. PCDD/PCDF are suspected to be potent carcinogens. The most toxic congeners are 2,3,7,8-tetrachlorodibenzo(p)dioxin and 2,3,7,8-tetrachlorodibenzofuran. Many scientists agree that the potency of these compounds decreases as chlorination increases beyond four chlorine atoms per molecule.



2,3,7,8-Tetrachlorodibenzo-(p)-dioxin

Figure 50. Typical dioxin molecules.



2,3,7,8-Tetrachlorodibenzofuran

Figure 51. Typical furan molecules.

AVAILABLE DATABASE ON TRACE ORGANIC EMISSIONS

In recent studies by the California Air Resources Board (34-38), emissions of many organic compounds were measured. The results of these studies are summarized in Table 16. The relative risk associated with these emission levels has not been completely assessed.

Several additional studies have been conducted both by California Air Resources Board and other organizations in the U.S. and Canada in which the dioxin emissions from medical waste incinerators have been measured (39). Figure 52 compares the PCDD/PCDF emissions from medical waste incinerators with the emissions from municipal waste and hazardous waste incinerators. PCDD/PCDF emissions from medical waste incinerators are higher than those from other modern waste combustion facilities. However, care must

TABLE 16. TRACE ORGANIC EMISSIONS FROM MEDICAL WASTE INCINERATORS

Compound	Emissions Rate, lb/hr x 10 ⁴				
	Sutter General	Stanford	St. Agnes	St. Bernadines	Cedars-Sinai
Dichlorofluoromethane	46	1.3	1.6	4.3	
Dichloromethane	390	160	550	34	
Trichlorofluoromethane	75	2.1	6.8	3.2	
Trichloromethane N.D.	30	2.5	N.M.		
1,2-dichloroethane N.D.	170	1600	2.2		
1,1,1-trichloroethane	270	41	700	31	
Carbon tetrachloride	N.D.	2.9	28	1.9	52
trichloroethene	61	11	550	0.76	12
1,2-Dibromomethane	N.D.	1.8	5.8	0.25	
Tetrachloroethene	280	10	170	11	56
Trichlorotrifluoroethane	130	10	27	4.7	22
Benzene	240	740	250000	33	
Toluene	540	76	100	68	
Ethyl Benzene	150	17	40	3.4	
P-Xylene	120	140	4.2		
P+M-Xylene		3000			
M-Xylene	280	120		37	
Cumene	N.D.	28	150	2.1	
O-Xylene	160	24	23	28	
Mesitylene	54	130	100	1.4	
Naphthalene	42	59	N.M.	21	
Methyl Isobutyl Ketone	N.D.	250-4	N.M.	5.1	
Dioxins (tetra-octa)	7.9	0.037	3.9	0.078	1.3
Furans (tetra-octa)	15	0.077	7.9	0.19	4.2

1 lb/hr = 0.454 Kg/hr

Cedars-Sinai resin samples may have been contaminated and were not reported.

N.M. = Not measured

N.D. = Not detected

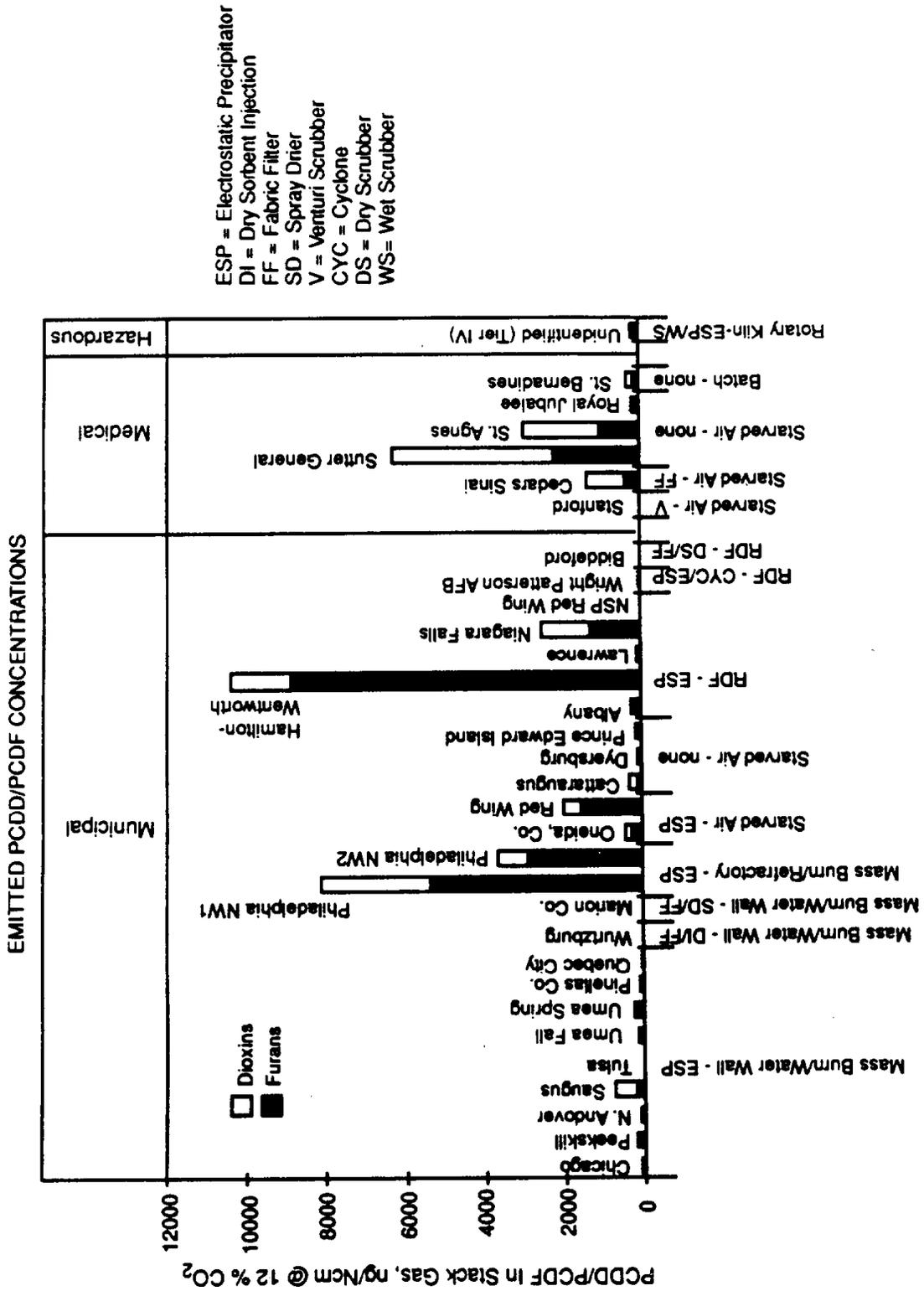


Figure 52. Comparison of PCDD/PCDF emissions from a variety of incinerators.

be taken in making these comparisons. Many different technologies are involved, and it would be inappropriate to only look at the concentration of dioxins in the stack gases.

One of the major differences between medical waste incinerators and other technologies is that medical waste incinerators are not typically equipped with pollution control equipment. Figure 53 shows the concentration of PCDD/PCDF in the flue gases before any air pollution control equipment in several incineration units. The emissions from medical waste incinerators seem to be higher than from other incinerators. However, most of the municipal incinerators for which PCDD/PCDF measurements were obtained before the APCD are modern systems which make use of the latest advances in incinerator design.

Figure 54 compares the emissions of PCDD/PCDF from incinerators equipped with air pollution control equipment. Many municipal waste incinerators shown in this Figure have much higher dioxin emissions than medical waste incinerators. The data are not sufficient to allow a conclusion to be made on the impact of waste type on the emissions of PCDD/PCDF. However, a comparison of similar equipment types (i.e., starved-air units as shown in Figure 53) does appear to indicate higher emissions, in general, when burning medical waste relative to municipal waste. It is unclear if this is due to operational differences or due to the smaller equipment sizes used in medical institutions.

The EPA is developing standards for municipal solid waste incinerators to control PCDD/PCDF emissions. Several proposed standards are being considered based on a determination of what levels are achievable. The current proposals would restrict new units to PCDD/PCDF emissions as low as 10 ng/Ncm (nano grams/normal cubic meter) total PCDD/PCDF (tetra- through octa-) and existing units to 125 ng/Ncm. Based on the data in Figures 52, 53 and 54, medical waste incinerators do not currently attain these levels.

POTENTIAL FORMATION MECHANISMS

Dioxins were first detected in incinerator emissions in 1977 by Ollie et al. (40). Since that time, many researchers have tried to identify the mechanisms which lead to PCDD/PCDF emissions. However, no consensus has been reached.

Figure 55 illustrates the various potential emission mechanisms that have been proposed. One of the simplest mechanisms is that the emitted dioxins were originally present in the waste and were not destroyed in the incinerator. While this mechanism may be responsible for a small fraction of the emitted PCDD/PCDF, most wastes do not contain sufficient quantities of PCDD/PCDF to account for the observed emission levels (41). There has been no concerted effort to measure PCDD/PCDF concentrations in medical waste, but there is no obvious source of PCDD/PCDF in the waste.

In the second potential mechanism, dioxins are formed as intermediates in the oxidation of more complex hydrocarbons. The hydrocarbons may be chlorinated (such as polyvinylchloride) or not (such as cellulose). If the intermediates are originally unchlorinated, the chlorination must happen as a second step. Medical waste contains both unchlorinated and chlorinated organics that have been identified as potential precursors to dioxins by this mechanism.

The third potential dioxin formation mechanism involves reactions between simple gas-phase precursors such as phenols and chlorobenzenes. Shaub and Tsang (42) developed a kinetic model to study the characteristics of the proposed reactions. They compared the model's predictions with emissions data, but could not determine if the proposed reactions were responsible for the dioxin emissions. Ballschmiter et al. (43) and Benfenanti et al. (44) examined the emissions from full-scale municipal waste incinerators and found a close relationship between the dioxin emissions and the quantity of polychlorobiphenol (PCB) and polychlorophenol (PCP) in the exhaust. They suggested that this indicates that dioxins are formed by reactions involving PCBs and PCPs. However, it is also possible that the compounds are all formed by similar sets of reactions.

UNCONTROLLED PCDD/PCDF CONCENTRATIONS

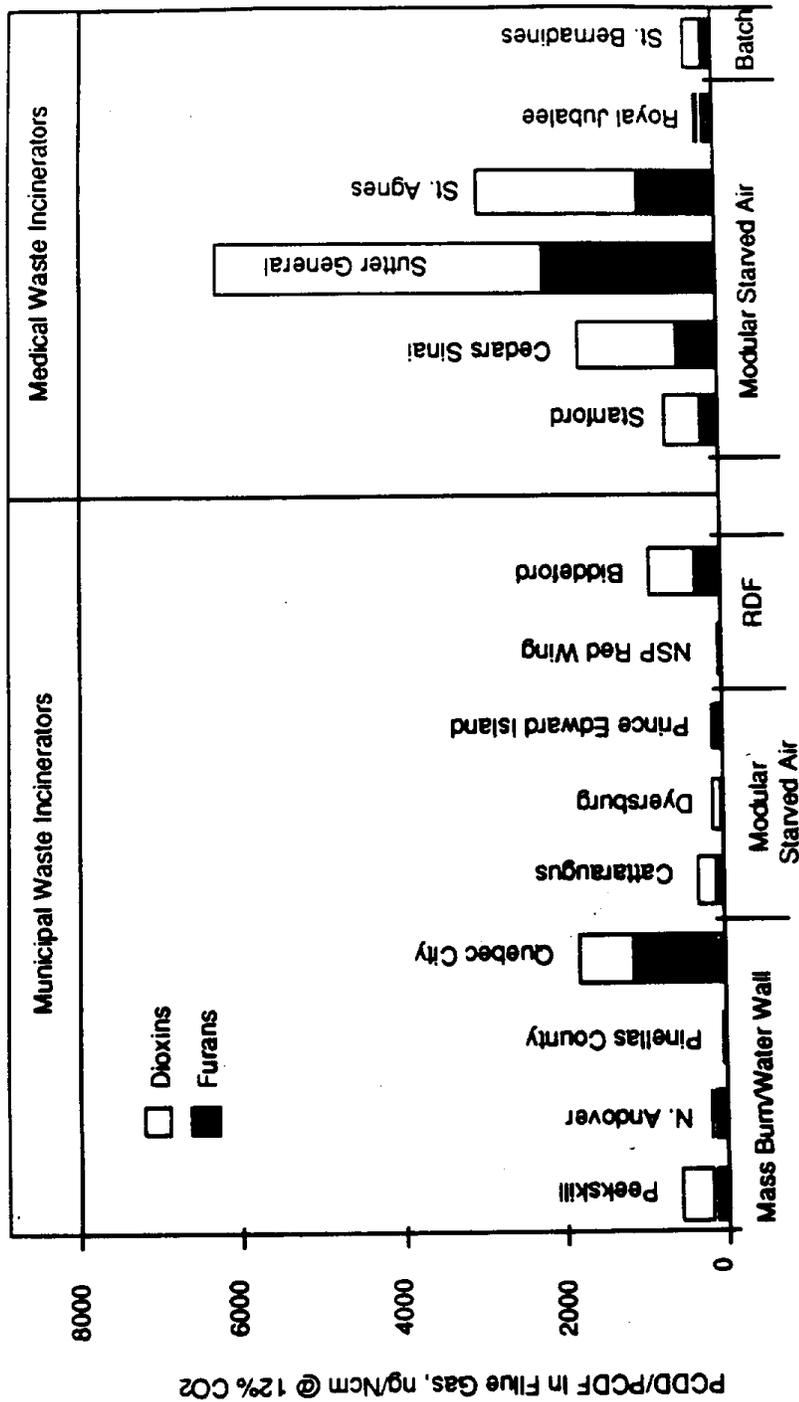


Figure 53. Comparison of PCDD/PCDF concentrations in the flue gases before any APCDs for a variety of municipal and medical waste incinerators.

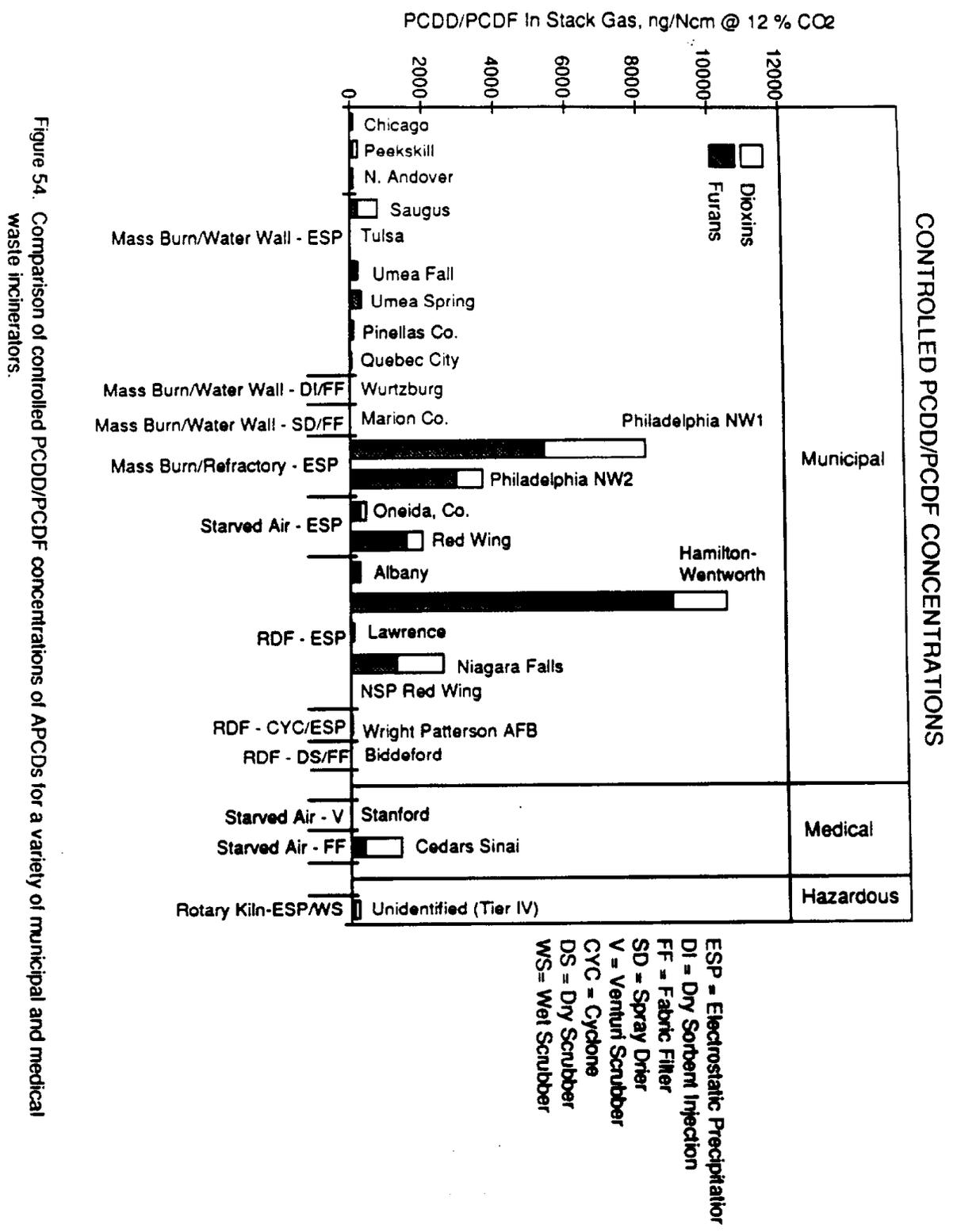


Figure 54. Comparison of controlled PCDD/PCDF concentrations of APCDs for a variety of municipal and medical waste incinerators.

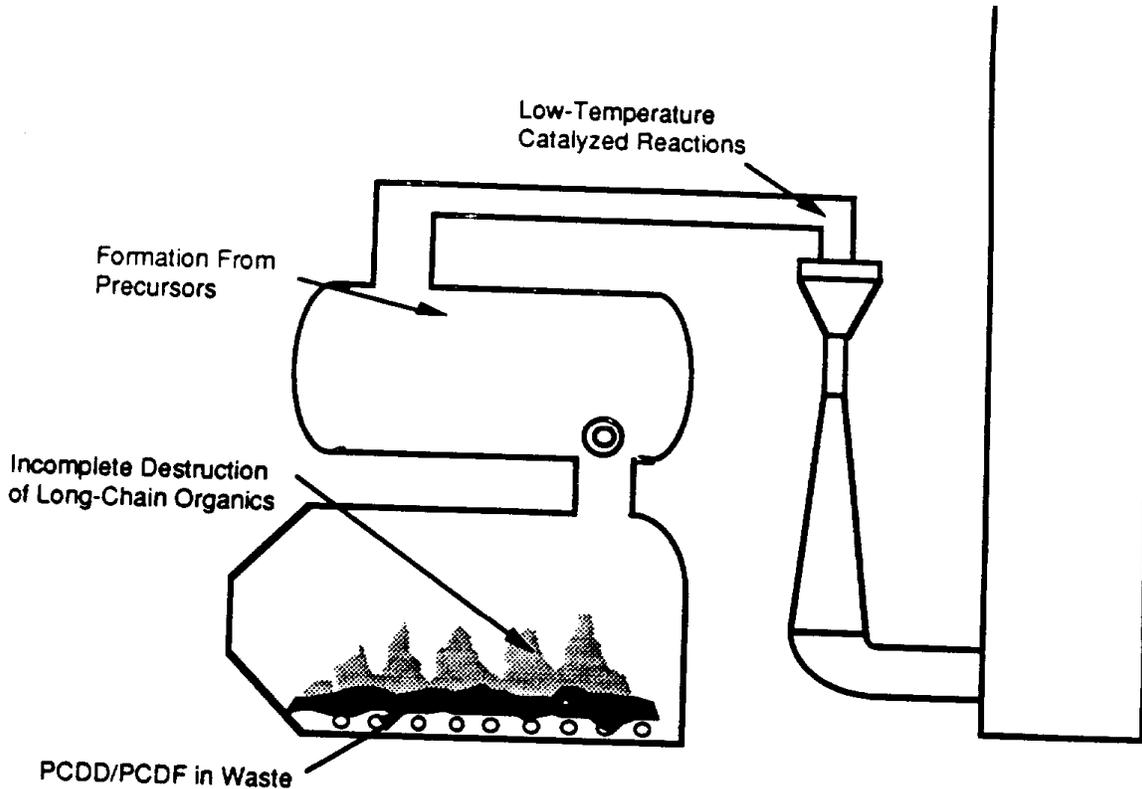


Figure 55. Proposed PCDD/PCDF emission mechanisms in waste incinerators.

The final mechanism proposes fly ash-catalyzed formation of dioxins in cool regions of the incinerator. This last mechanism was originally proposed by Vogg and Stieglitz (45) and is supported by laboratory experiments. In the experiments, flyash is placed in an oven and heated under controlled conditions. The experimenters found that the quantity of PCDD/PCDF increased significantly during the heating when oxygen is present. All the chlorine and organic precursors needed to form the dioxins were present on the particle, since none were added during the test. Karesek et al. (46) also found that dioxins form on flyash particles without gas-phase chlorine. In addition, Karesek found that it was possible for adsorbed inorganic chlorides to chlorinate aromatic rings and promote the formation of dioxins. None of these studies determined the importance of the mechanisms in full-scale incinerators. Extensive experiments are proceeding in Germany, Canada, and the U.S. to extend Vogg and Stieglitz's work to full-scale systems.

The theories concerning dioxin formation have now reached a state where they can be used to examine incinerator data. For the EPA, Energy and Environmental Research Corporation has conducted a statistical analysis of data collected by Environment Canada (47) in conjunction with the testing of the Quebec Urban Community's municipal solid waste incinerator under Canada's National Incinerator Testing and Evaluation

Program (NITEP) (48). This study evaluated proposed dioxin formation mechanisms in light of the NITEP data. Regression analysis was used to determine whether dioxin emissions from the incinerator could be statistically correlated with various parameters that could serve as indicators of the controlling mechanism. The parameters were either measured values or were derived from combinations of measured values.

The analysis was carried out in two stages. First, single-parameter correlations were performed using many parameters to choose or eliminate certain mechanistic pathways. Second, two-parameter correlations were performed using a few variables to further narrow the field. These data show that PCDD/PCDF emissions are strongly related to particle escape from the incinerator. Further analysis shows that HCl concentrations may also play a role, but HCl is not as important as entrained particles.

Based on this analysis and other data, a mechanism for the emission of dioxins can be hypothesized. The mechanism involves a series of steps. First, ash or unburned waste particles are entrained by the gas flow. A very small fraction of the hydrocarbons in the waste escape destruction in the incinerator chamber. Upon reaching a reaction zone, the hydrocarbons react with HCl on the surfaces of the particles to form dioxins. The proposed mechanism is consistent with recent studies which show that the reactions occur at temperatures between 520 and 620 K (480°F and 660°F). The data indicate that this zone occurs within the ESP in the Quebec City incinerator, but in other systems the temperature window might occur in different components depending on the system configuration.

This analysis can be extended to other incinerators. Figure 56 shows the relationship between PCDD/PCDF emissions and entrained particulate for municipal and medical waste incinerators. Sufficient data on hazardous waste incinerators is not available. In every case, PCDD/PCDF emissions increase with increasing particulate entrainment. This indicates that the same fundamental mechanism may be responsible for the PCDD/PCDF emissions. The dependence of PCDD/PCDF emissions on particulate entrainment varies from facility to facility. PCDD/PCDF emissions from the municipal waste combustion facility on Prince Edward Island (a starved-air system) exhibits a stronger dependence on entrained particulate loading than mass burn municipal waste incinerators. This can perhaps be seen more clearly in Figure 57.

The mechanism described above can be applied to typical medical waste incinerators as shown in Figure 58. Based on this mechanism, it can be hypothesized that PCDD/PCDF formation can be minimized by controlling particle and trace organic emission levels within the combustion zone, minimizing the time that particles are held at key temperatures [between 520 and 620 K (480 and 660°F)] and by maximizing the destruction of precursors, both vapor- and particle-bound, within the incinerator. Also, dioxins can ultimately be removed from the flue gas by low-temperature fine particulate control since PCDD/PCDF will condense on particles at low temperatures. This last approach, however, merely transfers the dioxins from one medium (air) to another (ash).

If the hypothesis described are true, then the parameters expected to affect PCDD/PCDF emissions from medical waste incinerators include the following:

- Primary chamber gas velocities which influence particle entrainment.
- Primary chamber combustion air flow which determines gas velocity and stoichiometry.
- Secondary chamber temperature which partially determines the organic destruction in this chamber.
- Uniformity of temperature (both spatial and temporal) in the secondary chamber.
- Particle residence time in the critical temperature zone [520-620 K (480-660°F)].

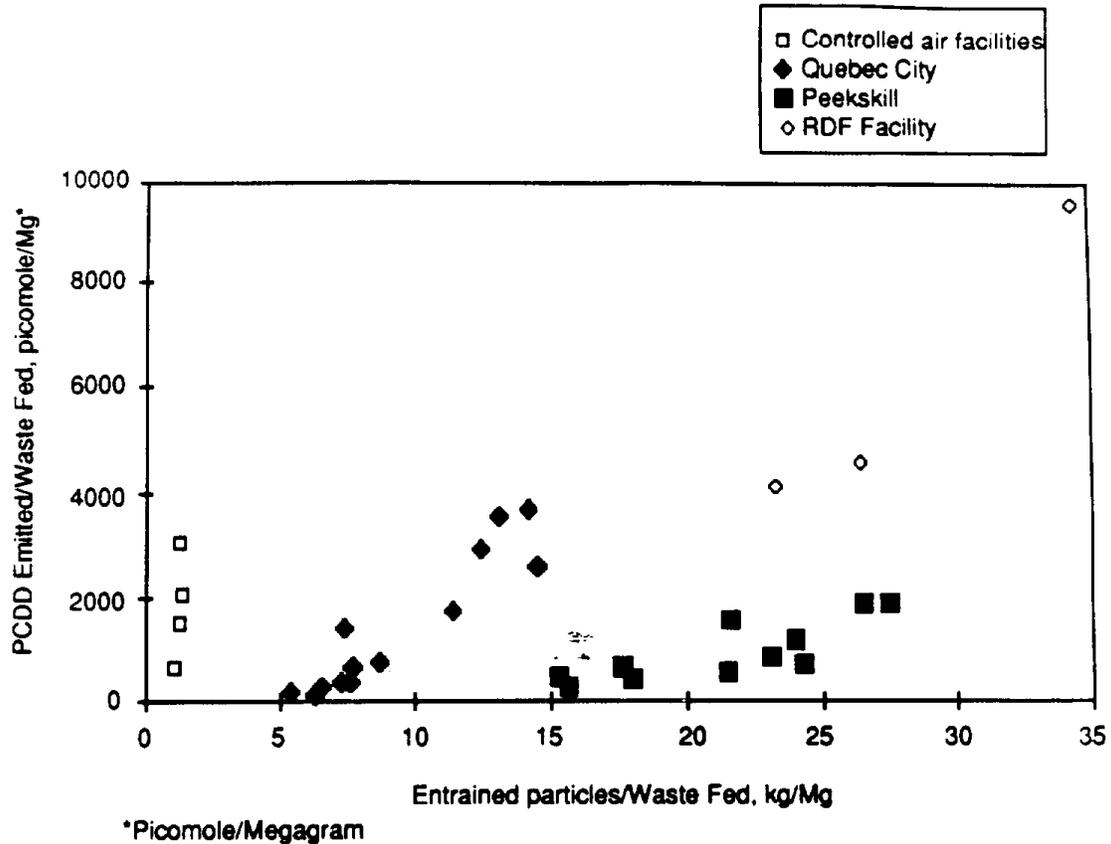


Figure 56. Relationship between PCDD/PCDF emissions and entrained particulate for a variety of municipal and medical waste incinerators.

- Flue gas temperature in the particle control device which determines condensation of PCDD/PCDF on particles.
- Fine particle control which determines the amount of PCDD/PCDF on particles removed from the flue gas.

The impact of some of these parameters can be partially assessed by careful examination of the data gathered by the California Air Resources Board's tests of medical waste incinerators. The analysis is, however, subject to an important limitation. None of the incinerators varied much in operation during the tests. Thus, the full impact of each parameter cannot be assessed. In addition, care must be taken to compare similar data. Comparison of the concentration of PCDD/PCDF in the stack at St Bernadines (a small, single-chambered, batch-fed incinerator with no pollution control equipment) and in the stack at Cedars-Sinai (a large, starved-air system equipped with heat recovery equipment and a baghouse) may be interesting but provides little information on the fundamental parameters controlling PCDD/PCDF emissions.

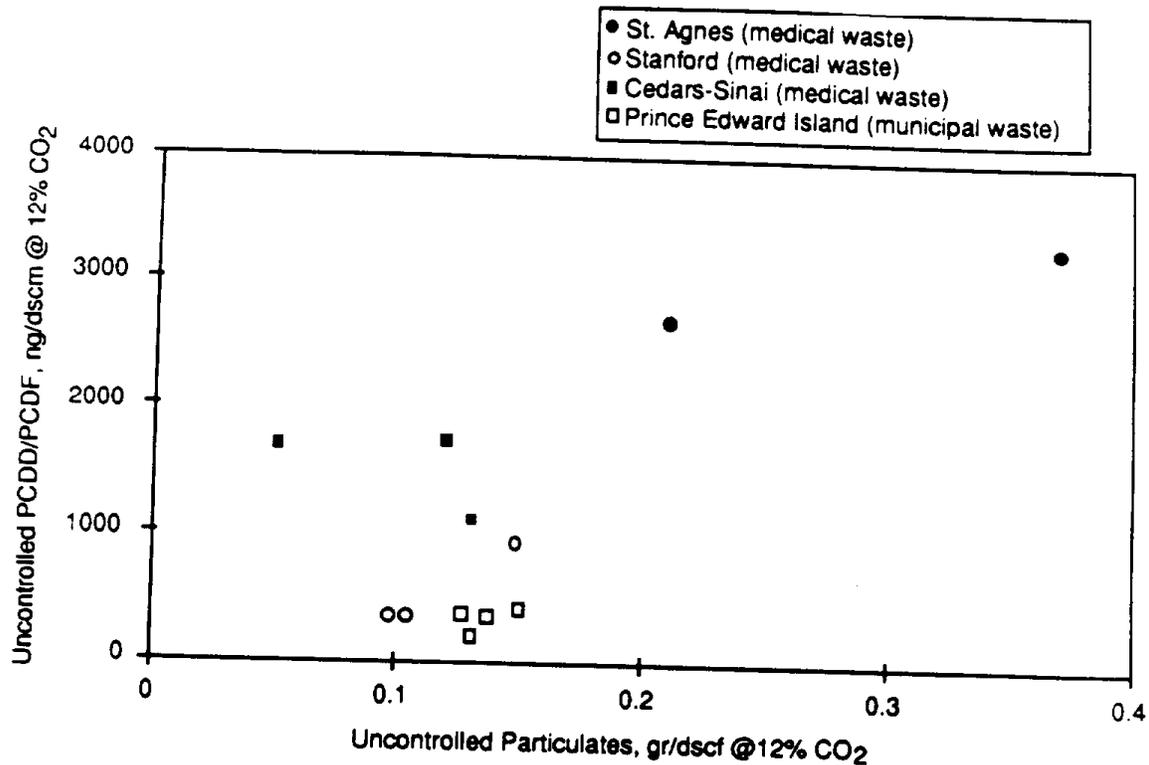


Figure 57. Comparison of PCDD/PCDF emissions and entrained particles for medical waste incinerators.

Neither of the two major parameters which control particle entrainment (primary zone gas velocity and total primary air) in starved-air systems were measured during the tests. However, particle entrainment was determined. Figure 57 shows the relationship between the concentration of particles in the flue gas before any air pollution control equipment and the concentration of dioxins in the flue gas. Data from a starved-air municipal waste incinerator (Prince Edward Island) is included for comparison. It is difficult to detect any trend in the medical waste incinerator data. However, this may be due to the limited data available and the lack of variation in operating conditions.

The flue gas temperature in the afterburner is one of the parameters which may determine the level of destruction of organic compounds. No matter what mechanism is responsible for PCDD/PCDF formation, PCDD/PCDFs will not be emitted if all the organic material in the flue gas is destroyed. Figure 59 shows the impact of afterburner temperature on the concentration of dioxins in the flue gas for medical waste incinerators. The data do not correlate with afterburner temperature for these particular systems. In fact, the lowest uncontrolled level of PCDD/PCDF was found for the incinerator with the lowest afterburner temperature. Because trace levels of PCDD/PCDF are of interest (in the parts per trillion range), the spatial and temporal uniformity of the gas in the secondary chamber may be more important than the mean flue gas temperature. In addition, downstream formation may add to the PCDD/PCDF formation that occurs within the furnace. Nonetheless, it is worth noting that a system with a mean afterburner temperature of only 1030 K (1400°F) was capable of achieving low PCDD/PCDF emissions. This implies that a mean temperature of 1030 K (1400°F) may be sufficient to minimize dioxin formation if spatial and temporal variations are carefully

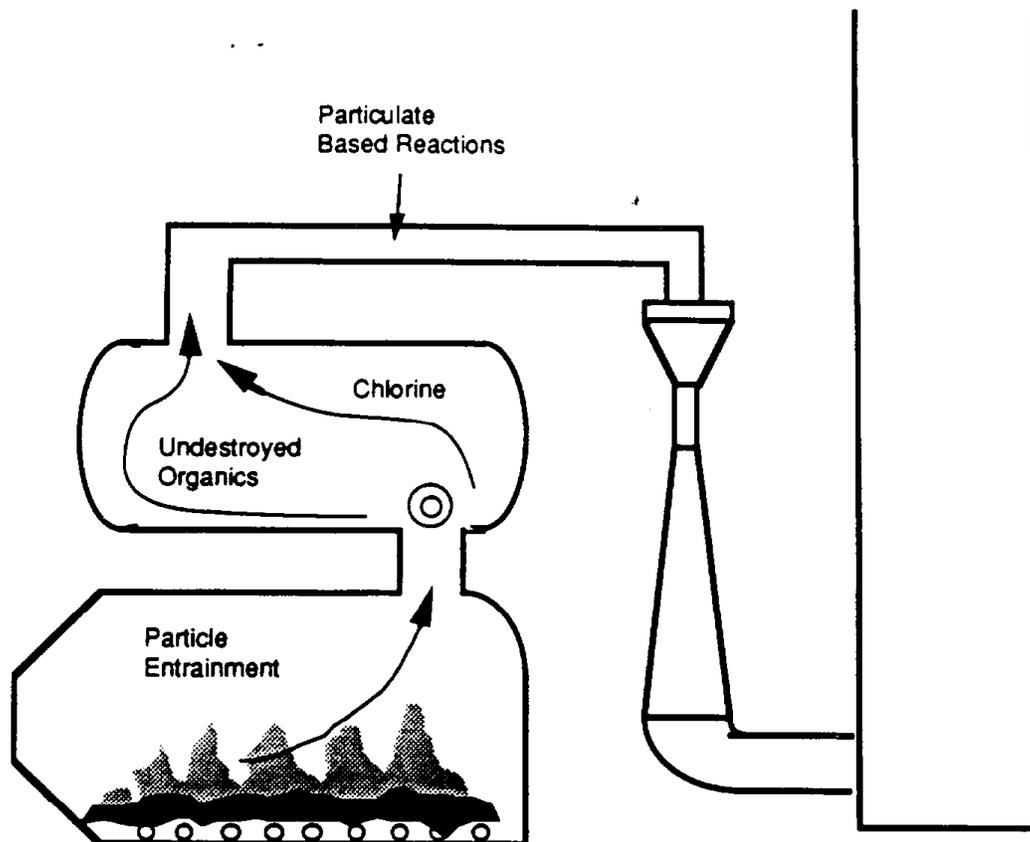


Figure 58. Hypothesized dioxin formation mechanism based on analysis of Quebec City data.

controlled. If these variations cannot be controlled, then a higher mean temperature would be needed to ensure that even the isolated cold pockets achieve the minimum temperature needed for destruction.

The affect of air pollution control equipment operation can be seen by comparing the dioxin emissions from Cedars-Sinai with those from Stanford. Figure 60 shows the concentration of dioxins before and after the control devices. The key characteristics of the air pollution control equipment associated with the two incinerators are shown in Table 17. The Cedars-Sinai incinerator facility is significantly more effective at capturing particulate material but the PCDD/PCDF emissions are greater than those for Stanford's incinerator. The fabric filter at Cedars-Sinai is operated at much higher temperatures than the scrubber at Stanford. Figure 61 shows the dioxin vapor pressure as a function of temperature. At 440 K (330°F), slightly cooler than Cedars-Sinai's baghouse, the vapor pressures of different dioxin congeners ranges from 200 to 20 Pa (2×10^{-3} to 2×10^{-4} atm). At 350 K (175°F), the vapor pressure range is 3 to 0.08 Pa (3×10^{-5} to 8×10^{-7}). The vapor pressure of dioxins in the air pollution control device at Stanford is about three orders of magnitude lower than that at Cedars-Sinai. Thus, a significant fraction of the PCDD/PCDF in the gas stream may not condense before reaching Cedars-Sinai's fabric filter and will not be captured. However, the temperature is below 520 K (480°F), the lower limit of the temperature range at which dioxins are suspected to form. The fact that no dioxins appear to form in the fabric filter does not contradict the laboratory evidence that dioxins form at

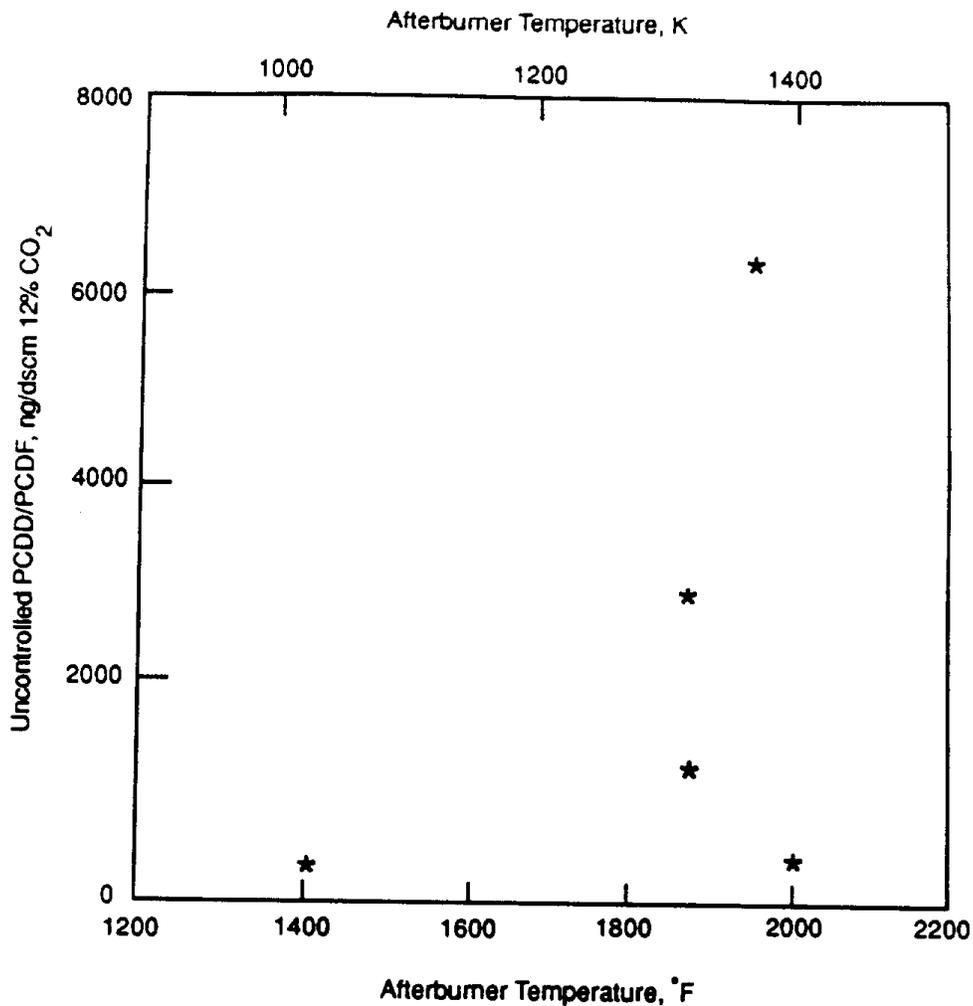


Figure 59. Comparison of afterburner temperature with PCDD/PCDF emissions for medical waste incinerators.

temperatures between 520 and 620 K (480 and 660°F). These data indicate that the temperature of the particle removal device may be as important as the effectiveness of particle removal in determining PCDD/PCDF emissions.

CURRENT CONTROL PRACTICE

TYPES OF CONTROL

Trace organic compound emissions control strategies fall into one of two categories:

- Combustion system-based strategies
- Air pollution control device-based strategies

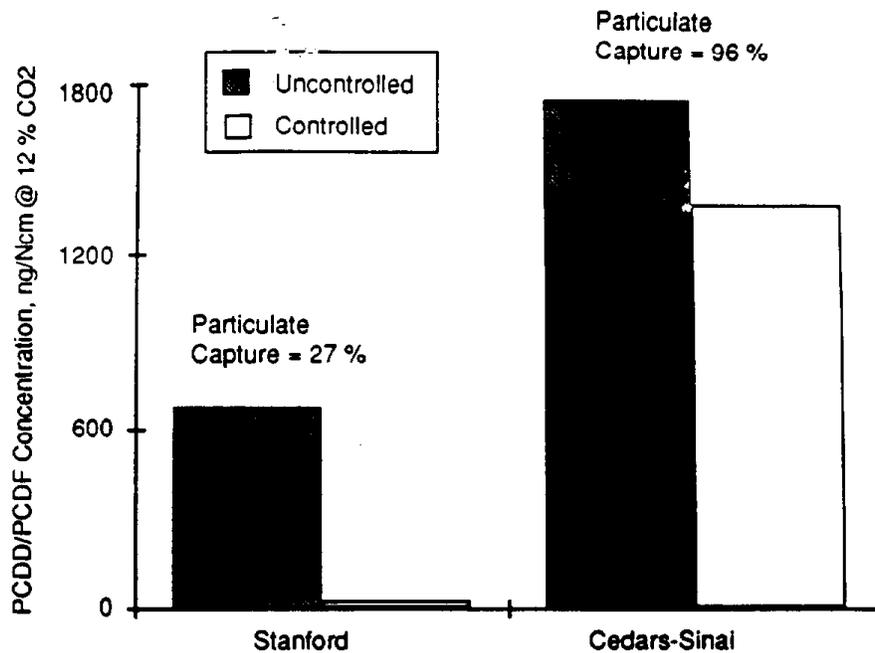


Figure 60. Comparison of the PCDD capture at Stanford and Cedars-Sinai.

TABLE 17. SELECTED APCD CHARACTERISTICS FOR STANFORD AND CEDARS-SINAI

	Cedars-Sinai	Stanford
APCD Type	Fabric Filter	Venturi Scrubber
APCD Temperature	363°F	175°F
Particulate Control Efficiency	96 %	27 %

Baghouse cleaning cycle and detailed scrubber operating conditions not available.

CURRENT COMBUSTION SYSTEM-BASED STRATEGIES

Combustion system-based strategies seek to maximize the destruction of organic material and minimize the quantity of entrained particles. The strategies now used vary with the type of incinerator system.

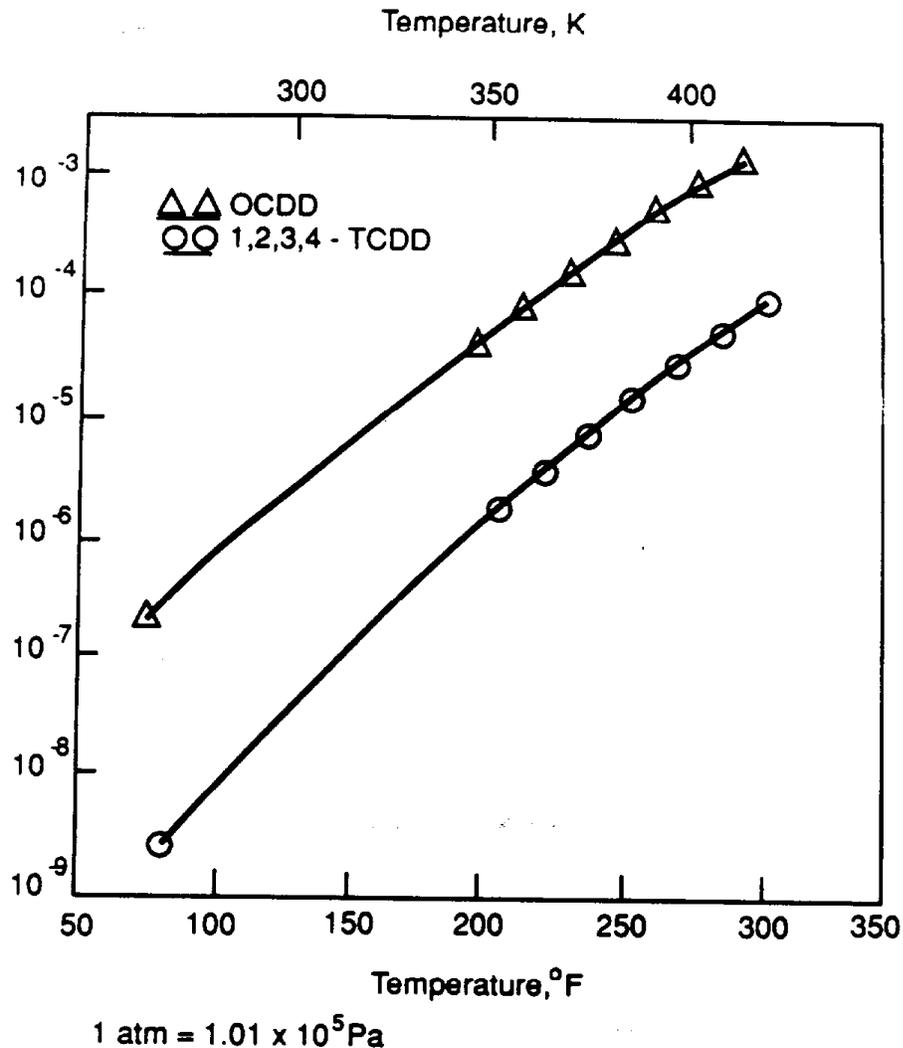


Figure 61. Vapor pressures of octa- and tetrachlorodibenzo-(p) dioxins.

Batch Incinerators--

Destruction of organic material in batch incinerators is maximized through the use of afterburners and in newer units through the use of secondary combustion chambers. Afterburners are usually fueled with a fossil fuel (such as natural gas) which raise the temperature of the exhaust gases from the primary combustion chamber. The higher temperatures are intended to increase the rate at which gas-phase organic compounds are destroyed. In addition, the temperatures help to burn the carbon remaining on entrained particles. Typically, the afterburner maintains a gas temperature of 1030-1370 K (1400-2000°F). The recent trend has been to use higher afterburner temperatures with larger residence times.

The secondary chamber is simply a large tank placed between the incinerator and the stack to increase the amount of time the exhaust gases are maintained at high temperatures. Longer residence times are

supposed to ensure that all gas-phase reactions proceed to completion. The secondary chamber is usually equipped with an afterburner to help maintain the temperature. Secondary chamber residence times are generally 1 to 2 seconds. Again, the trend has been to increase gas residence times.

Multi-chamber Starved-air Systems--

In this type of system, the primary zone functions as a gasifier satisfying perhaps only 40 percent of the theoretical air requirements. The large volume of this chamber, coupled with low air flow, results in low gas velocity and minimal particle entrainment. The combustion is completed in the secondary chamber where an excess of air is added to the combustion gases. In addition, the secondary chamber is usually equipped with an afterburner to maintain chamber temperature.

To ensure complete destruction of the organic materials, it is vital that the air added in the secondary chamber be completely mixed with the combustion gases. Several different strategies have been developed to ensure that adequate mixing occurs. For example, several suppliers (such as Consumat, CIL Incinerator Systems, Joy and Simonds) use small flame ports and inject much of the air needed to complete combustion into these ports. The consensus of these manufacturers is that the high secondary air flow into the narrow ports will ensure adequate mixing of the air with combustion gases. After leaving the flame port, the combustion gases enter a large secondary chamber which provides for a long gas residence time. This is designed to allow all the organic compounds time to mix with the available oxygen. Other techniques for achieving the needed mixing between primary zone gases and secondary air involve significantly different approaches. The John Basic design involves a secondary (and tertiary) chamber which is long and narrow. The secondary air is added through small jets in a center body around which the primary gases flow. Thus, the short air jet lengths are required to penetrate the annular region. In the John Zink design, secondary air is added via jets directed towards the center-line of the chamber. More air is added through a series of wall jets. In the design developed by Thermtec, the secondary chambers are narrow and long. The length allows the gases the same residence time as the more common secondary chambers. The air needed to complete combustion of the organic material in the incinerator exhaust gases is added in the combustion chamber at the same location as the afterburner. The afterburner exhaust is designed to impinge on the walls of the narrow secondary chamber. This is done to ensure that the entire chamber is well-mixed and maintained at a uniform temperature.

For each of these designs, the goal is to ensure complete mixing of the secondary air with the primary zone gases, which is a key requirement for good organic burnout. Several manufacturers have recognized the problem with temporal variations in temperature. Operation of the feed ram can cause severe influxes of air which affect the secondary chamber's temperature. Some manufacturers have developed "anticipator" control systems which involve lowering the primary air flows just before beginning the feed cycle. Such control systems may be necessary for starved-air units to achieve optimum control of trace levels of organics.

AIR POLLUTION CONTROL DEVICE-BASED STRATEGIES

Air pollution control systems minimize the emissions of PCDD/PCDF by insuring that the conditions favorable for the downstream formation of PCDD/PCDF do not exist and that trace organic material formed in the combustion chambers is removed from the gas stream. The minimization of PCDD/PCDF formation and combustion system-based control strategies are considered to be preferable to the capture of PCDD/PCDF-bearing materials. Once PCDD/PCDF are captured the ash must be disposed of. Thus, capture of PCDD/PCDF in a flue gas cleaning device merely trades one problem for another. However, stabilization of the ash so that the captured PCDD/PCDF cannot leave the ash may be a solution to the air pollution control device ash problem.

Capture of dioxin-bearing particulates is now the primary air pollution control device-based PCDD/PCDF control strategy. According to the prevailing theory, to capture dioxin bearing particles, it is first necessary to condense the PCDD/PCDF onto particles. The data from Cedars-Sinai and Stanford seem to indicate that

temperatures around 350 K (175°F) are needed to condense the PCDD/PCDF. However, as shown in Figure 61, PCDD/PCDF still exhibit a significant vapor pressure at temperatures as low as 290 K (70°F). A vapor pressure of 1×10^{-4} Pa can result in a gas-phase dioxin concentration of 1 ppb. Because of this, control devices cannot completely eliminate PCDD/PCDF emissions but they can significantly reduce emissions.

An alternative theory suggests that gas-phase PCDD/PCDF are absorbed by the scrubbing media or filter cake. If this theory proves correct, then control device temperature plays a less important role than discussed previously. More data is needed to determine the mechanisms controlling PCDD/PCDF capture.

Air pollution control devices are not commonly used on medical waste incinerators. This is due to the cost of these devices relative to the incinerator and to the fact that systems could be designed to meet existing regulations without them. The most common system used involves venturi scrubbing to remove particulates and acid gas absorbers. This type of system has been shown in one test to achieve over 95 percent removal of particulate material. Other systems, such as spray dryer/baghouse combinations, have been proven to achieve higher particulate removal levels for municipal solid waste combustion systems but have not been used in medical waste incineration and have not yet been tested for this application.

ANALYSIS OF CONTROL PRACTICE

COMBUSTION SYSTEM BASED-STRATEGIES

Clearly for PCDD/PCDF to be emitted, organic material must survive destruction in the incinerator. The vast bulk of the organic material is destroyed as a natural result of combustion, producing products which are primarily of CO_2 and H_2O . However, because of the suspected toxicity of PCDD/PCDF, it is essential that all the organics be destroyed as completely as possible. Thus, combustion-based control strategies should be based on the simple principle of maximizing destruction of all organic material.

The strategy for maximizing destruction of combustion intermediates from medical waste incinerators is similar to that previously suggested for municipal solid waste incinerators (49) and is based upon the need to provide an environment which will ensure the effective destruction of gaseous and particulate organic species. This optimum environment requires the presence of oxygen at a sufficiently high temperature. Furthermore, it is necessary that, to the extent possible, all combustion gases experience the same environment. Mixing is vitally important because it will ensure uniform temperatures and composition. Mixing should be rapid and complete to maximize the use of the residence times for destruction of intermediates. The attainment of appropriate temperatures will depend upon the balance between the heat released and the heat absorbed. Following the above steps will promote high combustion efficiency.

The simplistic view of optimization of combustion by the "three Ts" (time, turbulence, and temperature) is not directly valid in this context. For example, the gas-phase residence time should not be considered solely as a necessary reaction time but also as a required mixing time. Time is required for oxygen and gaseous organics to mix. Once mixed at a sufficiently high temperature, the gas-phase destruction reactions take place in milliseconds. Turbulence on its own is not sufficient to ensure mixing. Two separate, highly turbulent gas streams in the furnace will not mix despite their high turbulence level unless they are in contact with each other.

Thus, the first question is: What temperature is required to ensure that trace organic destruction is maximized once the organics are mixed with sufficient air? The thermal decomposition data obtained by University of Dayton Research Institute (50) for the EPA can be used as a basis for determining the temperature needed to destroy organics. Because it is possible for dioxins to form downstream of the combustion units, it is important to examine the destruction of all potential dioxin precursors and not just PCDD/PCDF. Some reference data for a range of organics including PCDD/PCDFs, benzene and chlorinated hydrocarbons is provided in Figure 62. Unchlorinated dioxin species are usually unstable above 980 K (1300°F) although potential precursors such as chlorophenols are stable to 1090 K (1500°F). Hexachlorobenzene is a stable species; it does not quickly decompose below 1170 K (1650°F). This indicates that to ensure

complete destruction of PCDD/PCDF and their precursors, a temperature of 1170 K (1650°F) must be achieved after enough air is mixed with the combustion gases.

This is the minimum temperature that any gas should experience in a combustion unit. Because nearly all medical waste incinerators are refractory-lined, the temperature variations within each combustion chamber are unlikely to deviate dramatically. Thus, an average temperature of 1200 K (1700°F) should be sufficient to ensure that the needed minimum temperature is attained.

The greatest potential for low temperature pathways through an incineration system exists during the feeding cycle of starved-air systems. The primary combustion chambers are generally maintained at a slightly negative pressure to prevent fugitive emissions. Thus, when the guillotine door is opened, a puff of air will normally enter the chamber. When mixed with this air, volatile organic materials in the primary chamber gases will burn. These circumstances will cause a larger than normal volume of gas containing little combustible material to enter the secondary chamber. These gases may cause a low temperature puff to move through the incinerator before the burner in the secondary chamber can respond.

Mixing is a second key requirement for complete destruction of organic material. In medical waste incinerators, gaseous emissions are maintained at high temperatures for a set amount of time (usually from one to two seconds). This time is supposed to give all the exhaust gases time to reach the appropriate destruction temperature and to mix with the needed quantities of air. However, this approach is not adequate. Mixing is highly dependent on the specific design of an incinerator. It is possible for a system with a nominal retention time of 2 seconds to fail to mix all the exhaust gases (poor mixing) or fail to retain a significant amount of material for the nominal retention time (short-circuiting).

Poor mixing happens when air is not added with enough energy and in such a manner to ensure that it mixes intimately with the exhaust gases. Figure 63 is a diagram of a hypothetical unit which does not achieve proper mixing. In this unit, the exhaust gases from the primary chamber move through the secondary chamber without contacting the jet of air or the afterburner flame. When this occurs, excessive quantities of PCDD/PCDF and PCDD/PCDF precursors will probably escape the secondary combustion zone.

Figure 63 also illustrates another potential failure mode, i.e. short-circuiting. The stream of combustion products from the primary chamber will move through the secondary chamber with a velocity higher than the superficial velocity calculated for the chamber. This stream of gas increases the possibility of poor mixing and decreases gas residence time.

In a series of recent research programs, the effectiveness of afterburner systems to control PCDD/PCDF emissions has been examined (51). While these programs have focused on municipal waste combustion, many of the findings apply to medical waste incineration systems. As discussed previously, downstream formation of dioxins has been observed in the laboratory and in full-scale incinerators. However, data from recent studies of refuse-derived fuel (RDF) incinerators show that significant concentrations of PCDD/PCDF may be present in the gases leaving the combustion chambers (Figure 64). This indicates that PCDD/PCDF formation may also take place in the furnace. Examination of the conditions within the combustion chamber indicate that significant spatial and temporal variations in temperature occur. Figure 65 shows the temperature of the combustion chamber as a function of time. A 220 K (400°F) fluctuation occurs over a 10-minute period. RDF is a more uniform feed material than medical waste. Medical waste incinerators exhibit fluctuations in primary chamber temperature partially as a result of variation in the waste feed. The afterburner evens out the temperature fluctuations and serves to ensure that all combustion products are exposed to sufficient temperatures for sufficient time so that the destruction of PCDD/PCDF and their precursors can be maximized.

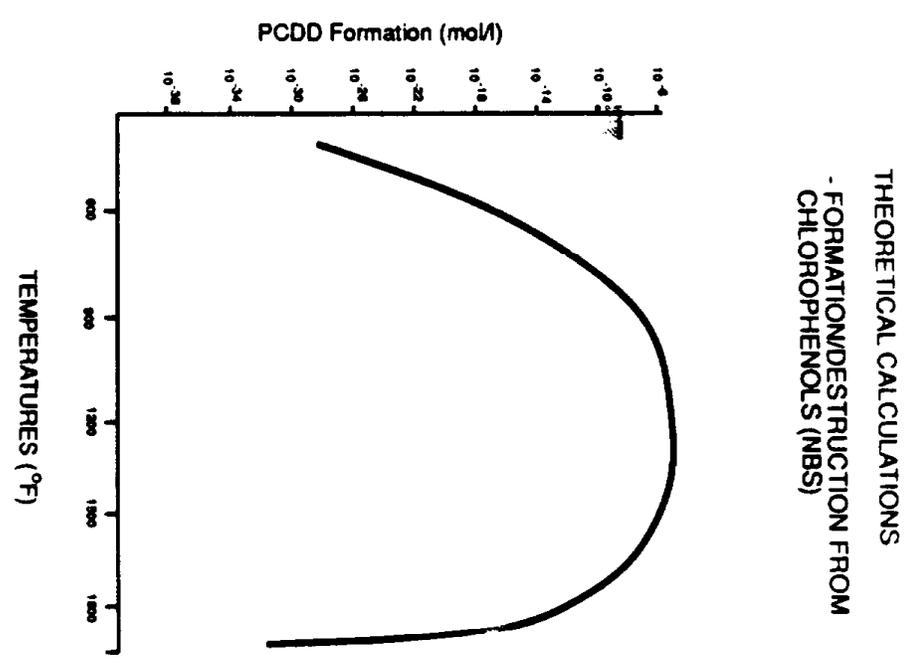
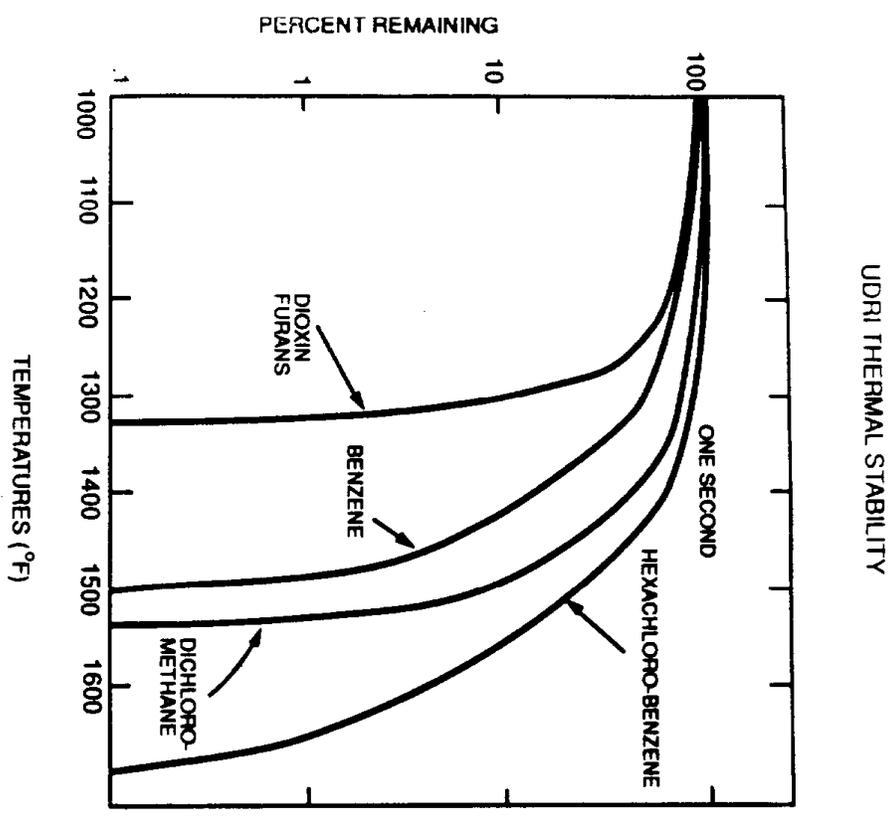


Figure 62. Thermal decomposition characteristics of selected hydrocarbons.

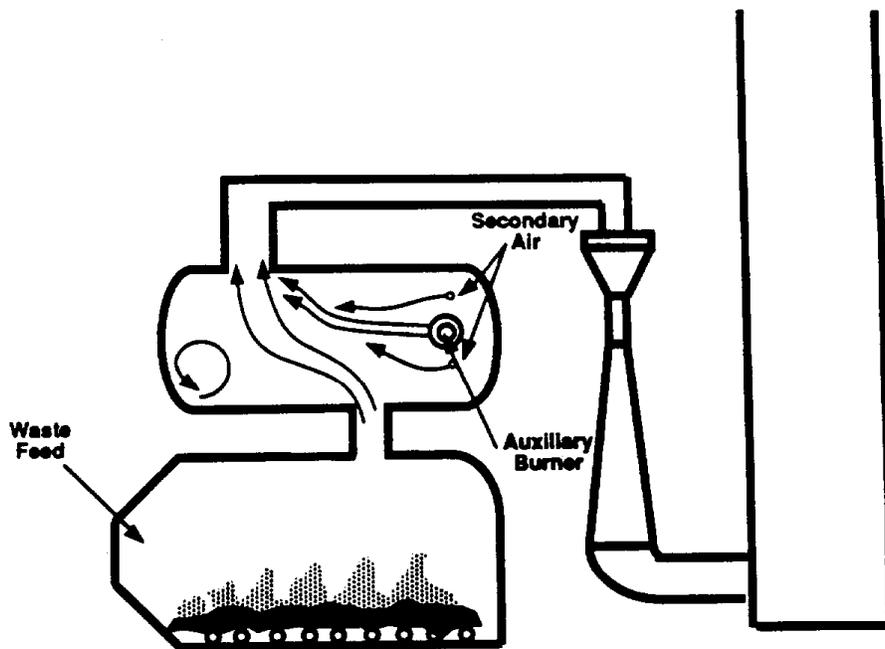


Figure 63. A hypothetical unit which fails to achieve good mixing in the secondary chamber.

ADDITIONAL RESEARCH NEEDS

Significant data are available from incinerators operating under normal conditions. However, this provides little new insight into the mechanisms responsible for dioxin formation. Thus, a series of experiments in which a medical waste incinerator is tested under a variety of operating conditions, which are expected to influence PCDD/PCDF emission is needed.

Based on the current understanding of PCDD/PCDF formation, several key parameters have been identified. These parameters include:

- Secondary air injection velocity
- Combustion zone mean temperature
- Afterburner (or secondary) gas mean temperature and distribution of temperatures
- Particle entrainment rate
- Fine particle control efficiency
- APCD temperature
- Particle loading exiting furnace

These key parameters should be measured concurrent with any PCDD/PCDF measurements.

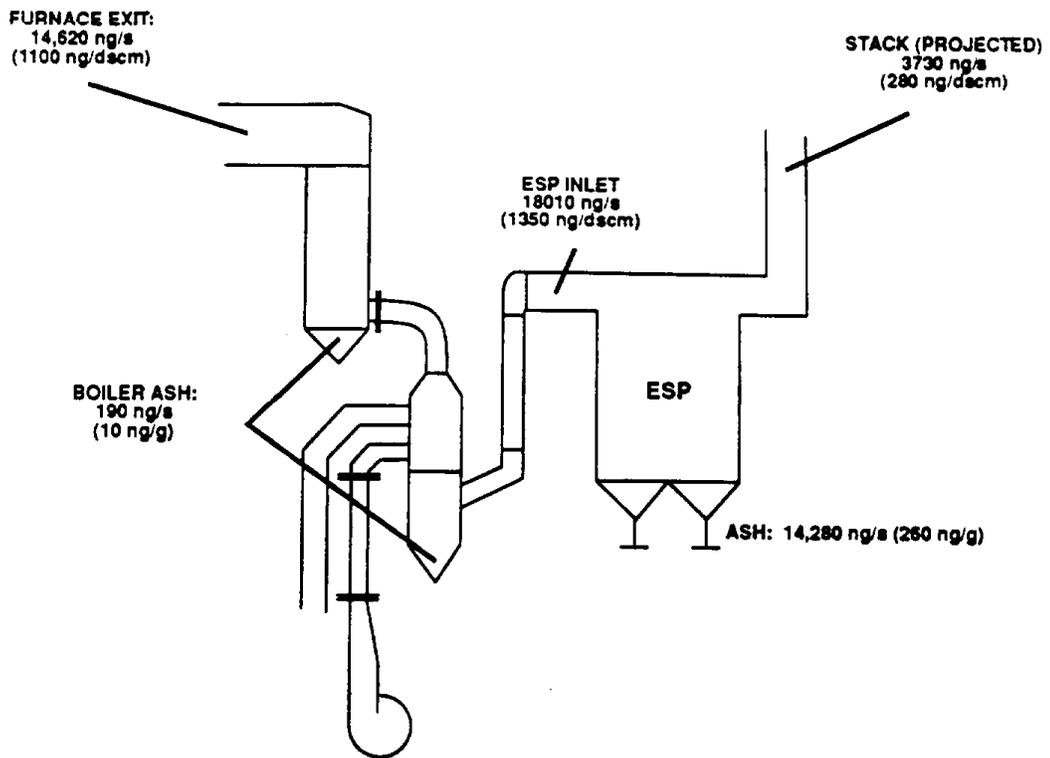


Figure 64. PCDD/PCDF data from full-scale field characterization of a municipal waste combustion unit.

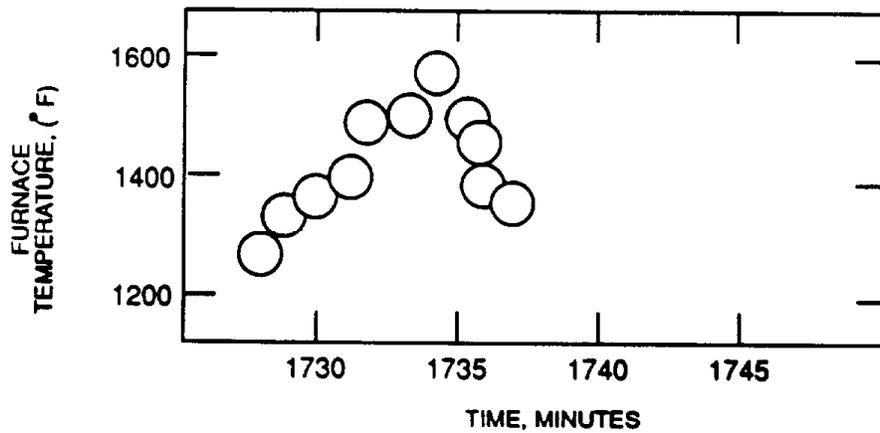


Figure 65. Temperature fluctuations in incinerator over time.

SECTION 8

PATHOGENS

Pathogens are the source of most of the general public's fears of medical wastes and the reason medical wastes are now receiving special attention. The pathogens present in medical wastes are a wide range of bacteria, viruses and other microorganisms sufficiently virulent to infect a human body if they are given an exposure route. Any infectious waste disposal method must be capable of destroying the virulence of or limiting the exposure routes for infectious agents.

POLLUTANT CHARACTERISTICS

The pathogens present in infectious waste are a complex mixture of bacteria, mycobacteria, fungi, parasites, viruses, and rickettsia (52). These pathogens are sent to the waste stream by hospital patients, visitors and health care personnel. As one would expect, hospitalized patients who have or are suspected of having a communicable disease are responsible for much of the infectious waste produced in a hospital (52). However, with the advent of "universal precautions," all patients suspected of having a communicable disease are being treated as though they had a communicable disease. While this will not significantly change the infectious agents present in the waste, it does increase the total amount of waste considered to be infectious.

Hospital wastes have been found to contain such organisms as:

- *Staphylococcus aureus*
- *Candida albicans*
- *Pseudomonas*
- *Clostridium perfringens*
- *Staphylococcus epidermidis*
- respiratory *Streptococci* (53,54)

The Center for Disease Control has estimated that bacterial infections were responsible for 90 percent of the recognized hospital-acquired infections in the U.S. (55).

From an incineration viewpoint, pathogens are very fragile. No pathogen can withstand exposure to the mean gas temperature in the primary chamber of the incinerator for typical incinerator gas residence times (around 1-2 seconds). Pathogens are composed mainly of water and easily oxidized organic chemicals. In addition, pathogens are always present in such low concentrations that they have no impact on the operation of the incinerator.

PATHOGEN ESCAPE MECHANISMS

Since pathogens are easy to destroy when exposed to the mean conditions found in a typical medical waste incinerator, they can escape only when they do not experience these bulk conditions. Several potential escape pathways can be identified. Figure 66 illustrates several potential escape modes. The air emission routes are discussed in this section while survival of pathogens in residual ash will be discussed later.

One pathway involves entrained material. Entrained material moves through the incinerator with the exhaust gases. While the solids typically remain in the incinerator for several hours, gases only have a few seconds residence time. Thus, pathogens on entrained material will remain in the incinerator for only a few seconds. Because of this, it is important that the particles experience high temperatures to be sure that all the pathogens are destroyed. If any of the gas stream bypasses the high temperature regions of the afterburner, pathogens may survive and be emitted to the atmosphere. This pathway is a particular concern in ram-fed units during the part of the cycle when the door is open and an uncontrolled puff of air can enter the lower chamber.

Pathogens may also escape before introduction into the furnace. These fugitive emissions can only occur when infectious waste bags are ruptured or when pathogen containing materials are not placed in sealed containers.

CURRENT CONTROL PRACTICE

DESIGN

Incinerator manufacturers treat the destruction of pathogens in much the same way they treat the destruction of organic material. The key design features, as discussed previously are:

- Moderate bulk gas temperatures in the primary combustion chamber. In starved-air systems, only volatilization and pyrolysis should occur. In batch incinerators, the temperature is higher and the objective is maximum destruction of organic materials.
- High bulk gas temperatures in the secondary chamber to ensure complete destruction of organic materials.
- 1- or 2-second residence time in the secondary chamber to allow sufficient time for mixing between organics and oxygen to occur.
- Promote mixing in the secondary chamber to ensure contact between organic materials and oxygen.

Pathogens are much easier to destroy than many organic materials. Thus, the conditions which maximize the destruction of organic material in an incinerator will also maximize the destruction of pathogens.

OPERATION

The primary aim of the unit operators is to ensure that no pathogens escape before the waste enters the incinerator. Generally, this has typically only involved ensuring that the bags of infectious waste were not ruptured. In batch-fed units, there is little opportunity for pathogen escape before the initiation of incineration. In ram-fed units, there is a slight chance of bag rupture during the feeding process.

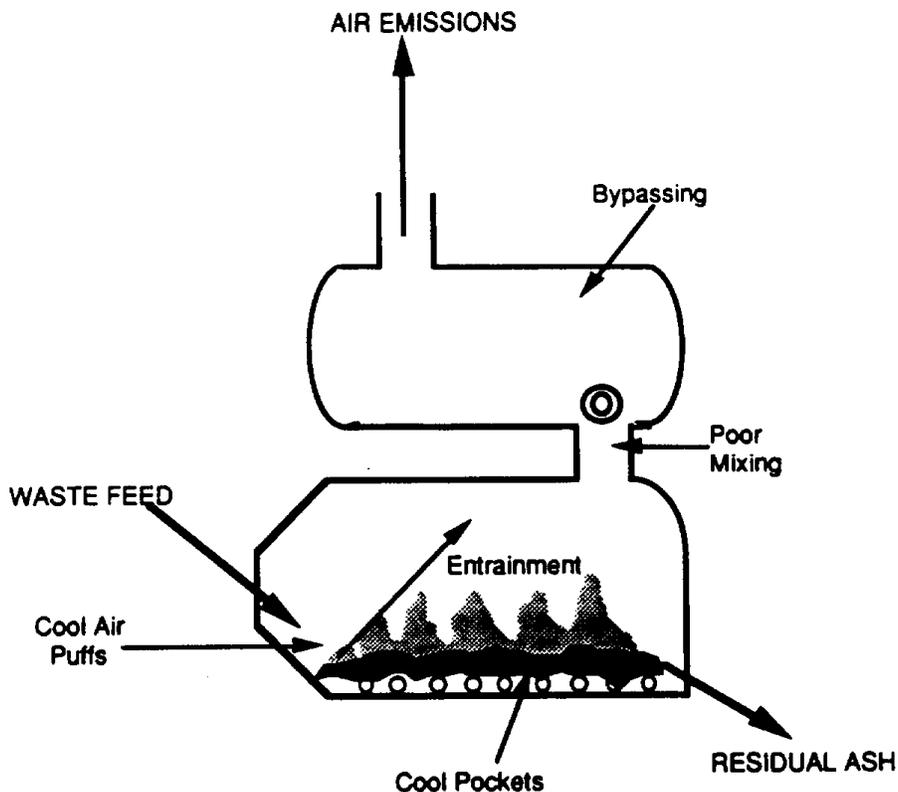


Figure 66. Potential pathogen emission pathways in a typical medical waste incinerator.

DATABASE ON DESTRUCTION OF PATHOGENS IN INCINERATORS

Several studies have been conducted to determine the ability of incinerators to destroy pathogens. These studies focus on the destruction of bacterial spores for two reasons:

- Bacterial spores are more heat resistant than any other microorganisms.
- Bacteria are responsible for 90 percent of all hospital-acquired infections (52).

In one of the earliest tests, Barbeito and Gremillion (56) spiked the wastes being incinerated in an industrial refuse incinerator with *Bacillus subtilis* spores. *Bacillus subtilis* spores are resistant to many types of environmental stresses, including high temperature and low pH. *Bacillus subtilis* can survive over 30 minutes at 322 K (121°F) but it is effectively killed when subjected to 433 K (320°F) dry heat for 30 minutes (57). To determine if any spores survived, a sample of incinerator exhaust gas was drawn through a glass fiber filter with a 99.995 percent filtration efficiency for particles 0.3 micrometers in diameter. The number of viable spores captured by the filter could be determined. It was found that a combination of a top-of-stack temperature of 575 K (575°F) and a combustion chamber residence time of 4.1 seconds was required to kill all the spores disseminated from a liquid suspension at a concentration of 1.9×10^{11} spores/m³ (5.3×10^8 spores/ft³) of air flowing through the incinerator.

Barbeito et al. (58,59) conducted two other test programs which involved spiking two large-volume incinerators and a small pathological incinerator with *Bacillus subtilis*. As in the early study, spores were collected in the stack using a filter. All the facilities could attain operating conditions at which no viable spores could be found in the exhaust gas.

There is some concern with these studies. It has been suggested that the act of collecting spores on a filter will destroy some of the spores in the stack (52). Impingement on the filter can rupture spores. Once collected on the filter, the spores would be subjected to a steady stream of hot gases. These gases would dehydrate and eventually destroy some spores.

Because of these concerns, the more recent studies of pathogen destruction have been conducted using impingers to capture escaping microbes. Typical impingers used to capture pathogens are shown in Figure 67. The impingers were filled with buffered nutrient solutions. Impingers are considered to be gentler than filters. Thus, there may be less chance that spores will be destroyed when captured in these devices. Any spores collected are sheltered from the stack gases and are nourished by the nutrient-rich solution. This testing approach was felt to give a more accurate representation of the number of viable microbes in the stack.

One of the first studies to use impingers to collect pathogens was carried out by the EPA (60) on a municipal waste incinerator. The incinerator was not spiked with microbes. Instead, tests were conducted to identify a broad range of microbes. An average of 2 gram-positive bacilli/ft³ of air were detected.

In 1982, Kelly et al. (61) used a specialized impinger, the Shipe impinger, to collect bacterial spores in the stack of a medical waste incinerator. The incinerator was a ram-fed, starved-air unit which burned both general refuse and infectious waste. The incinerator was not spiked with microorganisms. Kelly detected 231 organisms/m³ (6 organisms/ft³) of gas in the stack. The concentration of pathogens in the ambient air was 148 organisms/m³. The difference between stack gas microorganism content and the concentration of microorganisms in the ambient air was not statistically significant. The microorganisms in the stack gas were not identified, so it is unclear whether they came from the waste or from the ambient air.

In 1987, the Shipe impinger was again used to collect bacteria in the stack gas of a hospital waste incinerator (62). However, instead of actual medical waste, a synthetic waste was used. The synthetic waste consisted of wadded newspaper, copier paper, cardboard, tap water and *Bacillus subtilis*. The incinerator was a 45 kg/hr (100 lb/hr), two-chambered, batch-fed unit. Both chambers were maintained at 1030 K (1400°F). Though bacteria were detected in the stack, none of them were *Bacillus subtilis*. Brenniman and Allen (62) suggest that this indicates the combustion air was the likeliest source of the microbes found in the stack gas. Air leaking into the stack is another potential source of the pathogens.

ANALYSIS OF CONTROL PROCEDURES

Because microorganisms are generally more fragile than organic chemicals, the bulk conditions which maximize the destruction of organic material will also maximize the destruction of pathogens. Thus, the primary concern is the elimination of potential escape pathways. Two potential escape pathways have been identified previously; they are:

- Escape on entrained particles (fly ash) due to low temperature or short residence time pathways through the secondary chamber.
- Bypassing of the combustion zone by pathogens originally in combustion air.

The first escape mechanism is a particular concern in some incinerator designs such as that shown in the diagram in Figure 68. In these designs, the flame port is close to the first hearth. Particles which have not been in the incinerator very long can be entrained and carried directly into the secondary chamber. As discussed previously, unless the gases in the secondary chamber are well mixed, it is possible for a portion

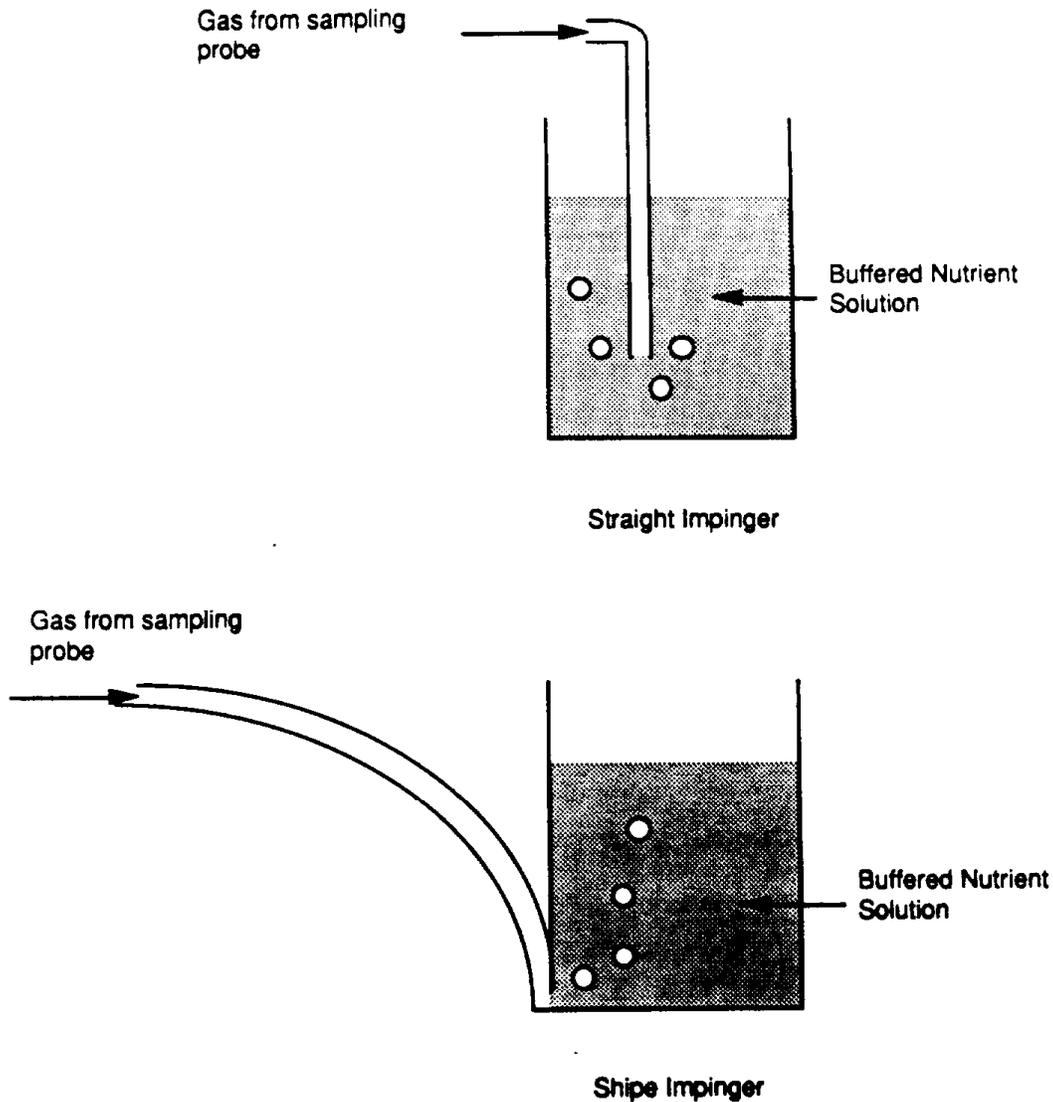


Figure 67. Impingers used to collect pathogen samples

of the gases to move directly from the flame port to the secondary chamber exit. Since only a portion of the secondary chamber is used in the flow, the residence times of some gases is much lower than expected. However, the limited stack tests in which pathogen emissions were measured tend to indicate that the mixing employed in current incineration systems is sufficient to ensure complete pathogen destruction.

The second potential escape mechanism involves the bypass of the combustion zone by fugitive pathogens in the combustion air. It is common practice to draw the combustion air from the waste storage areas to provide a negative draft for these areas. In addition, the incinerator is most often operated at a slightly negative pressure and is located in the waste storage area. Thus, the system can draw air potentially contaminated with pathogens into the air used for combustion or into other openings in the incinerator system.

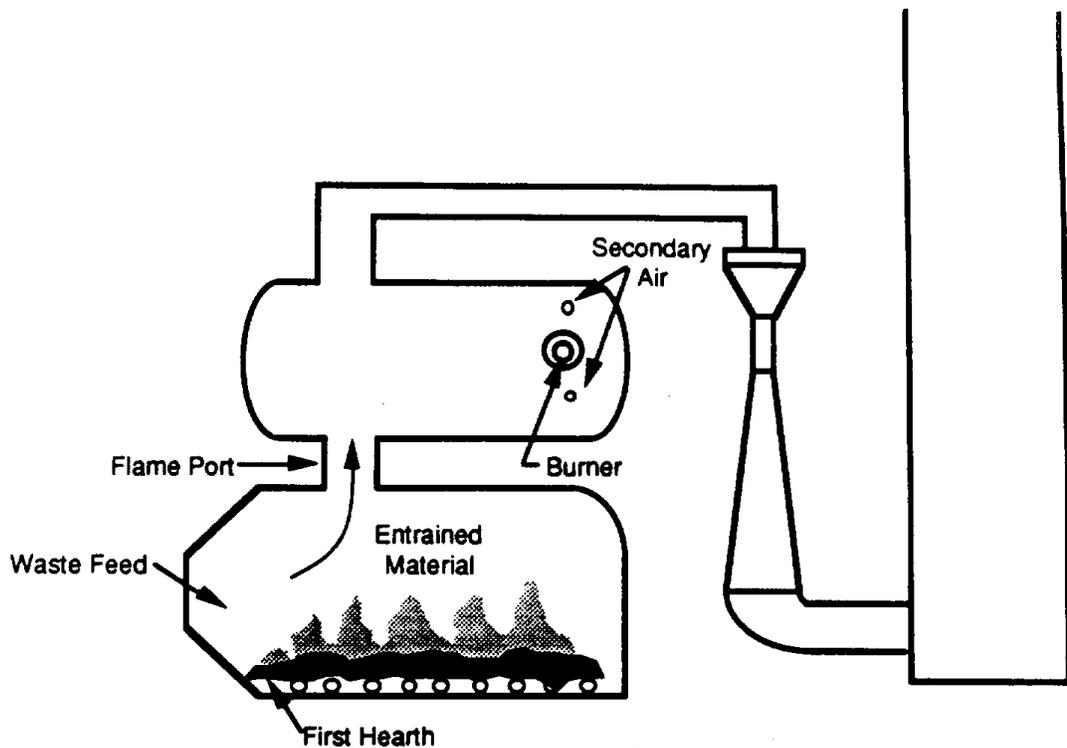


Figure 68. Incinerator design in which air emissions of pathogens are likely.

Attention must be placed on these other sources of pathogens if the stack is to be completely free from viable pathogens. This will involve ensuring that the combustion air and entrained air is not allowed to bypass the high temperature zones in any way.

NEEDED INFORMATION

There is a significant need for research into the destruction of microorganisms in medical waste incinerator if more appropriate design and operating practices are to be developed. It is unclear that current pathogen test procedures are appropriate to evaluate medical waste incinerator performance. *Bacillus subtilis* is not pathogenic and is not generally found in medical wastes. It is not the most heat resistant bacterial spore existing. There is no standard spore collection method. Thus, a program to develop and verify an appropriate method for testing the ability of an incinerator is to destroy all microorganisms is needed. Once this method is available, a comprehensive study of the affects of design and operating practice should be carried out.

SECTION 9

ACID GAS EMISSIONS

Exhaust gases from combustion of medical wastes contain constituents which are acidic or will form acids in the atmosphere. These constituents are:

- Nitrogen Oxides
- Sulfur Oxides
- Hydrogen Chloride

Combustion of any fuel in air produces nitrogen oxide (NO) which is oxidized in the atmosphere to nitrogen dioxide (NO₂). NO₂ is soluble in water and will precipitate from the atmosphere as nitric acid. Medical waste typically contains around 0.2 percent sulfur. When sulfur-containing fuels burn, sulfur dioxide and trace amounts of sulfur trioxide are formed. As with nitrogen oxides, SO₂ oxidizes to SO₃ in the atmosphere. SO₃ will precipitate as sulfuric acid. Most medical waste streams contain large quantities of plastics including polyvinyl chlorides and other chlorine-containing constituents. Typical wastes can contain 5 percent chlorine. When chlorinated compounds (or halogenated compounds in general) burn at high temperature, the equilibrium chemical form of chlorine is HCl (fluorine forms HF and bromine forms HBr). Thus, combustion of plastics will lead to direct emission of acid gases.

CHARACTERISTICS OF POLLUTANTS

The general concern for emission of acid gases is based on a series of issues. First, there is concern for welfare effects associated with excessive build up of acid gases in local environments. Without high stacks and substantial dispersion, acid gas concentrations can build up and cause substantial corrosion of stacks and metal structures near the stack. Such corrosion contributed to the decision to shut down incineration operations at Cedars-Sinai Hospital in California. A second basis for concern is the potential for adverse health effects from excessive acid build up in the local atmosphere. EPA has recently established an ambient air reference dosage (RfD) of 0.7 µg/m³ (annual average) for HCl. Incinerator emissions contribute to the general ambient background concentration of HCl. A third reason for regulatory concern over acid gas emissions is that SO₂ and NO_x are classified as criteria pollutants. Thus, according to dictates of the Clean Air Act, EPA is required to consider control of these acid gas precursors in establishing new source performance standards. Further, states must consider the various sources of SO₂ and NO_x in developing State Implementation Plans (SIPs) and may require controls for achieving or maintaining ambient air quality standards. Lastly, regulatory agencies have strongly weighed secondary benefits associated with requiring controls on acid gas emissions. For example, the combination of acid gas control and tight particulate matter control have been shown to minimize emission of trace metals and many condensable trace organic species.

FORMATION MECHANISMS AND AVAILABLE DATABASE

When fuel and air react, the various chemical constituents proceed through a complex series of reactions to eventually form the final combustion products. Given enough time, the elements will be distributed among several species at concentrations defined by thermodynamic equilibrium. Under high temperature conditions characteristic of flames, chlorine and sulfur present in the fuel will be converted to HCl and SO₂. For these elements, there are no significant chemical kinetic barriers to forming HCl or SO₂, and at high temperature the reactions are extremely fast. Thus, the concentrations of HCl and SO₂ formed in the combustion chamber are directly related to the amount of sulfur and chlorine in the fuel.

The characteristics of medical waste in the U.S. were discussed previously. Table 7 shows typical waste ultimate analysis. The sulfur content is typically 0.17 wt-percent while the chlorine content is 4.12 wt-percent. Assuming complete combustion and high temperature excess air conditions, the equilibrium concentration of SO₂ and HCl can be calculated as shown in Figure 69. The calculated concentrations of SO₂ and HCl are 143 ppm and 3133 ppm, respectively, both on a dry basis corrected to 7 percent O₂.

As combustion gas temperature decreases, the equilibrium distribution begins to shift from HCl to Cl₂ and from SO₂ to SO₃. To illustrate this thermodynamic effect, the waste elemental composition defined in Table 7 was combined with 90 percent excess air and the equilibrium product distribution calculated as a function of temperature using the NASA equilibrium computer code, CET-85. Figure 70 is a plot of the calculated equilibrium molar ratios HCl/(HCl + 2Cl₂) and SO₂/(SO₂ + SO₃ + H₂SO₄) as a function of temperature. As shown, Cl₂ is thermodynamically favored at stack gas temperature [<480 K (400°F)] while SO₃ is favored in the 760-870 K (900-1100°F) range. Below 760 K (900°F), the thermodynamically favored sulfur species is H₂SO₄.

Equilibrium calculations provide a good estimation of species concentrations when gases are provided extended periods of time to react or when there are no chemical kinetic limitations. As noted earlier, high temperature conditions characteristic of incinerator flame zones allow chlorine and sulfur in the waste to form HCl and SO₂. However, as the gases cool, chemical kinetic limitations prevent the large shifts in speciation suggested in Figure 71. The dominant reaction path for forming SO₃ is through the reaction



where M is any third body (63). This reaction proceeds to SO₃ only while ample atomic oxygen is available. Dissociation of molecular oxygen



is highly temperature-sensitive. As temperature falls, the oxygen atom concentration decreases exponentially and an essential reactant for the formation of SO₃ is no longer available. Based on field test data from fossil fuel-fired boilers, it is generally accepted that the sulfur species distribution is frozen at concentrations characteristic of equilibrium at 920-1030 K (1200-1400°F) (64). Typically, less than 9 percent of total sulfur leaves the system as SO₃. In the atmosphere, however, where there is a long time for reactions to occur, the sulfur will be slowly converted to sulfuric acid.

A similar reaction-freezing process occurs which limits the formation of Cl₂. Most of the chlorine in the waste exits the incinerator system as HCl.

Only limited field test data are available to characterize SO₂ and HCl emissions from medical waste incinerators. Available data were summarized in an EPA report and are repeated here as Tables 18 and 19 (15). As shown, HCl emissions are highly variable due to inconsistency in waste feed characteristics. A load of waste high in polyvinylchloride content will yield exceedingly high HCl concentration while a load of paper

Basis: 100 g of waste

<u>Waste Composition</u>		<u>Combustion Products</u>		<u>Oxygen Required</u>
Carbon	51.1 g → 4.26 mole	→	4.26 mole CO ₂	4.26 mole
Hydrogen	6.23 g → 6.23 mole	→	3.06 mole H ₂ O	1.53 mole
Oxygen	21.31 g → 1.33 mole	→	0.665 mole O ₂	-0.665 mole
Nitrogen	0.45 g → 0.0321 mole	→	0.0161 mole N ₂	0.0
Sulfur	0.17 g → 0.0053 mole	→	0.0053 mole SO ₂	0.0053
Chlorine	4.12 g → 0.1162 mole	→	0.1162 mole HCl	0.0
Water	9.00 g			
Ash	7.62 g			
			Total Oxygen Required	5.13 mole

$$X_{O_2} = \frac{P_{O_2}(Y_{CO_2}M_{CO_2} + Y_{N_2}M_{N_2} + Y_{SO_2}M_{SO_2} + Y_{HCl}M_{HCl}) + C_{O_2}M_{O_2}}{M_{O_2} - P_{O_2}(M_{O_2} + fM_{N_2})}$$

Where:

X_i = Total Quantity of i added in the combustion air in moles

P_{O_2} = Weight fraction of oxygen in exhaust gas on a dry basis

Y_i = Quantity of component i produced by combustion in moles

M_i = Molecular weight of component i

C_i = quantity of component i consumed in the combustion

f = ratio of moles of nitrogen to moles of oxygen in atmospheric air

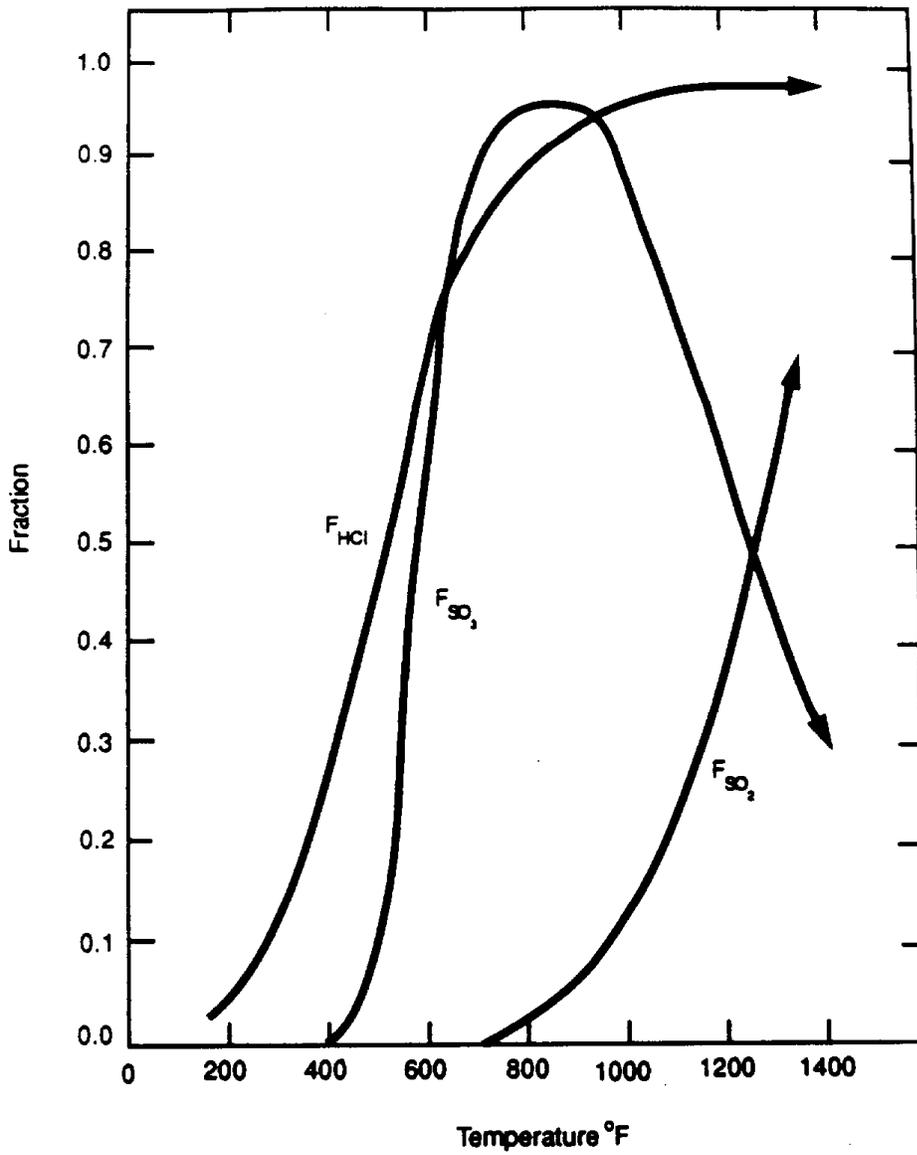
$$\text{Total Moles} = Y_{CO_2} + Y_{N_2} + Y_{SO_2} + Y_{HCl} + X_{O_2} - C_{O_2} + fX_{O_2}$$

Based on equations and data above, total moles of combustion gas (dry) = 37.03

Thus HCl concentration = $0.116/37.03 = 3133$ ppm

SO₂ concentration = $0.0053/37.03 = 143$ ppm

Figure 69. Calculation of SO₂ and HCl concentrations in stack gases assuming complete combustion and high temperature excess air conditions.



$$F_{\text{HCl}} = \frac{\text{HCl}}{\text{HCl} + 2\text{Cl}_2} \quad F_{\text{SO}_3} = \frac{\text{SO}_3}{\text{SO}_2 + \text{SO}_3 + \text{H}_2\text{SO}_4} \quad F_{\text{SO}_2} = \frac{\text{SO}_2}{\text{SO}_2 + \text{SO}_3 + \text{H}_2\text{SO}_4}$$

Figure 70. Calculated equilibrium molar ratios of HCl and SO as a function of temperature.

TABLE 18. DATA/FACTORS FOR HYDROGEN CHLORIDE EMISSIONS FROM MEDICAL WASTE INCINERATORS

Hospital	Control Device	Incinerator Feed Rate (lb/hr)	Stack HCl Concentration (ppm)	Emission Factor (lb/ton feed)
St. Agnes	None	783	845	13.7
Sutter General	None	474	237	17.7
St. Bernadines	None	47	728	62.6
Royal Jubilee	None	1,930	1250	16.5
Illinois Unit	None	500-800	550	8.60
Athabasca	None	85	41.0	14.0
Misericordia	None	740	670	13.6
Misericordia	None	740	687	13.0
Royal Alex	None	1160	553	17.4
Royal Alex	None	1200	562	16.4
Foothills	None	2500	702	15.0
Bonnyville	None	130	62.2	3.4
Willingdon	None	130	308	5.0
Lacombe	None	150	234.5	3.0
Ft. McMurray	None	265	700	10.0
St. Michaels	None	465	2095	20.5
Queen Elizabeth II	None	575	115	4.6
Queen Elizabeth II	None	700	287	3.9
Queen Elizabeth II	None	700	378	5.2
Red Deer	None	185	726	59.8
Stanford	Wet Scrubber	675	1.42	4.20
Lethbridge Gen.	Wet Scrubber	1060	44.6	1.20
Univ. of Alberta	Wet Scrubber	1400	64.7	0.1
Univ. of Alberta	Wet Scrubber	1400	25.4	0.9
Cedars-Sinai	Fabric Filter	980	462	14.5

1 lb/hr = 0.454 kg/hr

1 lb/ton feed - 0.5 kg/Mg feed

will produce only trace HCl. Generally, however, the data tend to show uncontrolled HCl concentrations of about 700 ppm and uncontrolled SO₂ concentrations near 50 ppm, or less. Regarding the relative amounts of HCl and Cl₂, a recent test performed on an incinerator at the University of Texas Cancer Center showed HCl and Cl₂ at the scrubber inlet to be 181 ppm and <1.9 ppm respectively. Very limited SO₂ data are available since most states do not regulate SO₂ from small waste incinerators.

The NO_x formed in waste incinerators occurs by two separate pathways, thermal fixation of molecular nitrogen from air ("thermal NO_x") and conversion of nitrogen from the fuel ("fuel NO_x"). The thermal fixation mechanism involves high temperature reactions of free radicals of nitrogen and oxygen. The controlling process is called the Zeldovich mechanism and includes reactions of the form

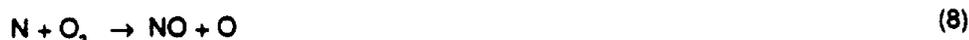


TABLE 19. DATA/FACTORS FOR SO₂ AND NO_x EMISSIONS FROM MEDICAL WASTE INCINERATORS

Pollutant	Cedar Sinai Medical Center Los Angeles, CA		St. Agnes Medical Center Fresno, CA		Emissions Factor (lb/ton feed)
	(ppmv)	(lb/ton feed)	(ppmv)	(lb/ton feed)	
Sulfur Dioxide					
High	50	3.01	20	1.54	3.01
Low	25	1.51	19	1.47	1.47
Average	37	2.22	19	1.47	1.85
Nitrogen Oxides					
High	270	7.82	155	5.75	7.82
Low	160	4.64	155	5.75	4.64
Average	217	6.29	155	5.75	6.02

1 lb/ton = 0.5 kg/Mg

These thermal fixation reactions are strongly temperature-dependent as shown by the 0 percent fuel nitrogen curve in Figure 72. This figure represents a computer simulation of the NO_x formed for a specific excess air condition and residence time (τ) and clearly shows the strong temperature dependence of thermal NO_x formation. The reason for the strong temperature dependence is that substantial energy is needed to break the N₂ bond of molecular nitrogen (the first step in the Zeldovich mechanism noted above).

The second source of NO_x is conversion of nitrogen bound in the waste feed. This mechanism was first discovered by burning coals and fuel oils in nitrogen-free oxidizers where the only nitrogen source was in the fuel. These studies have shown that the conversion of the fuel-bound nitrogen is highly dependent on the local availability of oxygen to react with volatile species, the amount of fuel bound nitrogen and the chemical structure of the nitrogen in the waste. The conversion efficiency for fuel-bound nitrogen in coal can vary from nearly 90 percent for highly mixed excess air conditions to nearly 9 percent for oxygen-starved staged combustion conditions (65). Since the nitrogen in fuel is typically bound as cyano or amine compounds, the NO_x formation process does not require rupturing the strong N₂ triple bond and thus, the reactions are not strongly temperature-dependent. This trend is illustrated by the 0.5 percent fuel nitrogen curve in Figure 71.

At high temperatures characteristic of flame reaction zones, the equilibrium concentration of NO_x can reach several thousand ppm and is almost totally shifted to NO (as opposed to NO₂). Fortunately, the availability of bound nitrogen in the fuel and chemical kinetic limitations prevent combustors from ever forming such high NO concentrations. As temperature drops, the equilibrium concentration of NO_x drops and the concentration of N₂ increases. The distribution of nitrogen oxides shifts toward NO₂. Unfortunately, chemical kinetics not only limit NO_x formation but also limit the back conversion of NO to N₂. Only minor NO₂ formation occurs, with over 99 percent of exhaust gas NO_x as NO.

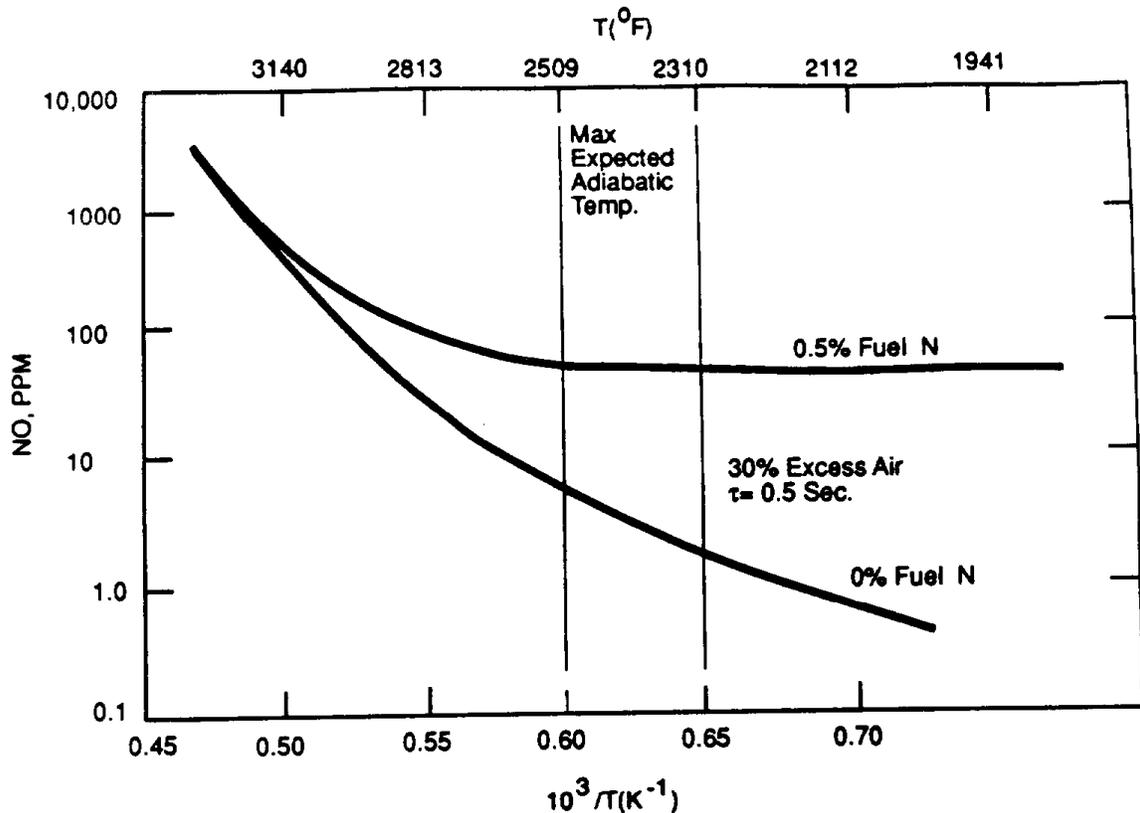


Figure 71. Impact of temperature and fuel nitrogen on NO_x emissions for excess air conditions (calculated using EER kinetic set).

Table 19 included limited NO_x emission data from two medical waste incinerators in California which had average NO_x levels between 155 and 217 ppm.

CURRENT CONTROL

A variety of control techniques may be used to limit acid gas emissions from incinerators. Until very recently, controls for medical waste incineration were rare. Nitrogen oxides may be controlled by careful design and operation of the combustion system while HCl and SO₂ require changes to the waste feed characteristics and/or add-on air pollution control devices.

COMBUSTION SYSTEM CONTROL

Nitrogen oxide emission rate from a combustion system is controlled by the quantity of NO_x formed in the furnace. As noted previously, the quantity of NO_x formed is controlled by chemical kinetic processes and thus, combustion modifications can be used to minimize emissions. Thermal NO_x is exponentially dependent upon temperature level and thus, combustion modifications which suppress peak flame temperature will decrease NO_x formation by this mechanism. Conversion of fuel-bound nitrogen to NO_x is highly dependent upon the availability of oxygen to react with volatile matter as it is released from the fuel.

The basic configuration of the controlled-air incinerator should be ideal for minimizing NO formation rates. Thermal NO_x formation is controlled by peak flame temperature and is significant only under excess air conditions. In a controlled-air incinerator, peak flame temperature occurs in the secondary chamber and is generally less than about 1530-1870 K (2300-2900°F), even for systems designed to achieve 1370 K (2000°F) at the secondary zone exit. As illustrated in Figure 72, chemical kinetic calculations suggest that thermal NO_x should be less than about 10 ppm and maybe less than 1 ppm (compared to 90 ppm for fuel NO_x).

Because of the above consideration, it appears that most the NO_x emitted from medical waste incineration is because of oxidation of fuel bound nitrogen. Using procedures similar to those illustrated in Figure 70, it can be determined that if the 0.49 wt-percent nitrogen in the waste defined in Table 7 was converted at 100 percent efficiency, the resultant NO_x level would be 1004 ppm (dry, at 7 percent O₂). However, conversion of fuel-bound nitrogen to NO_x is minimized by having the first stages of combustion happen under starved-air condition. This limits the availability of oxygen to react with nitrogen released with volatile matter. The data in Table 19 implies fuel nitrogen conversion to NO_x in the 19- to 20-percent range (assuming the bound nitrogen content is approximately equal to that listed in Table 7). For deeply staged combustion processes such as those used in medical waste incineration, lower conversion is expected.

A possible explanation for the NO_x levels observed in Table 19 is that very high NO_x levels could be formed during the waste charging process. If large quantities of tramp air are allowed to enter the combustion chamber during charging (without compensation in the underfire zone), that air could be available to oxidize the rapid release of volatiles and to oxidize volatilized fuel nitrogen to NO_x. If this is a correct assessment, it is expected that more modern municipal waste incinerators, which try to carefully control air in-leakage will also have much lower NO_x emissions. This does not imply, however, that 190-200 ppm NO_x is a particularly high emission rate.

AIR POLLUTION CONTROL EQUIPMENT

Traditionally, acid gas control has been achieved with add-on flue gas cleaning devices. These systems function by absorbing HCl and SO₂ in an aqueous solution (wet system) or by reacting HCl and SO₂ with solid sorbent material. Both wet and dry control systems were discussed in significant detail previously. The general level of HCl capture with wet systems is typically above 99 percent. For dry sorbent injection, HCl capture of 90 percent is typically achieved using Ca to Cl molar ratios of about 1.8:1 or less.

SECTION 10

TOXIC AND CARCINOGENIC METALS

Toxic metals are a major concern in medical waste incineration. They are emitted from incinerators on small particles capable of penetrating deep into human lungs. Thus, a clear understanding of metals behavior in medical waste incinerators is critical.

POLLUTANT CHARACTERISTICS

EPA has issued guidance to regional permit writers outlining procedures that should be used to regulate metals emissions (66) from hazardous waste incinerators. This guidance identifies ten metals from 40 CFR 261, Appendix VIII, of most concern. Table 20 lists these metals. Four of the ten metals are classified as carcinogenic. The EPA's Carcinogen Assessment Group has estimated the carcinogenic potency for humans exposed to low levels of carcinogens. An assigned "Unit Risk" indicates the relative health threat of the metals. Unit Risk is the incremental risk of developing cancer to a person exposed for a lifetime to ambient air containing one microgram of the compound per cubic meter of air. Inhalation is the only exposure pathway considered in determining Unit Risk. Table 21 presents the Unit Risks for the four carcinogenic metals (66).

TABLE 20. TOXIC METALS IDENTIFIED IN EPA'S GUIDANCE FOR METALS EMISSIONS FROM HAZAROUS WASTE INCINERATORS

<u>Carcinogenic Metals</u>	<u>Toxic Metals</u>
Arsenic	Antimony
Beryllium	Barium
Cadmium	Lead
Chromium	Mercury
	Silver
	Thallium

Chromium is unique. Only its hexavalent oxidation state is toxic. Chromium most commonly exists in nature in its trivalent state. Hexavalent chromium, the second most stable state, is mainly formed from industrial processes. The ability of hexavalent chromium compounds to cross biological membranes and their strong oxidizing power accounts for much of their toxic properties (67).

TABLE 21. UNIT RISK VALUES FOR THE FOUR CARCINOGENIC METALS OF PRIMARY CONCERN

Metal	Unit Risk
Arsenic	0.0043
Beryllium	0.0025
Cadmium	0.0017
Chromium (Hexavalent)	0.012

TABLE 22. REFERENCE AIR CONCENTRATIONS FOR SIX TOXIC METALS OF PRIMARY CONCERN

Metal	RAC ($\mu\text{g}/\text{m}^3$)
Antimony	0.025
Barium	50.00
Lead	0.09
Mercury	1.70
Silver	5.00
Thallium	500.00

Toxicity data can be used to define concentrations for the other six metals below which they are not considered dangerous. Ambient concentrations should not exceed this concentration. The EPA has defined the minimum toxic concentration, or Reference Air Concentration (RAC), for each metal. If ground level concentrations of any of these metals exceeds its RAC, adverse health effects are likely. Table 22 lists the RACs for the six non-carcinogenic metals listed in the guidance (66).

Metals cannot be destroyed in an incinerator. Thus, they must exit the incinerator or accumulate on the system's walls. Figure 72 illustrates the potential paths that metals may follow. Most of the metals will stay in the ash. A small fraction of the ash is entrained by the combustion gases and carried out of the primary chamber. The remainder of the ash forms residual ash. Volatile metals may vaporize in the combustion chamber and leave the ash. These metals recondense to form very small particles as the combustion gases cool. Some entrained ash and condensed metals are captured in the air pollution control device. The rest enter the atmosphere.

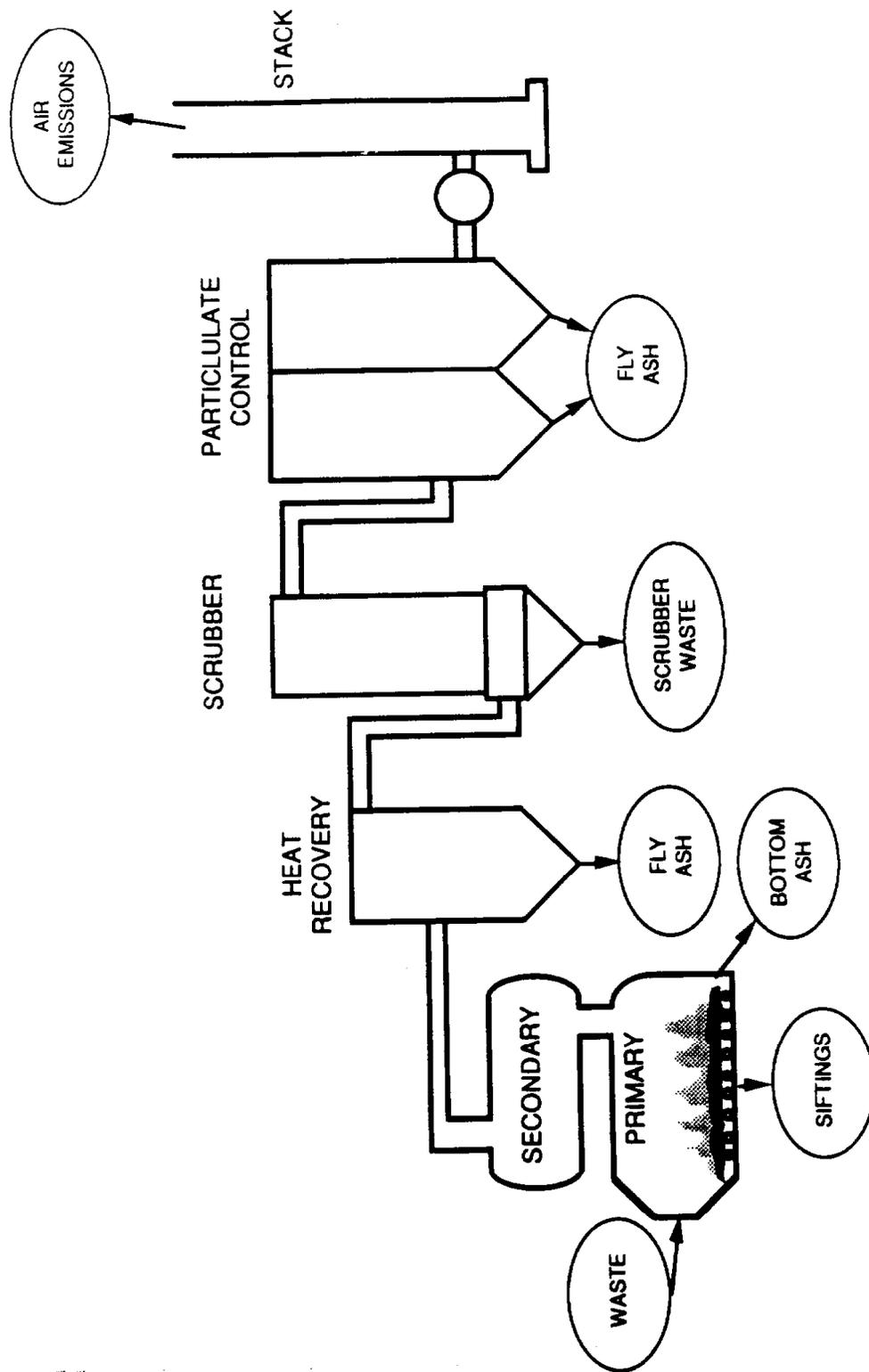


Figure 72. Metals escape pathways.

AVAILABLE DATABASE

Metals emissions data from medical waste incineration are scarce. The largest set of data was obtained by the California Air Resources Board in its medical waste field test program (34-38).

AIR EMISSIONS

Figures 73, 74, 75 and 76 compare the concentration of arsenic, cadmium, chromium, and lead in flue gases before any APCDs, and in emitted gases for a variety of incinerators. As shown, a wide variety of flue gas cleaning equipment is used. The Figures indicate the effectiveness of flue gas cleaning systems at capturing the four metals. The concentrations of metals in medical waste incinerator flue gases are lower than for municipal waste incinerators. Chromium concentrations in particular are several orders of magnitude lower. Lead, cadmium and arsenic are more volatile than chromium. Significant amounts of lead, cadmium and arsenic vaporize in an incinerator while almost no chromium does so. Any chromium leaving the primary chamber would probably be carried on entrained particles. Thus, the low chromium concentrations in medical waste incinerators may reflect the low particle entrainment rate which is characteristic of starved-air incinerators. Since lead, cadmium and arsenic are volatile, their concentrations in flue gas should not be related to particle entrainment. Instead, the concentrations reflect the concentration of these metals in the waste and the primary chamber temperatures.

Examination of the metals control efficiency for those units where sufficient data are available indicates fabric filters yield the lowest overall metals emissions. This feature is most obvious when comparing the two hospital incinerators with flue gas cleaning systems, Stanford and Cedars-Sinai. Metals emissions from Cedars-Sinai were two or more orders of magnitude lower those at Stanford. Figure 77 summarizes the capture efficiency of other common flue gas cleaning systems. Of the systems shown, only the venturi scrubber is routinely used with medical waste incinerators.

POTENTIAL ESCAPE MECHANISMS

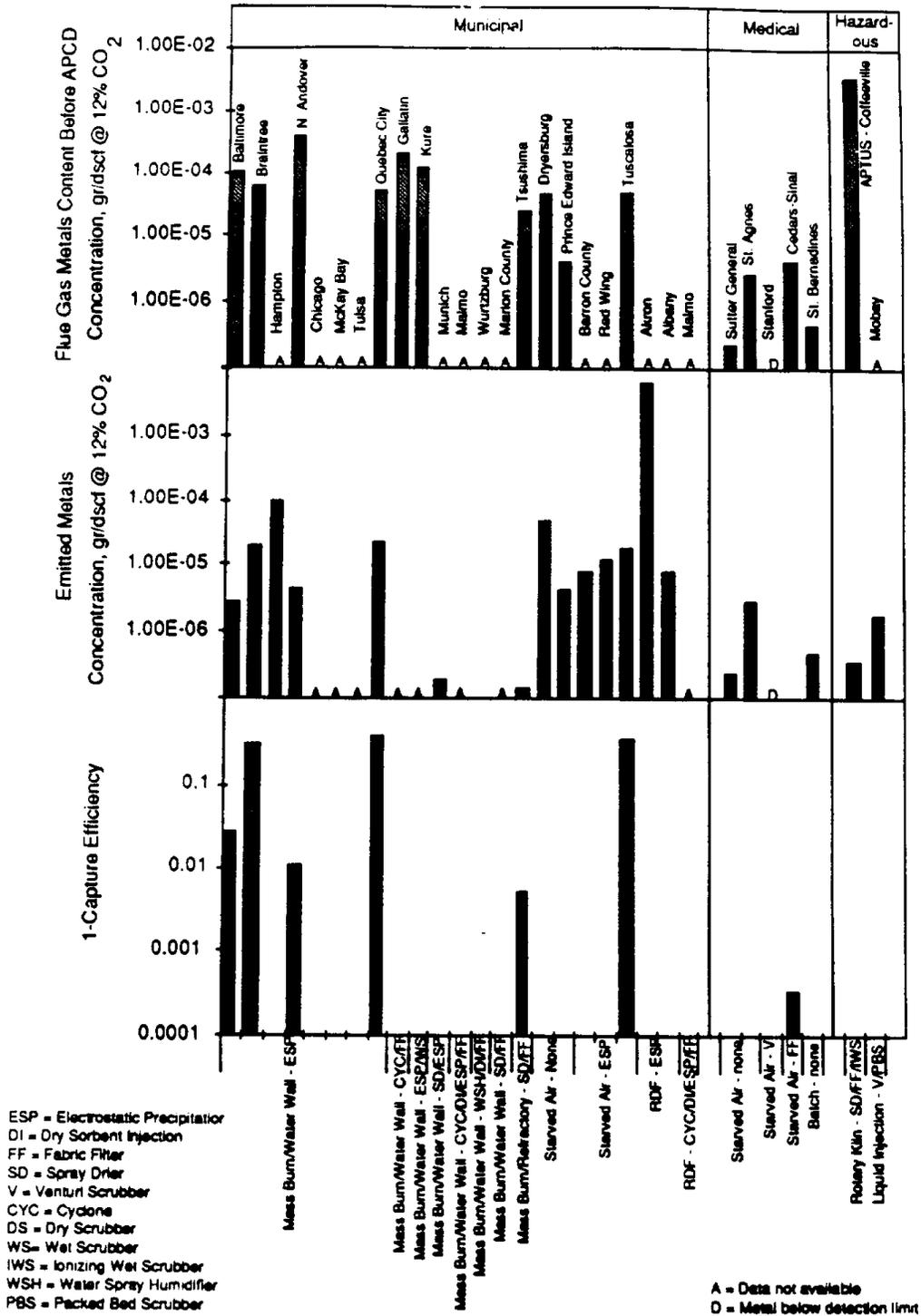
As shown in Figure 72, metals emissions may take any one of many different pathways through an incinerator. Several mechanisms influence the path a given metal will take. These mechanisms, illustrated in Figure 78, are similar to those which control the behavior of metals in other types of combustion systems (68).

The inorganic portion of the waste contains most metals and metal species (69). Most of the inorganic material remains inert during incineration and forms ash particles (70). A small fraction of the ash is entrained by the combustion gases (fly ash) while the rest stays in the combustion chamber (residual or bottom ash). The quantity of material entrained depends on the size, shape, and density of the ash particles as well as the incinerator operating conditions (71). The entrained particles can range in size from 1 μm to over 50 μm . However, they are usually less than 20 μm in diameter (72,73).

Some metals and metal species found in waste materials are volatile and will evaporate at the conditions found in the incinerator (74). The vapors are carried away from the waste by the exhaust gas and recondense as the gas cools. The vapors condense both homogeneously to form new particles and heterogeneously on the surfaces of existing fly ash particles (75). Homogeneous condensation produces particles much less than 1 μm in diameter (76). Heterogeneous condensation also tends to favor small particles because of their higher unit surface area (surface area/unit mass). Thus, the small entrained particles have higher concentrations of volatile metals than large particles or the original waste (69).

Metals may exhibit a third type of behavior during the combustion of waste materials. A high temperature, reducing environment can be created near the burning waste even when the incinerator is operated at an overall excess air condition (70). The exact conditions in this area depend on the physical

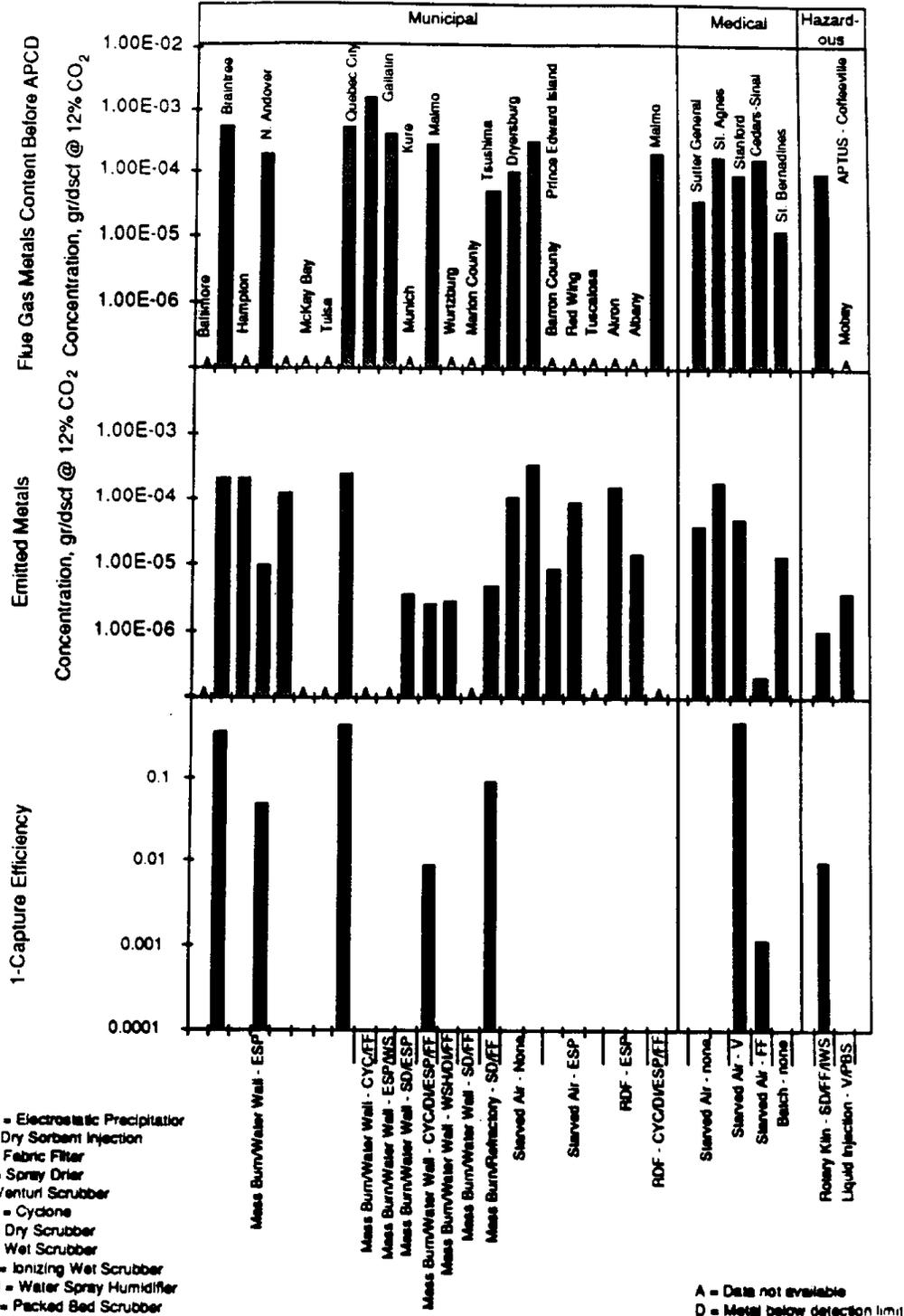
Arsenic



1 gridsct = 2.29 g/Ncm

Figure 73. Data on arsenic emissions from a variety of incinerators.

Cadmium



1 gr/dscf = 2.29 g/Ncm

Figure 74. Data on cadmium emissions from a variety of incinerators.

Chromium

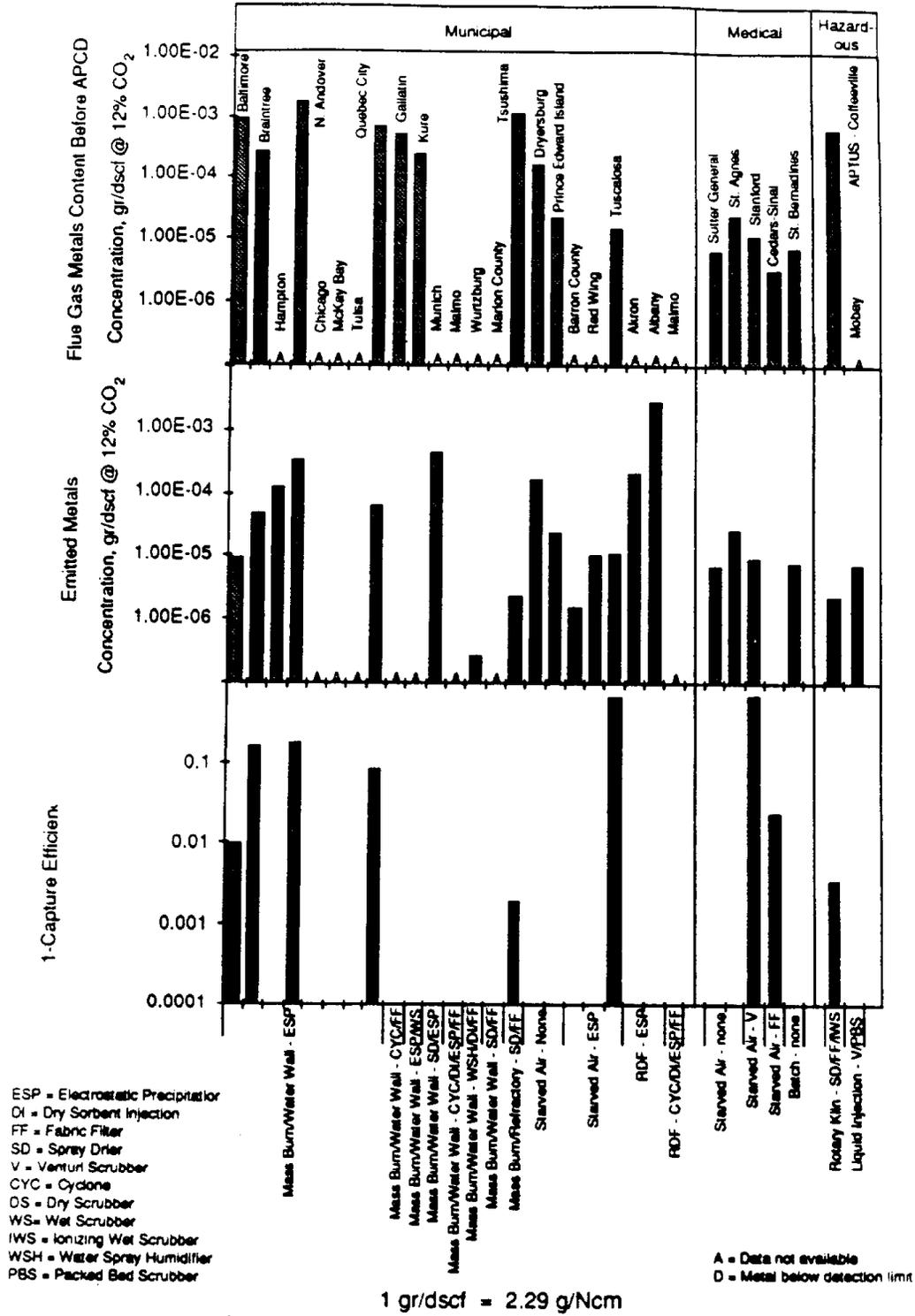
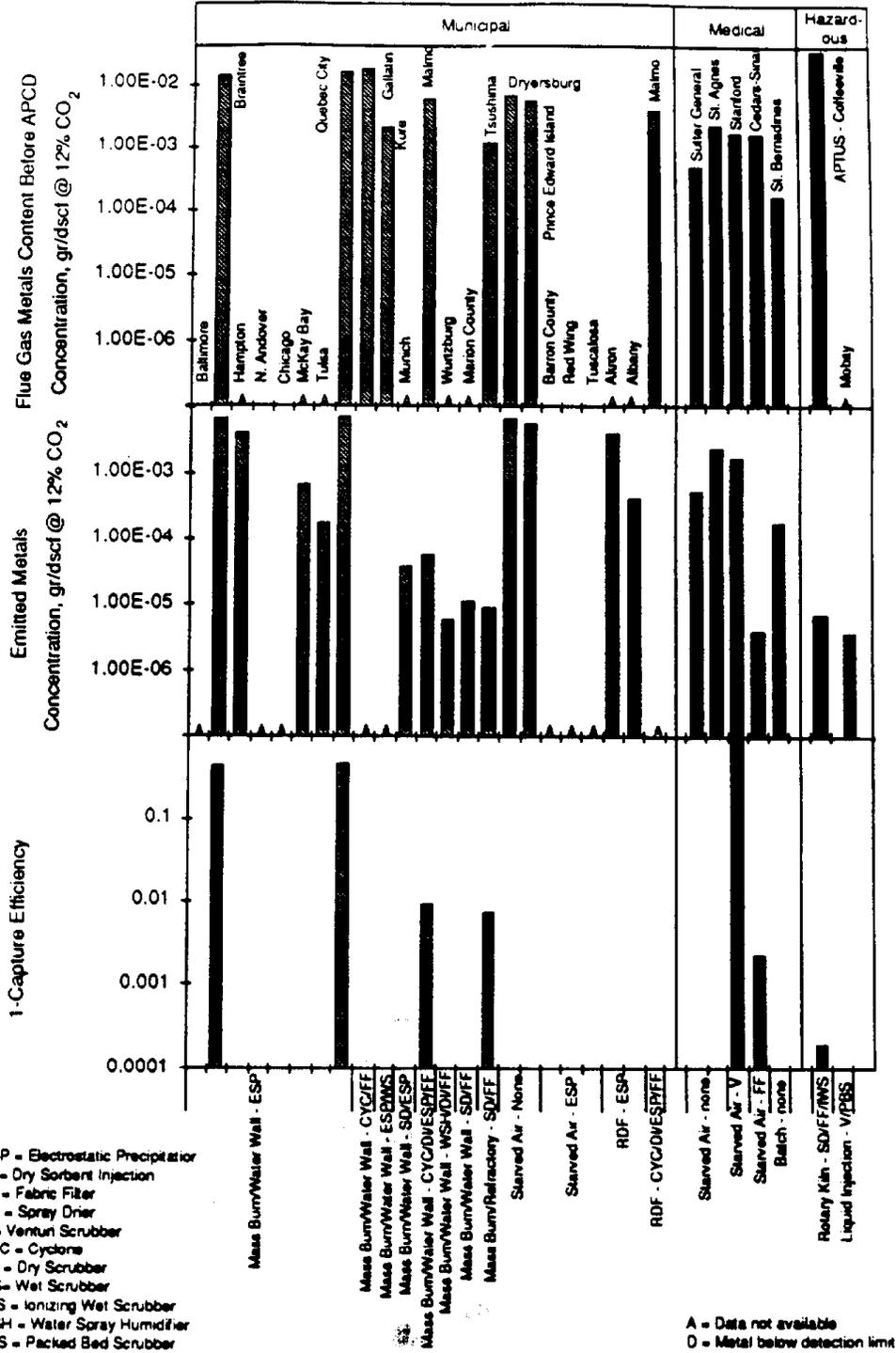


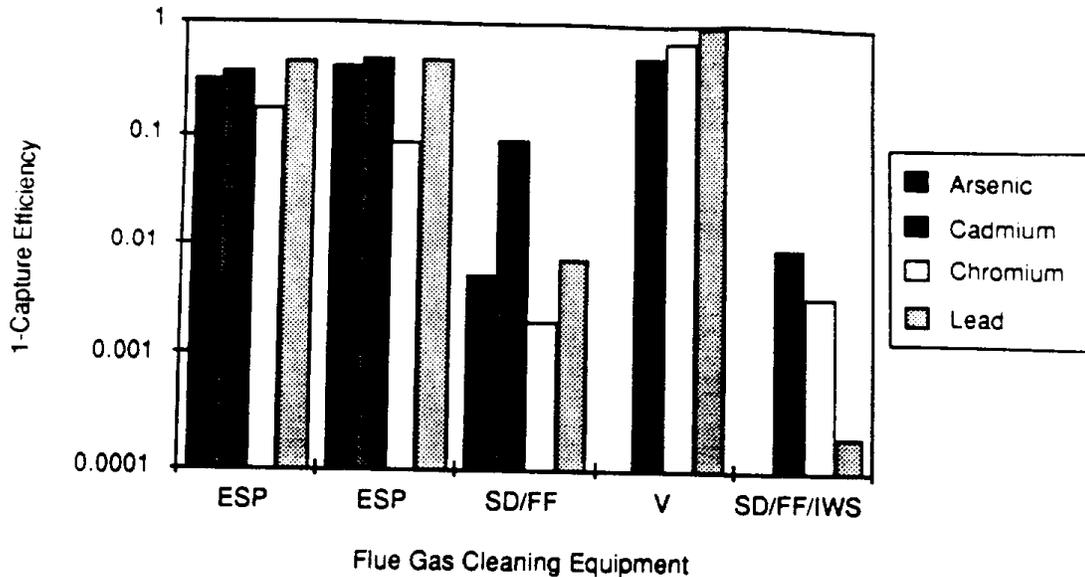
Figure 75. Data on chromium emissions from a variety of incinerators.

Lead



1 gr/dscf = 2.29 g/Ncm

Figure 76. Data on lead emissions from a variety of incinerators.



ESP = Electrostatic precipitator
SD/FF = Spray drier-fabric filter
V = Venturi scrubber
SD/FF/IWS = Spray drier, fabric filter and ionizing wet scrubber

Figure 77. Metals capture efficiency of various air pollution control systems.

characteristics of the waste and the configuration and operation of the incinerator. Under these conditions, some metal species react to form new compounds such as metal chlorides, fluorides, and reduced species. These new compounds are often more volatile than the original species and therefore, vaporize. Once the vapors move away from the waste and encounter the lower temperatures and higher oxygen concentrations found in the exhaust gases, they may undergo secondary reactions, convert back to their original form and condense (77). This condensation is mainly homogeneous.

In the second set of reactions, some metals combine with elements in the waste such as chlorine. Again, the newly formed species may be more volatile than the original metal species. These newly formed volatile species may vaporize and join the exhaust gases. As the gas cools, the species will condense.

As the particles formed by homogeneous condensation and the entrained particles move through the incinerator, they collide both with one another and with the vessel's walls. Often, the colliding particles stick together and form a single larger particle. Similarly, many particles which collide with the walls stick to them and are removed.

Barton et al. (78) summarized four key variables affecting the vaporization of metals. The variables are:

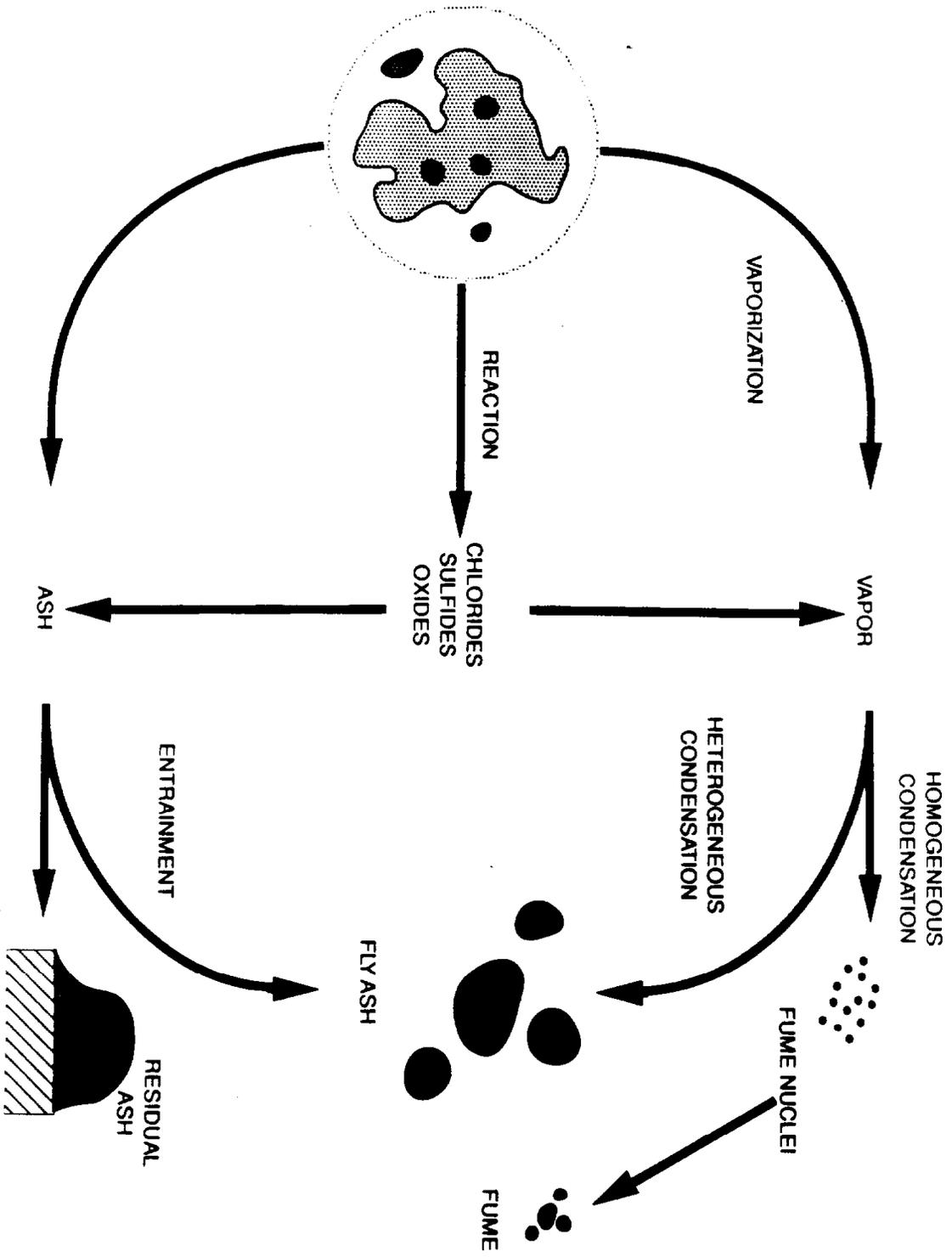


Figure 78. Transformation of mineral matter during combustion of metals-containing waste.

- Chlorine concentration in the waste
- Temperature profiles in the incinerator
- Metal species concentration in the waste
- Local oxygen concentration

The escape of metals on entrained particles would be controlled by

- Primary zone gas velocities
- Metals concentration in waste.

CURRENT CONTROL PRACTICE

Two strategies are used to minimize metals emissions. First, the primary chamber is operated at conditions which do not promote vaporization or entrainment of metals. Second, any metals which do escape are captured in the air pollution control device, if present. The parameters usually used to control the escape of metals from the primary chamber are the primary chamber temperature and gas velocity. The key air pollution control device parameters are specific to the device used.

COMBUSTION SYSTEM

Most operating hospital incinerators are simple, single-chamber units with an afterburner located in the stack. Figure 13 depicts the basic configuration of these units. The ability of batch incinerators to control metals emissions is limited because only the temperature in the stack is usually monitored. The incinerator at St. Bernadines Medical Center is typical of this design. Data indicate that metals emissions from St. Bernadines' incinerator are low (Figures 73 to 76) despite limited control capability. These low metals emissions probably result from the low temperatures and low gas flow rates in this unit.

As described earlier, most new incinerators are starved-air units. The primary chamber is designed to operate at low temperatures and low gas flow rates. This minimizes the amount of material entrained or vaporized.

To ensure that metals emissions are minimized, operators must maintain the primary chamber at the temperatures and gas flow rates for which it was designed. Usually, the only parameter that system operators can directly control is feed rate. High feed rates can lead to high temperatures and high gas velocities. Thus, many operators weigh the waste before placing it in the feed hopper. This enables them to carefully control the feed rate. The feed rate is reduced when primary temperatures increase.

AIR POLLUTION CONTROL EQUIPMENT

When they reach the air pollution control device, metals are present in one of three forms. Non-volatile metals are on large entrained particles. Metals which have vaporized and recondensed are present on fume particles with diameters less than 1 μm . Extremely volatile metals will be present as vapors. Table 23 summarizes the ability of common flue gas cleaning systems to control these different metals forms (66). The table is based on data and worst case case predictions.

Wet scrubbers may be used to reduce the temperature of the flue gases. Low temperatures ensure that all metal vapors have condensed. As indicated in Table 23, vapors are more difficult to capture than particles.

TABLE 23. TYPICAL AIR POLLUTION CONTROL DEVICE CONTROL EFFICIENCIES

APCD	Control Efficiency, %		
	Particulate	Fume	Vapor
Venturi Scrubber 20" Pressure Drop	90	85	60
Venturi Scrubber 60" Pressure Drop	98	97	90
Fabric Filter	95	90	50
Spray Dryer/Fabric Filter	99	95	90

ANALYSIS OF CONTROL PROCEDURES

The key control features are:

- Low primary temperatures
- Low entrainment velocities
- Low air pollution control device temperatures

The affect of operating conditions can be estimated with the EPA's Metals Partitioning Model (78). The model was developed to simulate the phenomena illustrated in Figure 79. It consists of a group of computer models and analytical approaches. These models simulate the individual physical and chemical processes which occur in the incineration of metal-bearing wastes. The phenomena simulated by the complete model include:

- Heat transfer and temperature profiles
- Mass transfer
- Particle entrainment
- Metals reactions and vaporization
- Aerosol dynamics
 - Condensation
 - Coagulation
- Particle removal by air pollution control device
 - Electrostatic Precipitators
 - Cyclones
 - Fabric Filters (Baghouses)
 - Wet Scrubbers

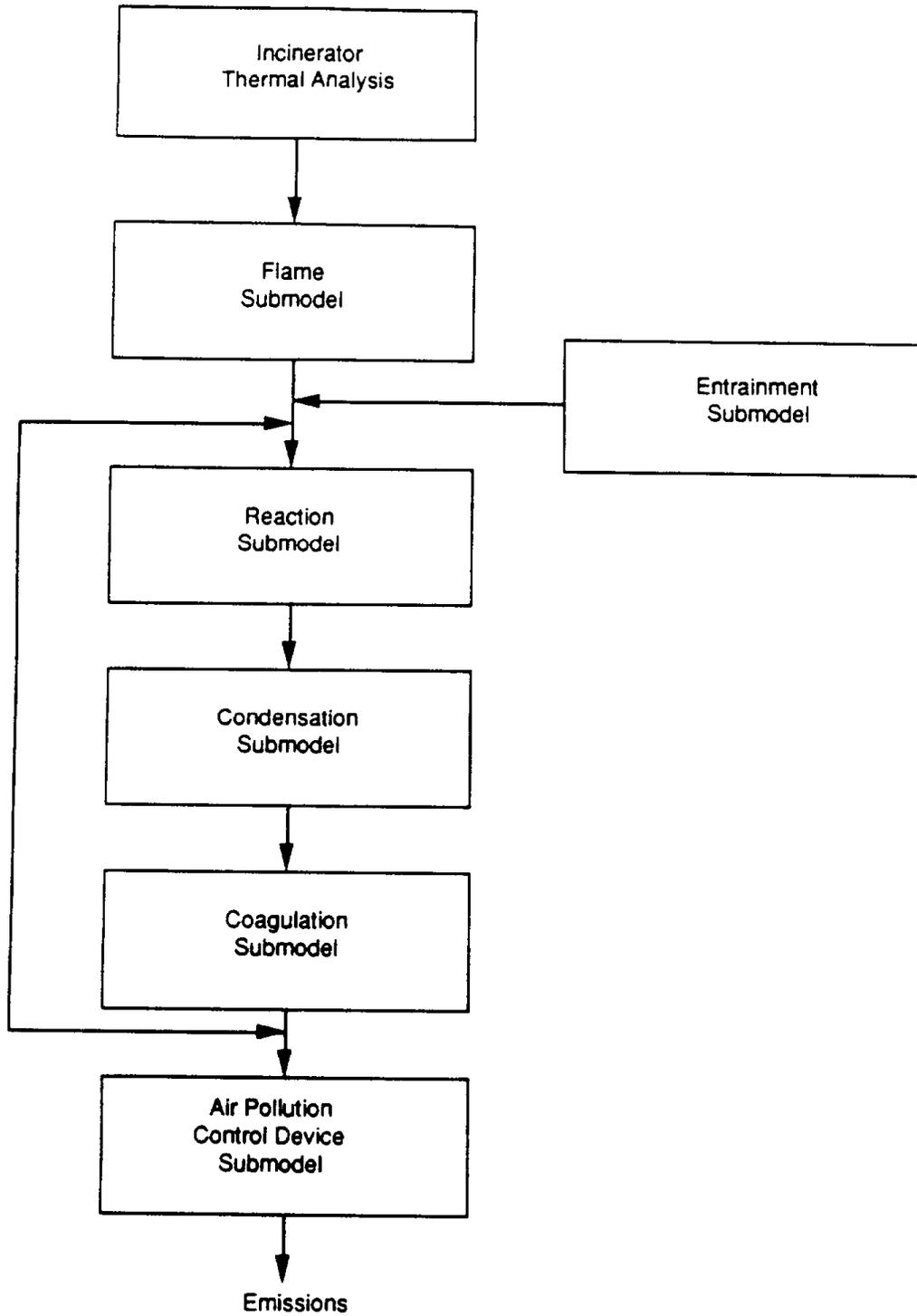


Figure 79. Metals partitioning model.

Table 24 lists the predicted "volatility temperatures" for ten toxic metals as a function of chlorine content in the waste. Volatility temperature is the temperature at which the combined vapor pressures of all species of a given metal that would be formed under given conditions is 10^{-4} atm. Volatility temperature is a more accurate indication of a metal's volatility than boiling point. As little as one-half of a percent chlorine in the waste drastically changes the volatility of lead and silver because of the affinity of these metals to form volatile chloride species.

TABLE 24. PREDICTED VOLATILITY TEMPERATURES OF SEVERAL TOXIC METALS AT VARIOUS WASTE CHLORINE CONCENTRATIONS

Metal	0% Cl		0.5% Cl		10% Cl		>0% Cl
	Temp., °F	Temp., K	Temp., °F	Temp., K	Temp., °F	Temp., K	
Lead	1160	900	5	260	5	260	PbCl ₄
Mercury	60	290	60	290	60	290	Hg
Arsenic	90	310	90	310	90	310	As ₂ O ₃
Thallium	280	410	280	410	280	410	TlOH
Cadmium	420	490	420	490	420	490	Cd
Silver	1660	1180	960	790	960	790	AgCl
Antimony	1220	930	1220	930	1220	930	Sb ₂ O ₃
Barium	1560	1120	1680	1190	1660	1190	BaCl ₂
Beryllium	2220	1490	2220	1490	1930	1330	Be(OH) ₂
Chromium	2930	1880	2930	1880	2930	1880	CrO ₂ Cl ₂ /CrO ₃

Figure 80 shows the effect of waste chlorine content and temperature on the volatility of chromium. Chromium is of particular interest because it is extremely carcinogenic in its hexavalent form. Chromium usually is not volatile. However, in the presence of chlorine, chromium will react to form chromium oxychloride which is extremely volatile. Chromium oxychloride formation is favored at low temperatures, high oxygen concentrations and high chlorine concentrations.

Figure 81 shows the affect of temperature on the vapor pressure of representative metals. Temperature has a dramatic impact on the vapor pressure of any metal. However, the temperature effect can only be seen over a narrow temperature range. For example, the vapor pressure of lead increases four orders of magnitude between 920 and 1140 K (1200°F and 1600°F). Above 1140 K (1600°F), the effect of temperature on vapor pressure decreases. Below 920 K (1200°F), so little lead vaporizes that changes in vapor pressure have no observable affect on lead vaporization.

Figure 82 shows the impact of stoichiometric ratio (ratio of oxygen available to oxygen theoretically required to completely oxidize the organic material in the waste) on metals' vapor pressure. The effect of

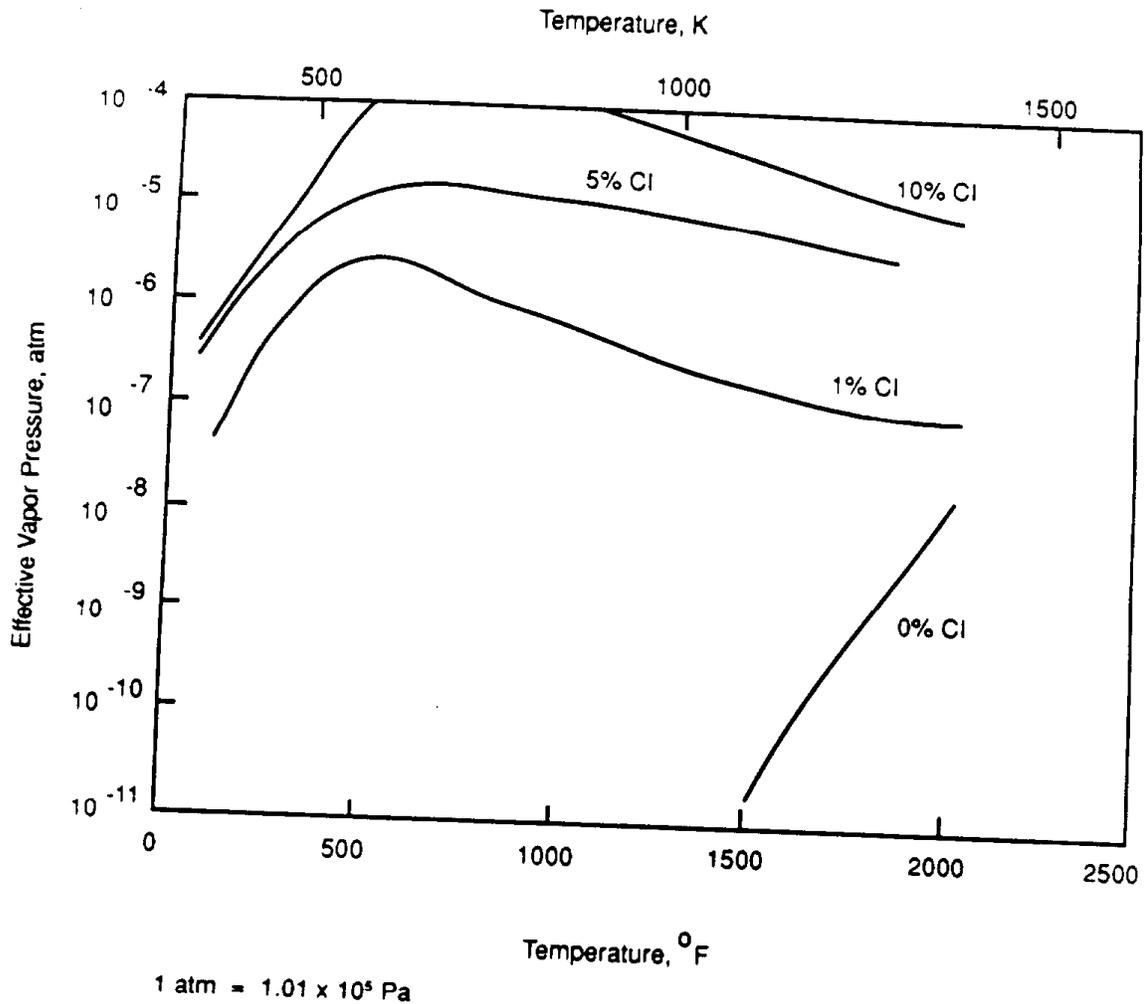


Figure 80. Chromium equilibrium vapor pressure at 7% O₂ as a function of waste chlorine content.

oxygen is strongly dependent on the metal of interest. However, oxygen concentration does not have as strong an effect on vapor pressure as temperature. Chromium behavior is of particular interest. At low stoichiometric ratios, chromium forms reduced species such as Cr and CrO. These species are more volatile than Cr₂O₃. Thus, at low stoichiometric ratios the effective volatility of chromium increases. At stoichiometric ratios around 0.6 to 1.0, Cr₂O₃ is favored. As the amount of oxygen increases beyond a stoichiometric ratio of 1.0, more CrO₃ begins to form. CrO₃ is also more volatile than Cr₂O₃. Thus, the effective vapor pressure begins to increase with stoichiometric ratio.

The effect of temperature, oxygen concentration and waste chlorine content on metals emissions from the incinerators studied by the California Air Resources Board was assessed. Metals concentrations in the flue gas showed no strong correlation with any of the characteristic operating temperatures (Figure 83). These

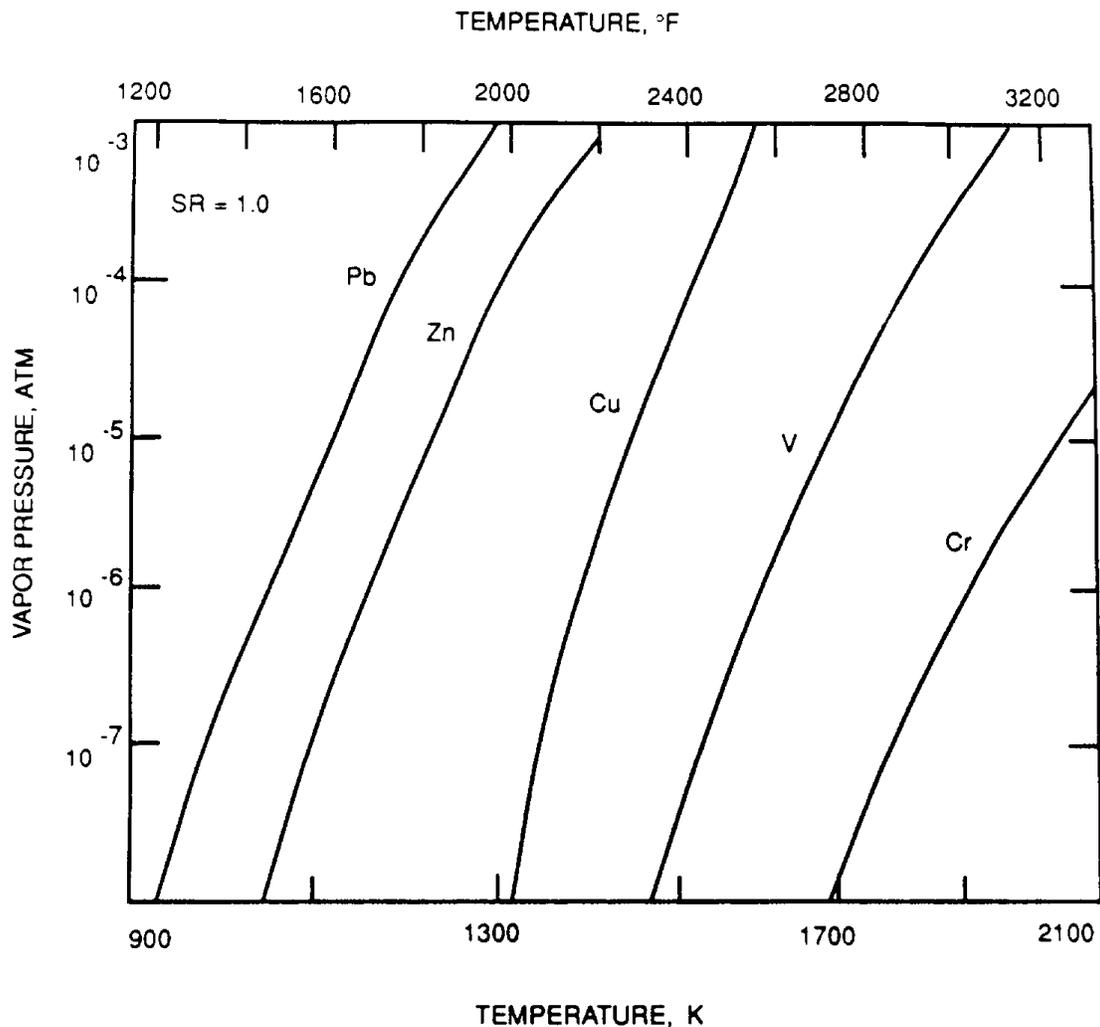


Figure 81. Metals vaporation increases sharply with temperature.

results do not contradict the current understanding of metals behavior. Arsenic, cadmium and lead should all be volatile at the incinerators' operating conditions. Little chromium would be expected to vaporize at temperature less than 1700 K (2600°F). Thus, no change in behavior would be expected for the range of temperatures at which the tested incinerators operate [920-1370 K (1200-2000°F)]. However, care must be taken in analyzing this data. The information was obtained from a variety of incinerators. Thus, some trends may be obscured by variations in feed composition and incinerator design and operation.

The metal concentrations in the flue gas from the medical waste incinerators showed no direct correlation with the flue gas particulate matter concentrations (Figure 84). This is partially consistent with current theory. Arsenic, cadmium and lead would be expected to vaporize. Thus, the emissions of these

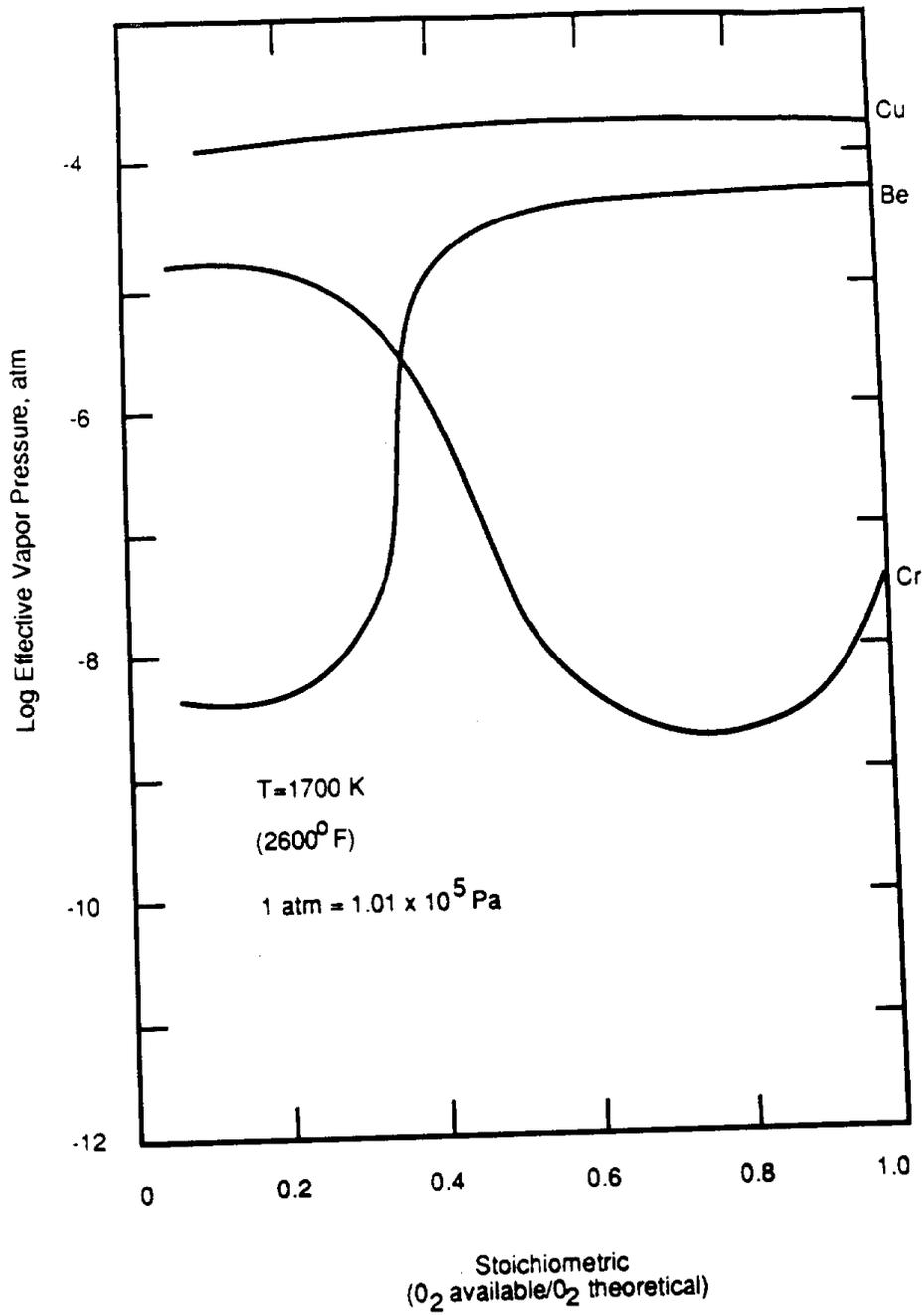


Figure 82. The volatility of representative metals as a function of oxygen concentration.

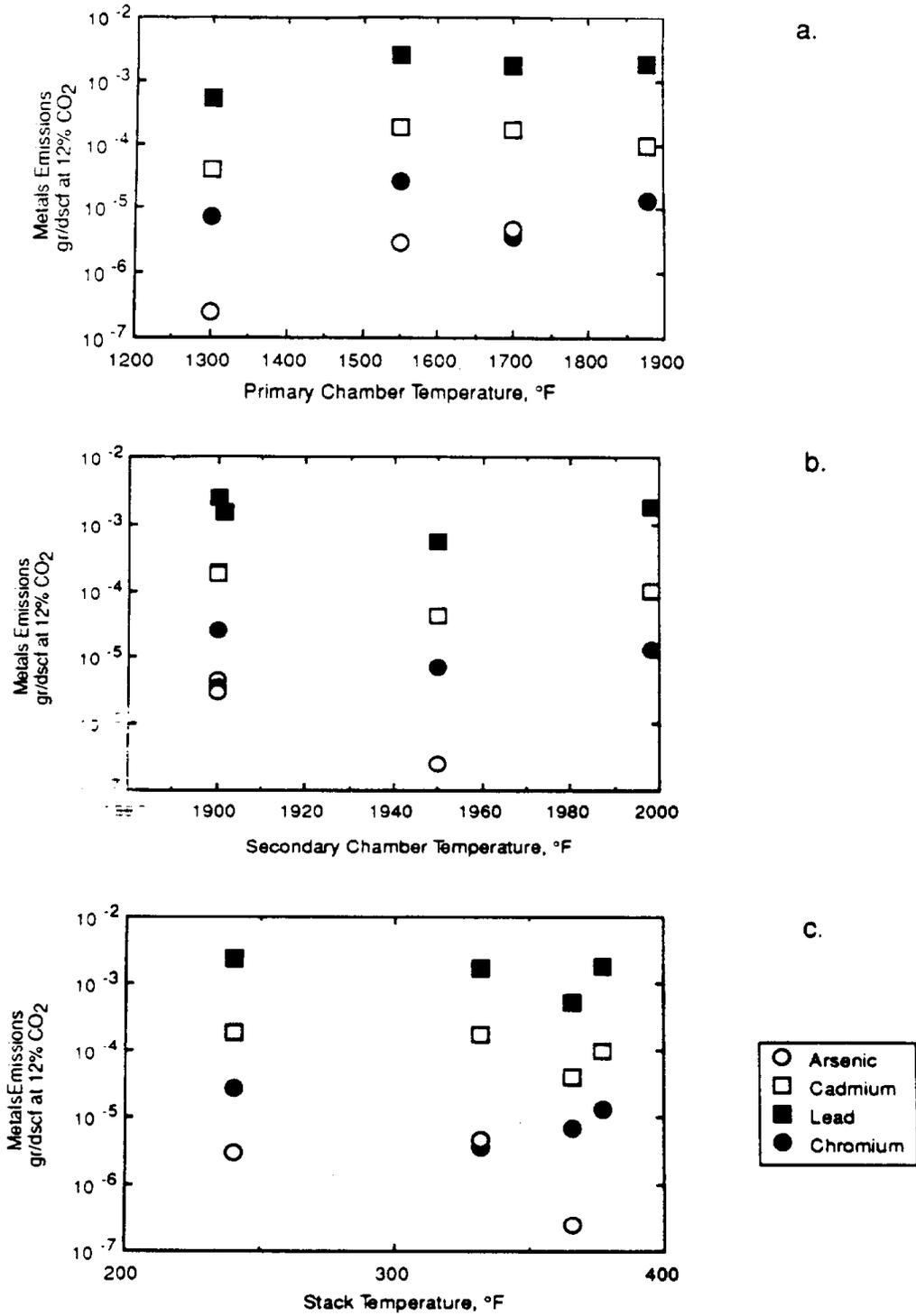


Figure 83. The relationship between operating temperatures and metals emissions in CARB tests.

metals would not be expected to be related to the entrainment of particles. Chromium, in contrast, should be related to particulate emissions. A slight relationship can be observed in Figure 84. However, the trend may be obscured because of the low concentrations of chromium present.

One other aspect of the data obtained by the California Air Resources Board warrants close examination. The fabric filter at Cedars-Sinai is very effective at capturing most metals. However, unexpectedly large amounts of chromium are found in the emissions. One possible explanation for this behavior illustrates the complexity of the interactions which control metals behavior. Chromium was probably present as chromium oxide (Cr_2O_3) on the fly ash particles. These particles were effectively captured by the fabric filter. As the particles were held on the filter, the gas passing through contains HCl and O_2 . The filter temperature was about 330°F. Under these conditions, the chromium oxide would react with the HCl to form chromium oxychloride. Chromium oxychloride is very volatile and could vaporize and exit the stack.

ADDITIONAL INFORMATION NEEDED

Data from operating medical waste facilities are needed. Specifically, data which represent a wide range of potential incinerator operating conditions would provide significant insight into metals behavior. The data should include the types and quantities of waste fed, standardized metals emissions, and ash analyses that include the same metals considered for the stack emissions. Although thorough medical waste characterization is desirable, it is recognized that this is not generally possible.

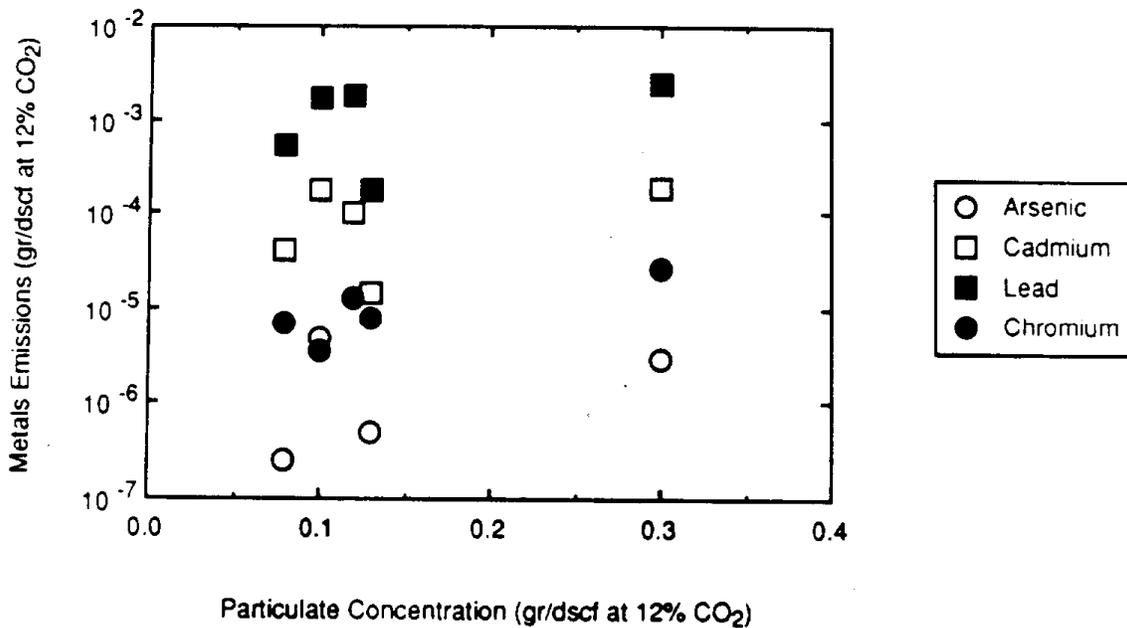


Figure 84. Concentrations of metals versus particulates in the flue gas for the medical waste incinerators tested by California Air Resources Board.

To overcome this inability to adequately characterize the waste, test burns can be performed with medical waste that has been spiked with known concentrations of toxic metals. Concentrations of these metals would be measured in all effluent streams to determine their distribution as a function of operating conditions. The distributions of the spiked metals could be used to predict the distributions of metals that would be expected to act similar to the spiked metals. A better understanding of the effect of operating conditions on metals emissions could be gained and applied to medical waste incinerator designs.

SECTION 11

CYTOTOXIC COMPOUNDS

Cytotoxic chemicals are substances capable of impairing, injuring, or killing cells. These hazardous pharmaceuticals are used in chemotherapy. Because of the acute nature of the hazards associated with these compounds, the goal is complete destruction.

POLLUTANT CHARACTERISTICS

Cytotoxic chemicals cause cell mutations, cancer, and birth defects. Seven cytotoxic compounds are on the RCRA "U" list and are considered hazardous wastes. These seven compounds should not be present in bulk quantities fed to medical waste incinerators unless the facility is RCRA-permitted. However, it is legal to dispose of contaminated containers with general medical waste if they contain less than 3 percent of their capacity by weight. Medical facilities, for example, need not dispose of spent syringes and empty containers as hazardous wastes. In addition, the seven RCRA-listed compounds are only a small fraction of all cytotoxic agents. Those agents not RCRA-listed can be incinerated without a RCRA hazardous waste incinerator permit.

Most cytotoxic compounds are similar in structure, mode of action, and toxicity (79). Figure 85 shows the structures of some of these compounds. Most of the structural similarity lies with the functional groups. Table 25 summarizes selected physical data for the seven listed cytotoxic compounds. In this context, both T_{99} and heat of combustion are criteria used to express the ease with which the compound can be burned. T_{99} is the temperature needed for 99 percent destruction at a two-second gas residence time and substoichiometric conditions. Oxygen-starved conditions were chosen for this ranking because theoretical considerations indicate that local oxygen-deficient conditions are primarily responsible for trace organic emissions (3,80).

The heat of combustion method assumes that the ease at which a compound burns relates directly to the amount of heat released from the combustion of one gram of compound. However, there is little theoretical or experimental data that correlate heat of combustion with destruction efficiency.

AVAILABLE DATABASE

No data on the emissions of cytotoxic compounds are available. There are some limited data and some evaluations on the ease with which cytotoxic compounds are destroyed. Many hospitals feel that incinerators do not effectively destroy these compounds at temperatures below 1260 K (1800°F) (81). If a medical facility uses an onsite incinerator to destroy cytotoxic wastes, the National Institute of Health recommends operating temperatures of 1260 K (1800°F) or higher and residence times of 2 seconds (11). However, data compiled by the University of Dayton Research Institute indicate that extreme temperatures are not needed to destroy cytotoxic materials (3, 50). These data will be discussed below.

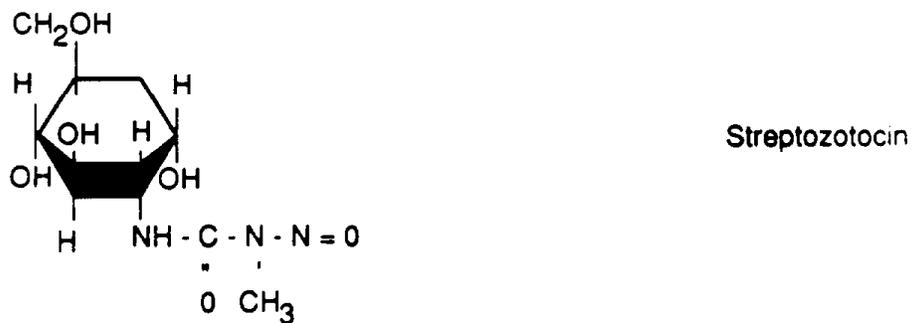
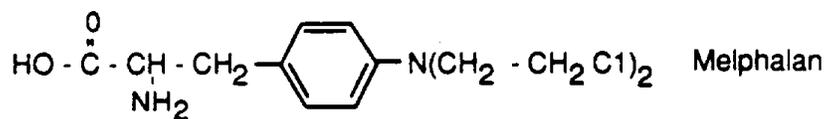
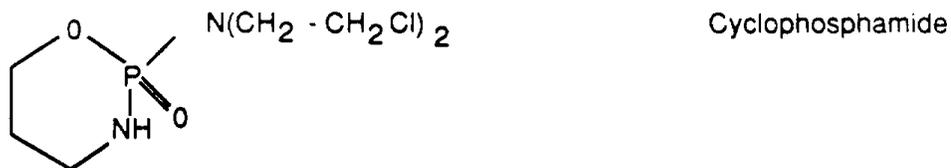
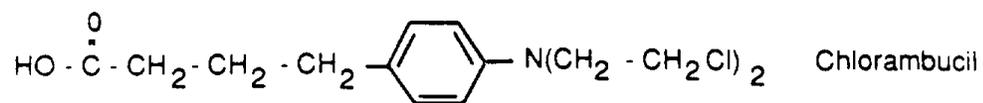


Figure 85. Chemical structures of 5 RCRA-listed cytotoxic compounds.

TABLE 25. PHYSICAL DATA FOR CYTOTOXIC COMPOUNDS ON THE RCRA "U" LIST.

Compound	Melting Point		Heat of Comb. (kcal/gram)	T99 Range	
	(°F)	(K)		(°F)	(K)
Chlorambucil	147-151		5.93	1247-1184	948-893
Cyclophosphamide	106-113	314-318		3.97	
Duanamycin				5.70	
Melphalan	360-361	455-456	5.21	1247-1184	948-893
Mitomycin					
Streptozotocin	239	388		464-212	513-373
Uracil Mustard	403	479	4.00	464-212	513-373

POTENTIAL ESCAPE MECHANISMS

Cytotoxic compounds follow the same potential escape pathways as pathogens and other organic compounds. These pathways were discussed previously. Briefly, organics escape complete combustion because of poor mixing, low temperatures, and short residence times.

CONTROL PRACTICE

DESIGN

Incinerator manufacturers do not specifically consider cytotoxic compounds when designing equipment. The design features which ensure organic and pathogen destruction are assumed to ensure the destruction of cytotoxic compounds. These features were described previously.

OPERATION

The principal concern of incinerator operators is the safe handling of the cytotoxic materials. Because of the dangerous and insidious nature of the materials, it is essential that they be prevented from spilling or from forming an aerosol.

ANALYSIS OF CONTROL PRACTICE

Available thermal decomposition data show that cytotoxic compounds should not be difficult to destroy compared with other species studied to date. Chlorambucil has the highest characteristic decomposition temperature (T_{99}), and it is in Class 5 out of 10 classes which rank ease of destruction (3, 50). More common compounds in the same class in terms of ease of destruction as chlorambucil include ethylene dichloride and pentachlorophenol. The PCDD/PCDF precursors shown in Figure 63 are ranked in Class 1. Thus, based on the destructibility ranking, cytotoxic compounds are much easier to destroy than the potential PCDD/PCDF precursors. This indicates that a temperature of 1170 K (1650°F) (the temperature found adequate in these controlled laboratory experiments to ensure 99 percent destruction of PCDD/PCDF precursors) should also be sufficient for 99 percent destruction of cytotoxic materials.

ADDITIONAL INFORMATION NEEDED

Researchers have not studied the fate of cytotoxic agents released into the environment (79). In addition, data on the total amounts of cytotoxic compounds incinerated are not available. This information is needed to assess the potential threat of cytotoxic emissions.

The conditions needed to destroy cytotoxic compounds are currently not well defined. Preliminary data from University of Dayton Research Institute indicate that temperatures less than 1170 K (1650°F) are needed if residence time of 2 seconds is maintained. However, these data are based mainly on theoretical considerations and must be confirmed experimentally. Until destruction data are available, cytotoxic waste generators must use very conservative assumptions. The recommendations of 1260 K (1800°F) for a minimum temperature may be excessively conservative, but more field data are needed to more definitely identify minimum operating temperatures.

SECTION 12

RADIOACTIVE MATERIALS

Low-level radioactive waste is sometimes present in medical waste. As with other components of medical waste, it is difficult to estimate the quantities of low-level radioactive wastes generated at medical facilities. The U.S. Food and Drug Administration estimates that more than 7 million radiopharmaceuticals are administered, 11 million nuclear medicine procedures are performed, and 100 million radio-immunology procedures are performed as in-vitro diagnostic studies yearly in the U.S. (14). Each of these procedures generates radioactive wastes, however the actual quantities that end up with the general medical waste or segregated as low-level radioactive waste has not been adequately determined.

CHARACTERISTICS OF POLLUTANTS

Low-level radioactive waste (<100 $\mu\text{Ci/g}$) (13) consists of slightly radioactive materials and materials contaminated by contact with radioactive substances. The most common radionuclides used for medical purposes are tritium, ^{32}P , ^{125}I , ^{131}I , and ^{14}C . All except tritium and ^{14}C have short half-lives (82).

The Nuclear Regulatory Commission requires that low-level radioactive medical waste be disinfected before shipment to a radioactive waste storage facility. Costs for shipment and storage of low-level radioactive waste range from \$10,600-\$35,300/ m^3 (\$300-1000/ ft^3). The Nuclear Regulatory Commission approves of low-level radioactive waste incineration with adequate atmospheric dilution of the stack gases. The Nuclear Regulatory Commission has deregulated some wastes such as animal carcasses with less than 0.05 microcuries of tritium or ^{14}C per gram. Incineration of this deregulated waste is an important alternative to landfilling. This is fortunate because hazardous waste landfill operators are becoming reluctant to accept low-level radioactive wastes (11).

AVAILABLE DATABASE

Radioactive emissions from medical waste incinerators have not been measured. However, emissions from incinerators dedicated to burning low-level radioactive wastes have been studied. The results from these studies indicate the effectiveness of incinerating radioactive wastes. Incinerators which only burn low-level radioactive wastes usually use starved air combustion and high efficiency particulate matter control.

POTENTIAL ESCAPE MECHANISMS

Radioactive materials behave like their non-radioactive counterparts. Thus, the fate of incinerated low-level radioactive waste depends on factors such as operating chamber temperature, air volumetric flow rate and velocity, extent of combustion, chemical and physical form of the waste, and the elements involved (82). Metallic radioisotopes follow the emissions pathways described previously for toxic metals. Tritium- and ^{14}C -containing organic compounds will behave like other organic compounds.

As expected, radioisotopes of carbon, hydrogen, and sulfur were essentially all oxidized in the studies mentioned above. Iodine is very volatile and was expected to completely vaporize in the incineration chamber. This agrees with the experimental data in which little or no radioactive iodine was detected in residual ash.

CURRENT CONTROL PRACTICE

Radioactivity cannot be altered by incineration. Incineration provides a means of transforming as much of the low-level radioactive waste as possible into the gaseous state. The gases are easily dispersed and diluted. The residual ash will retain some radioactive material. However, the ash is the result of a large reduction in the volume, weight, and general radioactivity of the initial low-level radioactive waste. To ensure maximum dispersion of radioactive substances, it is necessary to completely oxidize all combustible material in the ash.

Radioactive emissions may have to be controlled beyond simple dispersion. Local restrictions usually limit radioactive emissions to 100 microcuries per cubic meter daily volume (82). Activated carbon absorbers have been used with HEPA filters to control volatile radioactive emissions. Radioactive isotopes of iodine are major radioactive contaminants in medical waste and are extremely volatile. Systems designed to control iodine will also be effective at controlling many other contaminants, including dioxins and furans (83).

ANALYSIS OF CONTROL PRACTICE

The main goal when incinerating most low-level radioactive waste is to ensure complete ash burnout and maximum dispersion and dilution of combustion products. Dispersion of the combustion products is dependent on the location of the facility and the height of the stack. These parameters cannot be changed without significant difficulty. The factors controlling the oxidation of combustible material in the ash were discussed previously.

Incinerators dedicated to burning low-level radioactive waste have used highly efficient particulate capture methods to prevent emissions that can cause local radiation levels to exceed regulations. Similar measures may not be necessary for general medical waste incinerators because of significantly lower concentrations of radioactive material in these wastes.

ADDITIONAL INFORMATION NEEDED

Essentially all data on the behavior of radioactive materials during incineration have come from incinerators which burn only low-level radioactive waste. These units use state-of-the-art technologies and are operated by government agencies with extreme caution. Most medical waste incinerator operators do not have the resources to meet similar standards. Furthermore, medical wastes contain only small amounts of radioactive material. Radioactive emissions from medical waste incinerators will depend mainly on the concentrations of radioactive substances in the medical waste, particulate capture, and the dispersion characteristics at the stack. To assess the effects of radioactive emissions from incinerating medical waste, information is needed on the effectiveness of dispersion (local dispersion and dilution limits) and the typical radioactive content of medical waste. Field testing of the emission levels of radioactive content of emissions may provide some insight into the potential importance of radioactive materials which find their way into the general medical waste incinerator.

SECTION 13

PARTICULATE EMISSIONS

Medical waste incinerators may emit entrained particles of ash and soot. Particulate matter is a criteria pollutant and has many undesirable effects. These include simple soiling of objects, reduction of atmospheric visibility, and penetration of the human pulmonary system. Particles smaller than $1\ \mu\text{m}$ are of special concern even though they represent only a small fraction of the total weight of particulate matter emitted.

CHARACTERISTICS OF POLLUTANTS

Combustion gases will entrain a fraction of the ash in an incinerator. The entrained particles are carried out of the primary combustion chamber and through the rest of the system. This entrained ash is commonly known as fly ash. Fly ash consists of silica, alumina, and sulfates, combined with metals, acids, trace organics, and unburned carbon.

The fly ash produced by medical waste incinerators has not been examined in detail. Thus, it is necessary to turn to data from other types of combustion equipment to gain an understanding of fly ash characteristics. While the materials burned in other types of combustion equipment may be very different than medical waste, the phenomena which occur will be similar. Studies show that the particle composition varies as a function of particle size. The smallest particles contain much higher concentrations of volatile metals than larger particles. In addition, the composition of the smallest particles varies from location to location within the incinerator. The core consists mainly of the least volatile metals in the waste and successive layers contain progressively more volatile components.

Because the small particles contain high concentrations of toxic volatile metals they can represent a significant threat to human health. Particles with diameters around $1\ \mu\text{m}$ are deposited deep within the lungs when inhaled. The toxic metals on the particles are then in close contact with the blood supply (84). APCDs are often inefficient at capturing these tiny particles.

The fly ash particle size distribution is a complex function of operating variables. Important variables include feed size and ash content, ash composition, gas flow rates, and temperatures. The particle size distribution is often assumed to resemble a log normal distribution with respect to mass fraction. Field measurements indicate that the median size of fly ash particles in medical waste incinerators is $2\ \mu\text{m}$ (85). Fly ash particle size distribution data obtained from two municipal waste combustion facilities indicate mass median aerodynamic particle diameters of about 1.2 and $7.1\ \mu\text{m}$ (86).

Soot particles are formed by gas phase processes involving the volatile matter evolved from the waste during pyrolysis. Local oxygen deficiencies associated with flame fronts allow the gases to form condensed rings of carbon. Soot particles range in size from about 100 to 2000 angstroms (0.01 - $0.2\ \mu\text{m}$). The properties of soot particles are not sensitive to fuel or flame type. However, the extent of soot formation is drastically reduced by increased flame turbulence.

AVAILABLE DATABASE

Figure 86 compares particulate concentrations in the flue gases before any air pollution control device in medical waste, hazardous waste and municipal waste incinerators. The concentration of particles in the incinerator flue gas is much lower in starved-air incinerators than in any other type of device. Figure 87 compares the controlled particulate emissions from medical waste, hazardous waste and municipal waste incinerators. These values include the impact of the air pollution control device. As shown, air pollution control devices reduce particle concentrations by as much as two orders of magnitude. Figure 88 compares particle capture efficiencies. Fabric filters consistently had the highest particle capture efficiencies. ESP efficiencies were usually comparable with fabric filter efficiencies. The Tuscaloosa ESP efficiency is not typical. This unit was designed to have a 50 percent capture efficiency. The wet scrubber at Stanford showed low, variable capture efficiencies.

Table 26 summarizes particulate emissions data obtained by a medical waste incinerator manufacturer. Two different incinerators were used to burn similar medical waste (87). The first incinerator was a batch unit consisting of a primary and secondary chamber. The incinerator was operated with excess air in the primary chamber and was not equipped with any flue gas cleaning equipment. The second incinerator was a larger, reciprocating grate unit which was equipped with a wet scrubber. The batch unit produced lower particulate matter concentrations than the larger unit which was continuously fed and equipped with a venturi scrubber system.

Emissions data are available from other medical waste incinerators, but no reference flue gas oxygen or carbon dioxide concentrations were specified. Converting these data to 12 percent CO₂ may alter their value by a factor of two or more. Table 27 summarizes these data (88).

POTENTIAL ESCAPE MECHANISMS

Solid matter exits an incineration system as bottom ash, atmospheric particles, or as air pollution control device residue. For units without an air pollution control device, all particulate matter entrained in the flue gas is emitted from the stack. Emissions downstream of an air pollution control device depend on the operating conditions and design limitations of the air pollution control device. For solids to exit the stack, they must be entrained by the gas stream. Particle entrainment is promoted by high gas flow rates. A particle can be entrained if its terminal (falling) velocity is less than the opposing velocity component of the carrier gas stream. Small, light particles have low terminal velocities and are easy to entrain.

As discussed previously, venturi scrubbers require very high pressure drops to effectively capture particles less than two micrometers in diameter. Fly ash particles from starved air processes can have sufficient soot on their surface to render the particles hydrophobic if the secondary chamber is not effectively mixed. Hydrophobic particles are rejected by the scrubber spray water, allowing them to pass through, uncontrolled, to the scrubber outlet (23).

ESPs have slightly lower particle capture efficiencies for particles in the 0.1-10 micrometer size range than for both larger and smaller particles. The capture efficiency for these particles is usually 90-99 percent (compared to 99 percent+ for larger and smaller particles) depending on ESP design and fly ash characteristics. However, even if most of the submicron particles escape the air pollution control device, the overall particle capture efficiency may still be high because the submicron particles represent a small fraction by mass of the total fly ash generated.

Air pollution control device failure can result in significant emissions. Fabric filters can tear or catch on fire. Pressure drops across venturi scrubbers must be maintained to design specification. ESPs require minimum operating voltages. ESPs can have problems with "sneakage," in which particles bypass the electric

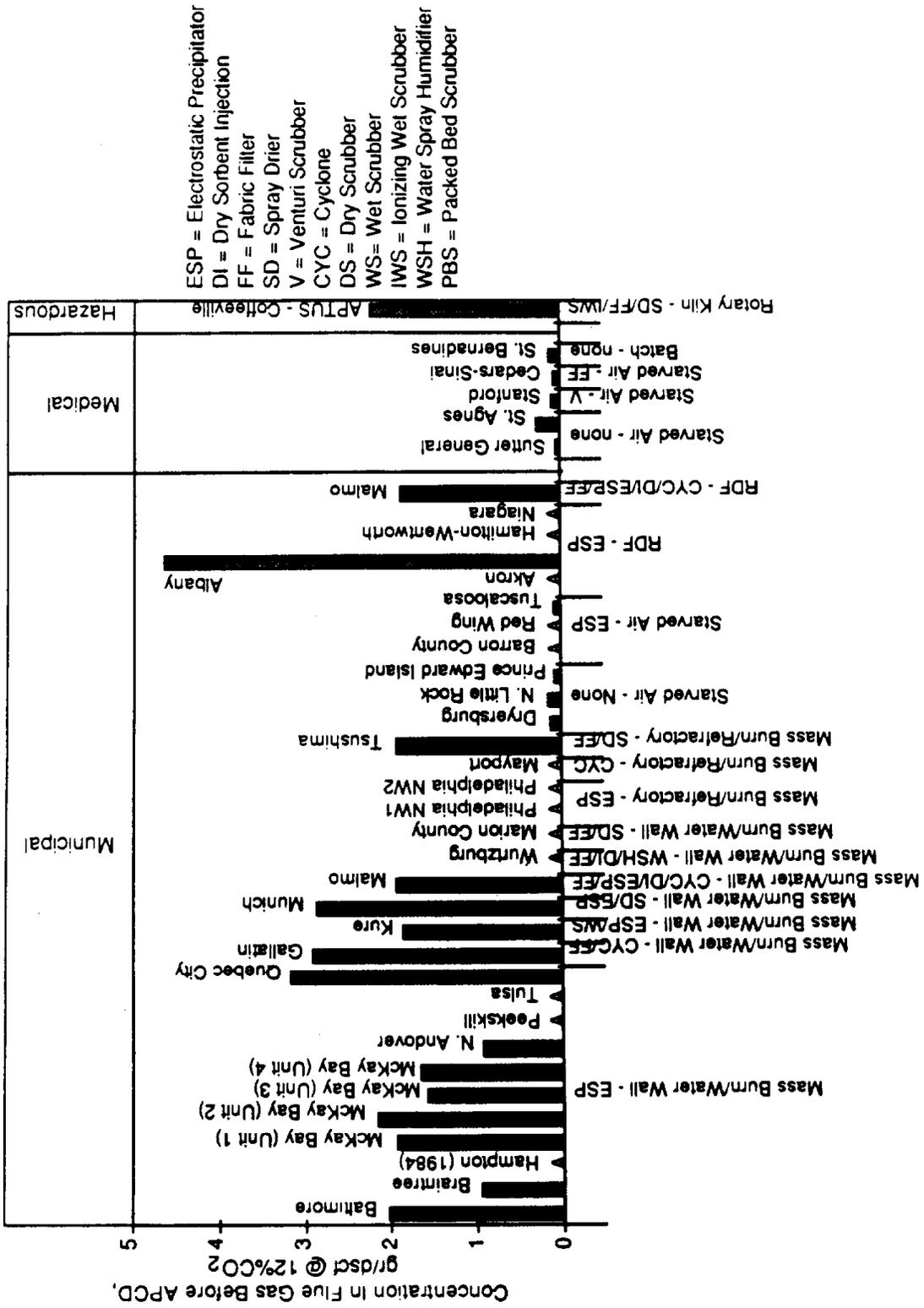


Figure 86. Flue gas particulate matter concentrations.

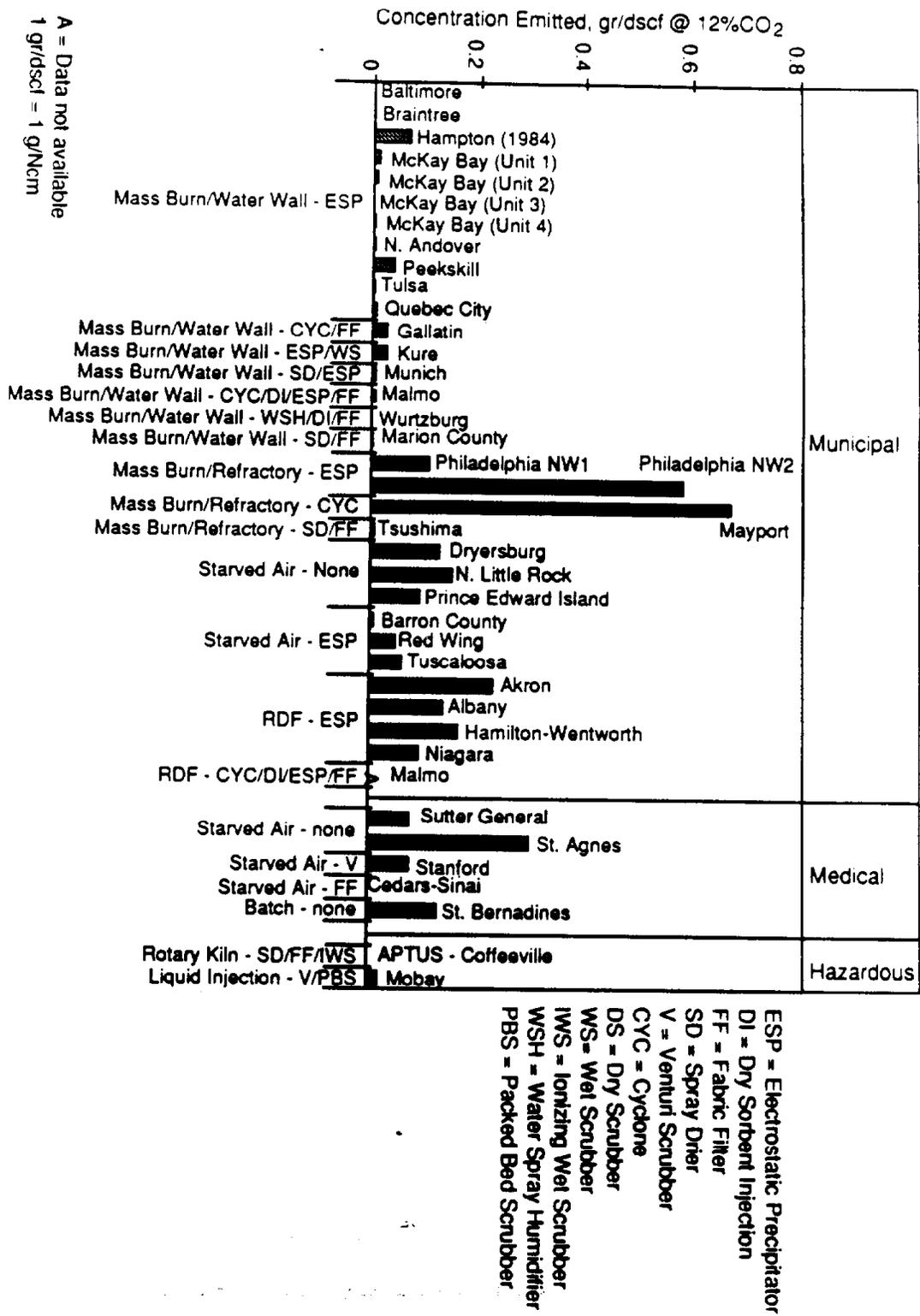
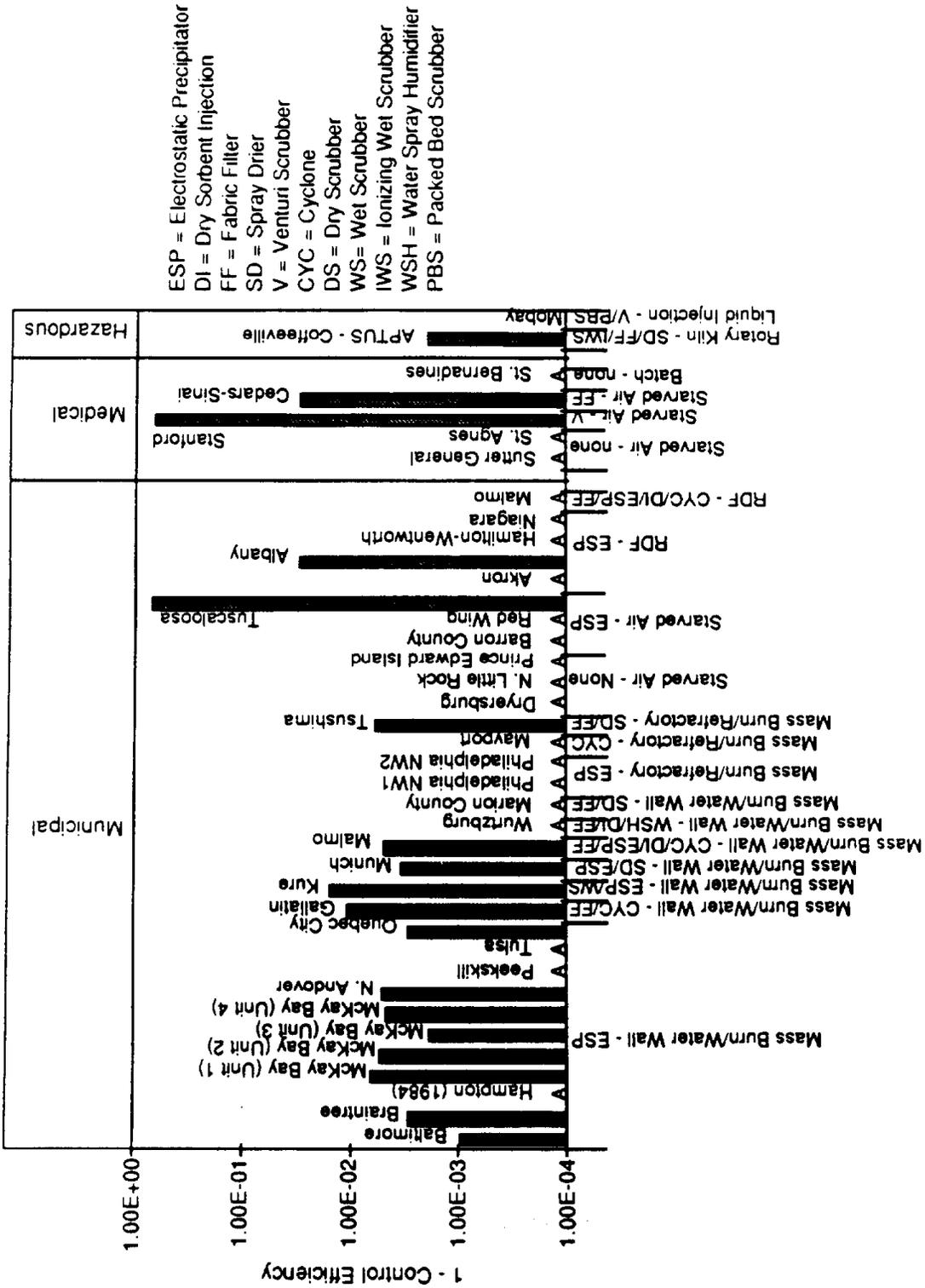


Figure 87. Emissions of particulate matter.



A = Data not available or calculation not relevant

Figure 88. Particulate capture efficiency of APCDs used in municipal, medical and hazardous waste incinerators

TABLE 26. PARTICULATE EMISSIONS FROM TWO MEDICAL WASTE INCINERATORS

Unit	Feed Rate,		Excess Air, Percent	Emissions,	
	lb/hr	kg/hr		gr/dscf	g/ Ncm
Batch	884	401	246	0.045	0.103
Continuous	1500	681	285	0.09	0.206

TABLE 27. UNCORRECTED PARTICULATE EMISSIONS DATA

Date	Hospital	Particulate Emissions, gr/dscf
4/81	Misericordia	0.06
4/81	Misericordia	0.10
11/81	Queen Eliz. II	0.03
11/82	Queen Eliz. II	0.03
5/83	St. Michaels	0.08
5/83	Royal Alex	0.03
5/83	Royal Alex	0.07
7/83	Red Deer	0.08
7/83	Univ of Alberta	0.02
8/83	Foothills	0.06
2/84	W.C. McKen.	0.02
2/84	Lacombe	0.07
3/84	Ft. McMurry	0.05
7/84	Athabasca	0.05
12/84	Lethbridge Gen.	0.04
3/85	Willingdon	0.07
5/85	Bonnyville	0.08

fields which affect their capture. Particle layer buildup on the plate electrodes of dry ESPs can reduce the voltage across the electrodes, resulting in lower particle capture. Also, some particles can be reentrained during cleaning (rapping) of dry ESPs.

Incinerators typically operate at slightly negative pressure to prevent fugitive emissions. However, when the door to the primary chamber is opened to feed more waste, air is likely to enter the chamber. A low temperature transient may move through the incinerator, briefly increasing emissions of soot and fly ash containing relatively large amounts of unburnt carbon.

The submicron carbonaceous particles, otherwise known as soot, can increase the opacity of the plume exiting the stack. High concentrations of soot also indicate poor burnout of the organic material in the waste. Properly operating afterburners or secondary combustion chambers should burn the soot that is generated during the fuel rich combustion in the primary combustion chamber.

CURRENT CONTROL PRACTICE

Particle matter emitted depends on the design and shape of the incinerator, combustion air flows and the waste's characteristics.

COMBUSTION SYSTEM

Most operating medical waste incinerators are small hospital incinerators that consist of one main combustion chamber plus a stack burner. These units were discussed previously. Batches of waste burn under excess air as a stationary bed in the main chamber. These stationary beds burn with low turbulence. The stack burner helps to complete the combustion of soot. This combination of low turbulence and soot burnout results in low particulate emissions.

Modular starved air systems are the predominant designs being manufactured today. The design calls for substoichiometric air in the primary combustion stage. Here the waste pyrolyzes and oxidizes yielding combustible gases and ash. The lift velocity (the vertical component of the gas velocity) in the primary chamber is low. At 1030 K (1400°F) the lift velocity is typically 0.46-0.61 m/s (1.5-2 ft/s). By comparison, rotary kilns typically have lift velocities of over 1.8 m/s (6 ft/s). A lift velocity of 0.46 m/s (1.5 ft/s) can theoretically entrain a 100-micrometer particle. A higher gas velocity would actually be needed to entrain the 100-micrometer particle because the gas must overcome blocking effects of larger particles and static friction.

Starved-air incinerators can be designed for batch or continuous operation. In batch units, the feed burns essentially as a stationary bed in the primary stage. The primary chamber is large and the gas flow rates are low. Thus, the lift velocity in the primary chamber is very low. In continuous units, the burning bed is mixed as it moves across the grate. This mixing may result in higher particle entrainment.

Soot particles formed under the substoichiometric conditions of the primary stage are destroyed in the secondary chamber. Soot burnout requires excess oxygen conditions and is promoted by higher temperatures. The soot burnout time is on the order of tenths of a second. Residence times in secondary chambers are usually one second or longer. Residence times in stacks equipped with stack burners are shorter.

Minimizing particulate production during incineration involves minimizing agitation of the burning bed. Overcharging often results in greater gas flow rates and higher emissions. Thus operators must ensure that the feed rate does not exceed these limits.

AIR POLLUTION CONTROL EQUIPMENT

Wet scrubbers are the predominant flue gas cleaning device used with medical waste incinerators. Fabric filters are uncommon, but their use is growing as both particulate matter and acid gas regulations get more stringent (89). Spray dryers are being considered for use upstream of fabric filters to affect acid gas removal and maximum particulate removal. ESPs are rarely used for medical waste incinerators.

Venturi scrubbers require that a high pressure drop be maintained across the throat. Furthermore, flue gases should be quenched before entering a venturi scrubber. Unquenched flue gases can cause the water droplets in the scrubber to "explode", which can release some of the captured particles back into the gas stream. Fabric filters must be maintained at a low temperature (<530 K (500°F)) so as not to damage the fabric or cause fires. However, high temperature fabrics [about 1090 K (1500°F)] are now available.

ANALYSIS OF CONTROL PRACTICE

As indicated in Table 26 and by comparing the data shown in Figures 86 and 87, the techniques currently used to limit particulate entrainment in the primary chamber are quite effective. Starved air systems routinely

emit less than 0.18 g/Ncm (0.08 gr/dscf) without flue gas cleaning equipment. Transient behavior is a major concern. In starved-air systems, uncontrolled quantities of air may enter the system during the feeding process. This air will increase particle entrainment for a brief period. Thus average particle emissions may not be the only appropriate parameter to measure. Peak emissions may also be a concern.

The influence of air pollution control device operating parameters on particulate capture efficiency was discussed previously. Venturi scrubbers in general can effectively capture larger particles but are capable of capturing the submicron material when operated at high pressure drop ($>1.5 \times 10^4$ Pa gauge (60 in. W.G.)). Fabric filters are very effective (> 99 percent capture efficiency) at controlling metals emissions. Any air pollution control equipment must be capable of controlling transient emissions. As mentioned above, relatively high flue gas particle concentrations may occur for short periods. In addition, batch units never achieve steady state operation.

ADDITIONAL INFORMATION NEEDED

While total particulate emissions from medical waste incinerators have been studied, transient behavior has not. Thus there is a significant need to study the potential impact of transient incinerator behavior on particulate emissions.

SECTION 14

SOLID AND LIQUID EFFLUENTS

Besides the air emissions discussed earlier, solid and liquid effluents from medical waste incinerators are of concern. Solid effluents are composed primarily of ash from the combustion chamber of an incinerator (residual ash). If the system is equipped with some type of dry air pollution control device (such as a baghouse), captured fly ash will also be present. Liquid effluents are produced by systems equipped with wet scrubbers. Both solid and liquid effluents may contain materials which are a threat to human health and the environment.

POLLUTANTS OF CONCERN

Many of the same pollutants which are of concern in air emissions also must be considered when dealing with solid and liquid effluents. The pollutants considered are:

- Trace Organics
- Pathogens
- Toxic and Carcinogenic Metals
- Cytotoxic Compounds
- Radioactive Materials

TRACE ORGANICS

As in air emissions, the trace organic materials of principal interest are PCDD/PCDF. The California Air Resources Board measured the concentration of dioxins in the ash of several medical waste incinerators (35-38). The data is shown in Figure 89 with the concentration of PCDD/PCDF in the ash from typical municipal waste incinerators. The quantities of PCDD/PCDF present vary over several orders of magnitude. The larger medical waste incinerators and the municipal waste incinerators had the lowest concentrations while the batch incinerator at St. Bernadines produced ash containing over 100 ppb dioxins.

The formation of PCDD/PCDF in residual ash has not been studied in detail. However, much of the data on the formation of PCDD/PCDF in air emissions can be applied. Two mechanisms can lead to the presence of PCDD/PCDF in the residual ash. First, PCDD/PCDF from the waste can pass through the incinerator undestroyed. Second, ash-based formation may occur. As discussed previously, several researchers have been studying the formation of PCDD/PCDF on fly ash particles. These studies have concluded that significant quantities of PCDD/PCDF can form from carbon on ash particles (45). However, these reactions are limited to a range of temperatures of between 520 and 620 K (480°F and 660°F). Most of the solids in the incinerator will experience temperatures much higher than this.

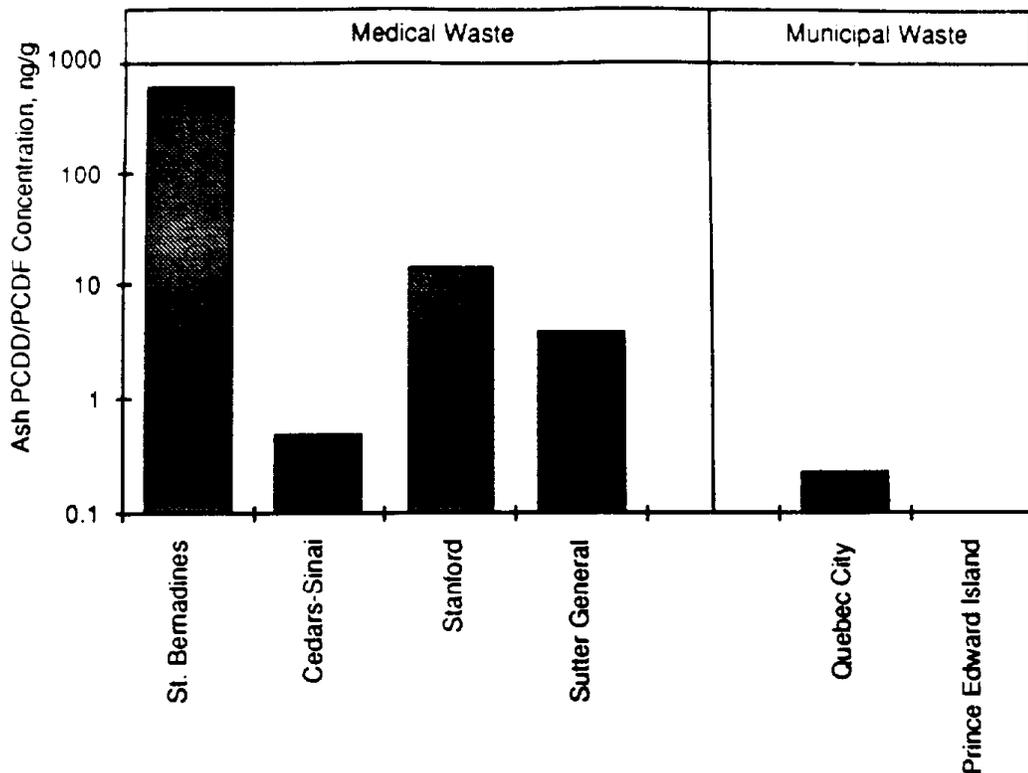


Figure 89. Comparison of PCDD/PCDF concentration in medical and municipal waste residues.

However, some items like thick stacks of paper and very moist materials will not be completely burned. In a study by Pinder (90) it was found that the static ash on the outside of dense materials insulates the interior. Examples of materials which exhibit this phenomena (commonly called the "Wet Phone Book Effect") are stacks of computer paper and books. Examination of the ash from operating incinerators reveals occasional clumps of paper burnt on the outside but are unchanged on the interior. This can lead to regions in which the temperature is favorable for the formation of PCDD/PCDF.

Currently two techniques are used to maximize the destruction of organic material and prevent the formation of PCDD/PCDF:

- Prolong ash residence time to ensure complete destruction of organic material.
- Promote mixing of solid residuals in the primary chamber to prevent formation of cold pockets.

Ash residence times are prolonged by enlarging the primary chamber and by limiting the maximum incinerator feed rate. One of the principal concerns expressed by many manufacturers was the practice of over-feeding incinerators. Many hospitals with limited waste disposal capacities must feed their incinerators at higher rates than the unit is designed for. This has a strong impact on air emissions and allows organic material to pass through the incinerator.

Mixing is promoted through the use of rams within the face of each step on the floor of starved air systems as shown in Figure 90. Typical batch incinerator designs contain no provisions to ensure that mixing occurs

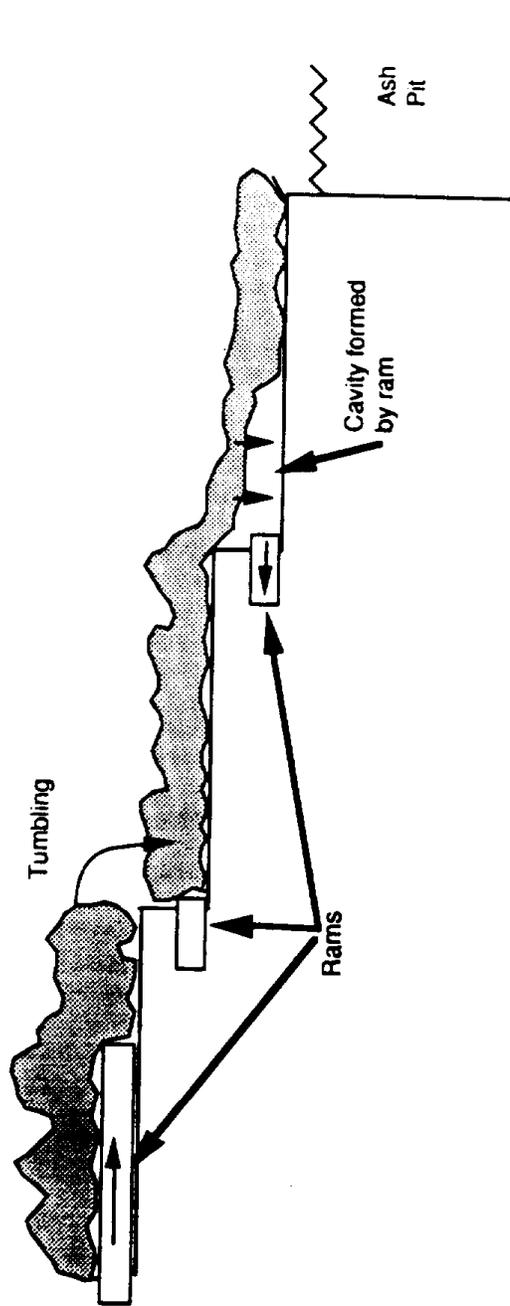


Figure 90. Solids mixing in ram-fed incinerators.

The batch incinerator studied by the California Air Resources Board had PCDD/PCDF concentrations in the ash that were orders of magnitude higher than any other incinerator. However, this may be an isolated incident and care must be taken in drawing any conclusions from these data.

PATHOGENS

The potential presence of pathogens in medical waste incinerator ash is a major concern in many regions of the country. Tests have been conducted to determine if viable pathogens are present in the ash from medical waste incinerators. Studies on municipal waste incinerators have shown that it is possible for pathogens to survive the incineration process (91). However, tests carried out in 1987 found that starved air medical waste incinerators effectively destroy pathogens in the ash (57). These tests involved spiking medical waste incinerators with *Bacillus subtilis*. Two methods were used to introduce the bacteria into the waste, encapsulation and seeding. In encapsulation, test strips containing 3.1×10^8 spores were wrapped in stainless steel foil and sealed in black iron pipe capped at both ends. The pipe was then placed in a bag of general refuse which was fed into the incinerator. In seeding, spores were suspended in distilled water. At set intervals, a bag of waste was opened and a set amount of the spore suspension was added. The bag was loaded into the incinerator in the normal manner.

The first unit tested was a 34 kg/hr (75 lb/hr) dual-chamber batch-fed unit. No *Bacillus subtilis* spores were found in the ash when either spiking method was used. Eight other incinerators were tested using only the encapsulation method. The incinerators ranged in size from 45 to 350 kg/hr (100 to 780 lb/hr). The tests are summarized in Table 28. In all except one of the units, bacterial spores did not survive. These tests indicate that it is unlikely that pathogens can escape destruction when exposed to the bulk conditions of the bed. However, some spores did survive in one of the incinerators operated at very low temperatures [870 K (1100°F)]. In addition, the test method did not examine the potential escape pathway in which some microorganisms do not experience the bulk conditions. This indicates that more study is needed.

Pathogens will not survive if exposed to the bulk conditions for the typical solids residence times (> 30 minutes) (52). Thus, the pathogens which escape must have been present in a pocket of material which was isolated from the bulk conditions. As discussed in the previous section, the interiors of very dense or wet materials tend to be insulated from bulk incinerator conditions.

The pathogen escape pathway is difficult to eliminate with existing technology. The principal current approach is to ensure that all carbon in the ash is oxidized. As described in the previous section, this is done by increasing ash residence times in the incinerator and by promoting mixing within the bed of waste. Figure 90 illustrates the techniques used to ensure adequate solids mixing in ram-fed, starved-air incinerators. The hearth is usually constructed of several steps. Ash mixes as it tumbles from one step to the next. In addition, rams push a portion of the bed onward. The remainder of the material falls into the space cleared.

It is important in ram-fed units that the waste bed not be excessively thick. When this happens, not only are the mixing techniques less effective but the entire bed acts like a single dense piece of material. The top of the bed serves to insulate the bottom from the high bulk gas temperatures. Estimates of the ideal bed depth vary around 0.6 m (2 ft) (92). Over-charging a unit will lead to deep beds and poor mixing.

TOXIC AND CARCINOGENIC METALS

The presence of toxic and carcinogenic metals in the solid and liquid residuals produced by an incinerator system are a significant concern. These metals may be leached from the ash into drinking water supplies. Thus, if significant quantities of leachable toxic and carcinogenic metals are present in the ash, it must be disposed of in specialized landfills. Ash composition is affected by the composition of the waste feed and the conditions in the primary combustion chamber. The fly ash and scrubber water compositions are further affected by the downstream temperature and oxygen concentration profiles (78). These parameters control the condensation of vaporized metal species downstream of the primary combustion zone.

TABLE 28. SUMMARY OF RESULTS OF ASH SPORE TESTS

UNIT SIZE (TYPICAL) RATING	TYPE OF WASTE	OPERATING TEMP. PRIMARY	TEST METHOD	TEST RESULT	NOTES/FEATURES
75 LB/HR	PATHOLOGICAL	1400-2000°F	1 & 2	ALL NEGATIVE	MANUAL LOADING
490 LB/HR	HOSPITAL	1600°-2200°F	1	ALL NEGATIVE	RAM LOADER STD. UNDERFIRE AIR HEAT RECOVERY TWO CHAMBER CONTROLLED AIR
780 LB/HR	HOSPITAL	1600-2200°F	1	ALL NEGATIVE	RAM LOADER PEBBLE HEARTH HEAT RECOVERY TWO CHAMBER CONTROLLED AIR
155 LB/HR	INFECTIOUS (BACKUP UNIT)	NO INDICATORS	1	ALL NEGATIVE	MANUAL LOAD TWO CHAMBER CONTROLLED AIR
735 LB/HR	HOSPITAL INFECTIOUS	1600-1900°F	1	ALL NEGATIVE	TWO CHAMBER CONTROLLED AIR RAM LOADER, UNDERFIRE AIR
200 LB/HR	PATHOLOGICAL	1500-1600°F	1	NEGATIVE	MULTI-CHAMBER EXCESS AIR DESIGN MANUAL SIDE DOOR LOADING
155 LB/HR	HOSPITAL INFECTIOUS	1350°F (SETPOINT NO INDICATION)	1	NEGATIVE	TWO CHAMBER CONTROLLED AIR VERTICAL DESIGN MANUAL LOAD
150 LB/HR	HOSPITAL INFECTIOUS	1550-1600°F	1	NEGATIVE	TWO CHAMBER CONTROLLED AIR VERTICAL DESIGN
100 LB/HR	PATHOLOGICAL	1100°F	1	POSITIVE	MULTI CHAMBER EXCESS AIR DESIGN BURNERS FIRE HORIZONTALLY ABOUT 16" ABOVE THE HEARTH. TOP CHUTE LOAD

TEST METHOD 1 - ENCAPSULATION
 TEST METHOD 2 - DIRECT SEEDING OF WASTE

Figure 91 summarizes the data available on the metals content of residual and fly ash from medical and municipal waste incinerators. No equivalent data is available for hazardous waste incinerators. The metals content of the ash from the medical waste incinerator is less than that for either of the municipal waste incinerators. Clapp et al. have suggested a close similarity between the ashes produced during the incineration of medical waste at that produced by municipal waste incineration (93). The study focused on the behavior of these ashes when subjected to the EPA's Extraction Procedure (EP) and the Toxicity Characteristic Leaching Procedure (TCLP). The total metals content of various ashes was also determined. Samples of medical waste and municipal solid waste were incinerated in the same facility. Figure 92 shows a diagram of the incinerator facility. It consisted of a primary chamber, an afterburner, gas quench tower, baghouse and venturi scrubber. Operating conditions for the incineration tests were not reported. Table 29 presents the results.

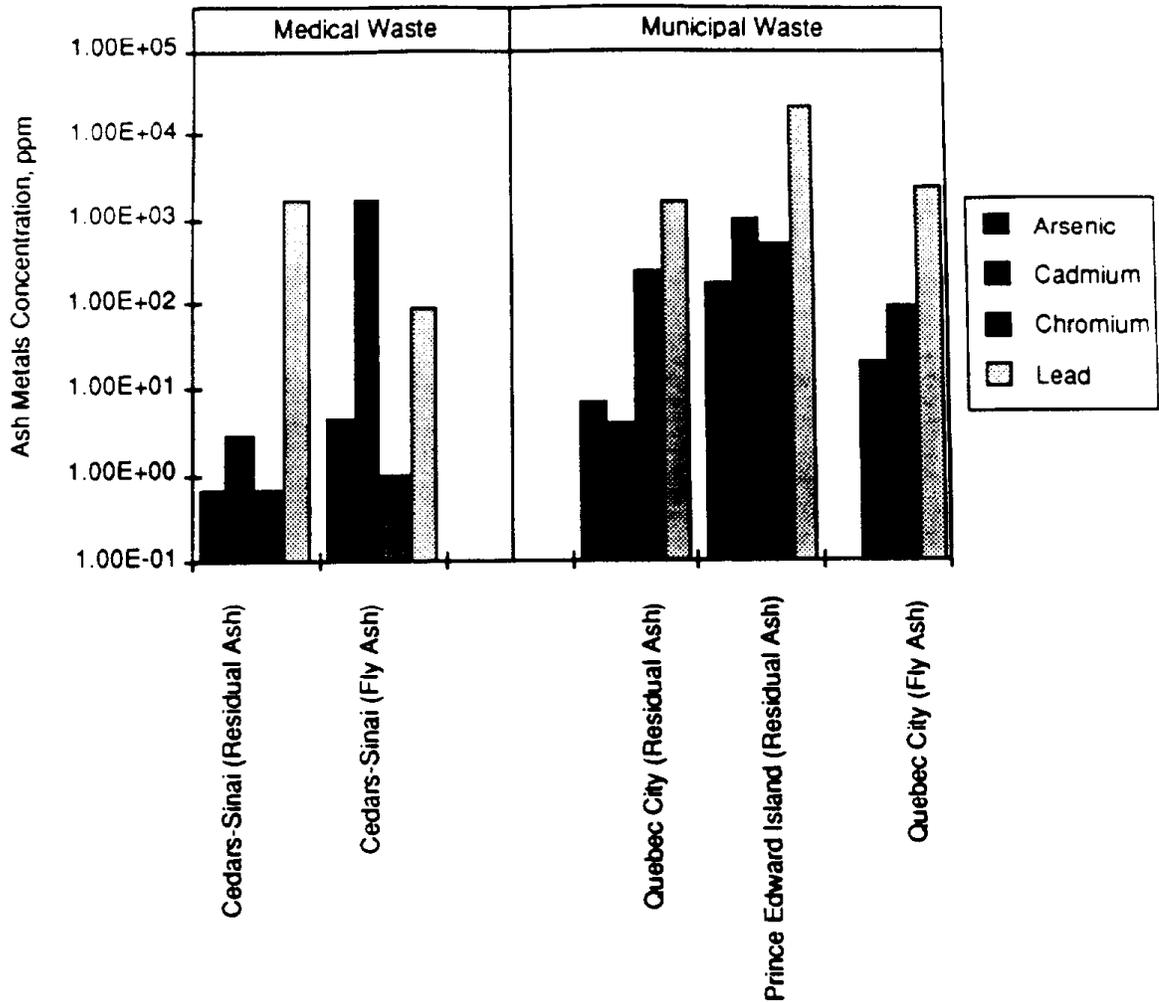


Figure 91. Comparison of metals concentration in medical and municipal waste residues.

The ash metals concentrations for the two wastes were similar, except the municipal solid waste contained more lead than the medical waste. The EP and TCLP results show that the leaching characteristics of the ashes were similar. Both cadmium and lead leached from the fly ash were found to exceed regulatory limits, although these values were only a fraction of the total concentrations in the ash.

Chromium and silver extractions were low for all test conditions, as were the concentrations of these metals in the ash. However, extractions of cadmium and lead in the fly ash were sensitive to both pH and liquid-to-solid ratio. Clapp et al. (93) found that the quantities of these metals available for extraction were high and may be underestimated by EP and TCLP determinations.

Unlike organic compounds, metals cannot be destroyed during the combustion process. Thus, all the metals in the waste must exit the incinerator. As previously described, it is preferable for the metals to stay in the ash or be captured by an air pollution control device than to have them emitted to the atmosphere.

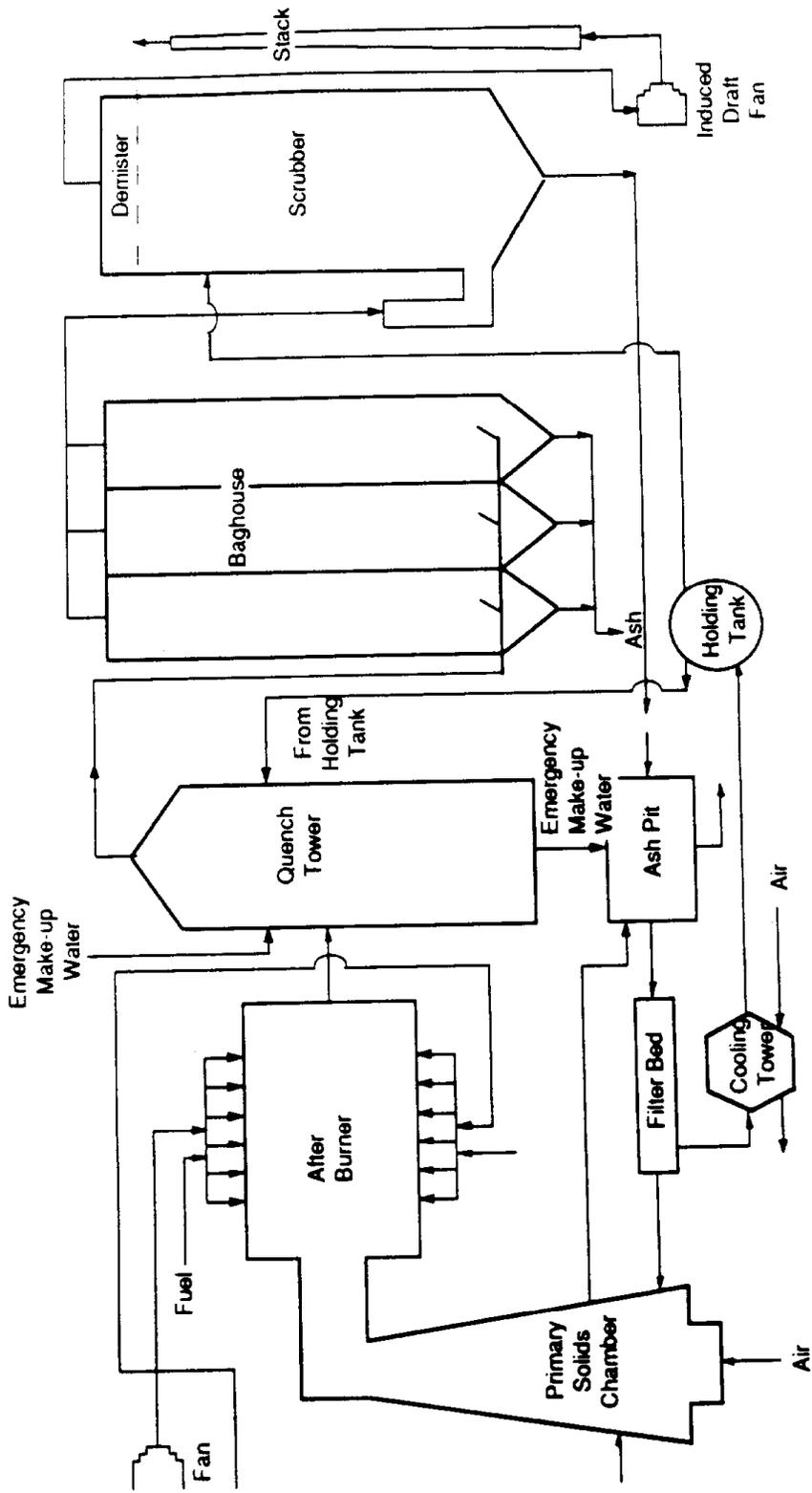


Figure 92. Incinerator system used in ash behavior study

TABLE 29. RESULTS OF ASH BEHAVIOR STUDY

<u>ACID DIGESTIONS AND REGULATED EXTRACTIONS</u>									
(ppm)									
	<u>HC10₄ DIGESTIONS</u>		<u>EP EXTRACTIONS</u>		<u>TCLP EXTRACTIONS</u>		<u>EP (TCLP) LIMITS</u>		
	<u>fly</u>	<u>bottom</u>	<u>fly</u>	<u>bottom</u>	<u>fly</u>	<u>bottom</u>			
Hospital Waste (Three combined service areas) 6/26/86									
Cr	52	125	1	<1	8	<1	5.0	(5.0)	
Cd	347	6	22	<1	26	<1	1.0	(1.0)	
Pb	2208	107	15	<1	31	<1	5.0	(0.2)	
Ag	32	3	1	<1	<1	<1	5.0	(5.0)	
Ba	1040	8600	<1	<1	<1	<1	100.0	(100.0)	
As	<1	<1	<1	<1	<1	<1	5.0	(5.0)	
Pennsauken MSW (One primarily residential service area) 8/20/85									
Cr	30	40	<1	<1	1	<1	5.0	(5.0)	
Cd	490	100	15	<1	18	<1	1.0	(1.0)	
Pb	4990	6790	27	3	44	<1	5.0	(0.2)	
Ag	<1	<1	<1	<1	<1	<1	5.0	(5.0)	
Ba	250	3225	1	3	2	2	100.0	(100.0)	
As	47	118	<1	<1	1	1	5.0	(5.0)	
Zn	4700	4400	-	-	-	-	-	-	

CYTOTOXIC COMPOUND

Because of the extreme toxicity of these compounds, they must be completely destroyed in the incinerator. The considerations discussed previously in conjunction with air emission of cytotoxic compounds also play an important role in their survival in the residual ash. All the ash must be exposed to bulk conditions within the combustion chamber. To ensure that this happens, the waste bed must be thoroughly mixed. No experimental data on the presence of cytotoxic compounds in residual ash is available.

TABLE 30. PERCENTAGE OF RADIOACTIVITY RETAINED IN ASH

Nuclide (n)	% Retained
³ H(5)	0.0
¹⁴ C(4)	0.8 ± 0.2
²² NA (5)	72.9 ± 2.8
³² P(4)	72.6 ± 5.3
³⁵ S(5)	0.0
⁴⁶ SC(5)	95.4 ± 1.1
⁴⁷ CA(5)	90.4 ± 1.5
⁵¹ CR(7)	71.1 ± 3.0
⁵⁷ CO(5)	72.7 ± 3.7
⁵⁷ CO(5)	76.9 ± 2.3
⁵⁸ FE(6)	65.0 ± 4.2
⁶⁷ GA(5)	63.2 ± 2.7
⁸⁵ SR(4)	81.0 ± 2.3
⁸⁵ SR(4)	79.3 ± 3.4
¹¹¹ IN(5)	35.7 ± 6.6
¹¹³ SN(5)	41.7 ± 3.7
¹²⁵ I(2)	0.0

*Microspheres

RADIOACTIVE MATERIALS

As listed previously, the most common radionuclides used for medical purposes are tritium, ³²P, ¹²⁵I, ¹³¹I and ¹⁴C. Most of these nuclides are volatile at the conditions within an incinerator. When waste containing these compounds are burned, many radioactive compounds vaporize and join the exhaust gas stream. Thus, incineration reduces the concentration of radioactive materials in the ash. This phenomena was studied by Classic et al (94). They found that incineration reduces the concentration of many radioactive materials in residual ash by several orders of magnitude. Table 30 lists the fraction of radioactivity retained in the residual ash of incinerated guinea pigs containing known amounts of several radionuclides. Subsequent leaching studies show that the ash was suitable for disposal in municipal landfills.

RESEARCH NEEDS

Ash from medical waste incinerators has not been widely studied. Other tests are needed in which the concentration of organic material, pathogens and toxic metals in ash is measured. Of particular interest is the affect of pockets of unburned material on the total emissions. In addition, research focused specifically on the destruction of cytotoxic compounds is needed. Currently, very little is known about the quantities of these compounds in the ash.

SECTION 15

STATE REGULATIONS

There are currently no comprehensive federal regulations governing the thermal treatment of medical wastes. However, the public is demanding rapid promulgation of medical waste disposal regulations. These forces have caused the States to enact a broad range of regulations governing various aspects of medical waste disposal including thermal treatment. This section summarizes the State regulations currently in force. It should be noted, however, that some States are developing regulations and have not yet completed their rules.

Table 31 summarizes the results of a recent National Solid Waste Management Association (NSWMA) survey of State regulations (95). At the time of the survey, a little over half of the States used an official definition of medical waste for regulatory or policy-making purposes. Table 32 indicates that many States have revised their medical waste handling regulations since 1988 (96). Three of the States shown did not make use of a definition of medical waste at the time of the NSWMA survey.

This illustrates an important feature of the State regulatory environment - the speed at which changes are occurring. Regulations are being rapidly developed by many States. These regulations will probably be promulgated before the expected date at which the EPA will begin to adopt regulations (1992).

Table 33 illustrates the current emission regulations for medical waste incinerators (97,98). In many States, regulations are merely general air quality protection rules which apply to all incinerators independent of the fuel burned. The emission most commonly regulated is particulate matter. Opacity limits are a second common emission requirement. Particulate emission limits vary from 0.035 g/Ncm (0.015 gr/dscf) to 0.7 g/Ncm (0.3 gr/dscf).

HCl and CO emissions are also sometimes regulated. As with the particulate emission regulations, the limits vary significantly. HCl emission limits vary from 50-800 ppm while CO emission limits vary from 75-2000 ppm. These variations make it difficult to select incineration systems for all States.

Regulations often specify secondary chamber temperatures and residence times. Again significant variations can be seen. As discussed previously, theoretical considerations indicate that temperatures as low as 1170 K (1650°F) may be sufficient to ensure destruction of potential organic emissions. Data from the California Air Resources Board's tests of medical waste incinerator emissions indicates that 1030 K (1400°F) may be sufficient. However, required temperatures may be as high as 1370 K (2000°F) or as low as 920 K (1200°F). The lower temperatures may not be sufficient to ensure destruction of all organic compounds.

As was shown earlier, many States are adopting new strict regulations. California, for example, is considering adopting regulations which limit particulate emissions to less than 0.03 g/Ncm (0.015 gr/dscf) in addition to strict limits on metals emissions. California has determined that PCDD/PCDF emissions represent

TABLE 31. SUMMARY OF STATE MEDICAL WASTE DISPOSAL REGULATION STATUS

	<u>Number of States</u>
Official definition of infectious waste for regulatory or policy-making purposes	28
Infectious waste is included in State's definition of hazardous waste	5
Segregation and labeling required for disposal in any permitted landfill	17
Require autoclaving	2
Require incineration	2
Require autoclaving or incineration	17
Other procedures are sometimes approved as acceptable means of disinfection (e.g. chemical sterilization)	33
Waste must be sterilized on-site (at medical facility)	8
Establish guidelines or requirements for moving untreated infectious waste to off-site facilities	15
Apply same regulations to hospitals and other medical waste generators	26

a significant threat to human health and is moving rapidly to limit the emissions of these pollutants. The regulations being considered are expected to shut down 90 percent of the medical waste incinerators in the State.

New York recently promulgated regulations so strict that no incinerator operating before the regulations were enacted could meet the emissions limits. New Jersey, Florida, North Carolina and South Carolina are either considering or have enacted new, stringent regulations for medical waste incinerators.

RESEARCH NEEDS

The wide variety of regulations being promulgated show there is no clear consensus about what regulations are needed to protect human health. A study aimed at determining the impact of medical waste incinerator operation and design on emissions. This information could then be used to develop consistent, scientifically sound regulations across the U.S.

TABLE 32. NEW AND REVISED MEDICAL WASTE HANDLING REGULATIONS

	FL	GA	IN	MD	MA	MI	MO	NJ	NM	NY	TN	TX	VT	WV
Definition	.	.	.	.	.	.	.²	.	.	.	.	.	.	.
Manifest			.	.	.		.	.		.			.
Special Packaging	.	.	.	.	.	.	.		.	.		.³	.	
Labels	.	.	.	.	.	.			.				.
Generator registration				.		.							.	
Transporter registration	.			.			.	.		.			.
Treatment permit	.	.					.						.
Storage conditions	.	.	.		.	.	.						.
Treatment required	.	.	.	.³	.		.		.	.		.		.
Approved methods ¹	.	.	.	.	.	.							.
Performance standards	.	.					.						.
SQG** exemption ² (lb/month)	25/ TRIP	100	0	80	0		220	0		0		220		
Footnotes	<p>1 Approved treatment methods (usually incineration or autoclave) 2 Small quantity generator (does not include households) exemption (These exemptions mainly apply to transportation requirements such as manifests, permits and fees.) 3 This regulation only applies to needles, scalpels and other "sharps"</p>													

TABLE 33. STATE INDUSTRIAL WASTE INCINERATION STANDARDS.

State	PM (gr/dscft) ¹	HC1	Temp/Time ²	CO/ppm	Other	Reg Impact
New York	0.03	90% Reduction	1800°F/1s	Yes	Opacity	No Unit Will Meet
South Carolina	0.03-0.1	Monitor	1800°F/2s	Monitor	Opacity	
California ³			1800°F/1s	Monitor	Exhaust <300°F Primary Chamber >1400 Opacity (Monitor) TCDD Equivalent <10 ng/kg Waste or 99% Reduction in Uncontrolled Emissions	
Massachusetts			1600°F/1s			
Pennsylvania	0.015-0.08	90% Reduction	2000°F/2s	100	Opacity	
Alabama	0.2 lb/100 lb waste				Opacity	
Alaska					Opacity	
Arizona	0.1				Opacity	
Arkansas	0.3				Opacity	
Connecticut	0.15	90% Reduction	2000°F/2s	100	Opacity	
Delaware			1400°F		Opacity	
District of Columbia	0.03		1800°F		Hours of Operation	
Florida ⁴					Opacity	

TABLE 33. STATE MEDICAL WASTE INCINERATION STANDARDS.

State	PM (gr/dscft) ¹	HC1	Temp/Time ²	CO/ppm	Other	Reg Impact
Georgia	1 lb/hr		1500°F			
Hawaii	0.2 lb/100 lb waste		Case by Case		Opacity	Opacity
Idaho	0.2 lb/100 lb waste				Opacity	Opacity
Illinois	0.1			500		
Indiana			1800°F/1s			
Iowa	0.35				Opacity	
Kansas	0.1-0.3				Opacity	
Maine	0.1		2000°F/2s		Opacity	
Maryland	0.1		1800°F/2s		Opacity	
Michigan			1800°F/2s		Opacity	
Minnesota	0.1-0.2		1200°F/0.3s			
Mississippi	0.1-0.2					
Missouri	0.2-0.3		1800°F/0.5s			
Montana	0.1				Opacity	
Nebraska	0.1-0.2				Opacity	
Nevada	Formula		1400°F/0.3s		Opacity	

TABLE 33. STATE MEDICAL WASTE INCINERATION STANDARDS

State	PM (gr/dscf) ¹	HC1	Temp/Time ²	CO/ppm	Other	Reg Impact
New Hampshire	0.3				Opacity	
New Jersey	0.01		1500°F/1s			
North Dakota	Formula		1500°F/0.3s		Opacity	
Ohio	0.2 lb/100 lb waste	<4 lb/hr	1600°F		Opacity	
Oklahoma					Opacity	
Oregon			1600°F		Opacity	
Puerto Rico	0.4 lb/100 lb waste				Opacity	
Rhode Island	0.08					
Tennessee	0.2 lb/100 lb waste				Opacity	
Vermont	0.1 lb/100 lb waste		1600°F/1s		Opacity	
Virginia	0.14				Opacity	
Washington	0.02-0.03	<50 ppm	1800°F		SO ₂	
West Virginia	5.43 lb/ton waste				Opacity	
Wisconsin	0.08	<50 ppm		75 ppm		
Wyoming	0.2 lb/100 lb waste				Opacity	

1. Particulate matter (1 gr/dscf = 2.29 g/Ncm).
 2. Secondary chamber exit temperature required and secondary chamber residence time required.
 3. These include only statewide restrictions. Local districts must have regulations at least as strict.

SECTION 16

SYSTEM MONITORING

Monitoring medical waste incinerators is becoming increasingly important. Regulations being developed often require that emissions monitoring equipment be installed on medical waste incinerators. System manufacturers are building incinerators equipped with more sophisticated control systems which make use of data from various system operation monitors. This section of the report discusses the different monitoring methods available.

Two classes of parameters to be monitored can be identified:

- Emissions
- Operating parameters

Emissions monitoring identifies and quantifies material leaving an incinerator while operating parameter monitors measure key variables associated with the operation of a system. The two classes are not exclusive. Some emissions measurements may also be good indicators of system operation.

EMISSIONS CHARACTERIZATION

As is discussed in other sections of this report, while federal regulations are being developed, there are currently no federal regulations which apply specifically to medical waste incinerators. Regulations governing most medical waste incinerators are those that were enacted by either State governments or local jurisdictions. These regulations are changing rapidly as new rules are enacted and existing rules are modified in response to the current high level of interest in the area. Because of this, it is not possible to define all the emissions monitoring which will be required for medical waste incinerators. However, monitoring and compliance testing will probably be required. The extent of testing required may approach that required for other types of incinerators.

Monitoring methods are strongly affected by the physical state of the material to be tested. A given incinerator system may have gaseous, liquid and solid effluents. Solid and gaseous effluents are the most common. Liquid effluents are typically only generated by some types of flue gas cleaning equipment.

AIR EMISSIONS

As with most incineration systems, air emissions are of primary concern. By analogy to other types of waste incinerators, the air pollutants which may require monitoring can be identified. These emissions are listed in Table 34. Aside from the materials listed in the Table, pathogen emissions from medical waste incinerators are of concern. Oxygen and carbon dioxide measurements are often required. Though oxygen and carbon dioxide are not pollutants, the concentrations are used to correct other emissions to standard

TABLE 34. AIR EMISSIONS WHICH MAY REQUIRE MONITORING

•	Acid Gases
	Nitrogen oxides Sulfur dioxide Hydrogen chloride
•	Particulate matter
	Total particulate matter concentration Particulate matter smaller than 10 micrometers Opacity
•	Organic compounds
	Total hydrocarbon emissions PCDD/PCDF Polyaromatic hydrocarbons Other specific organic materials
•	Metals

conditions. The EPA and ASTM have developed or are developing standard methods for measurement of these materials in incinerator effluents. The techniques required in the methods and the method designations are summarized in Table 35. The methods are rigorously defined in the Code of Federal Regulations, EPA reports and ASTM publications. Because of this, the techniques are only summarized in this section. For more details, refer to the appropriate EPA or ASTM testing protocol (99, 100, 101, 102).

The first goal of most air emissions monitoring equipment is to obtain a representative sample of the gases without interfering with the gas flow. To do this, the sampling probe illustrated in Figure 93 has been developed. Gases are withdrawn from carefully chosen locations in the duct through the probe. The velocity of the gas in the probe is adjusted so that it is close to that in the stack (isokinetic sampling). The probe may be either heated or cooled depending on the materials of interest.

- Continuous Emissions Monitoring Systems

Some of the most commonly used air emissions monitoring equipment are Continuous Emissions Monitoring Systems (CEMS). These systems can determine the concentrations of many principal gaseous species in the exhaust. CEMS are available for O₂, CO₂ (EPA Method 6-C), NO_x (Method 7-E), and CO (Method 25-A). CEMS systems are also available to determine the total quantity of hydrocarbons (THC) and the concentration of HCl in the gas. However, standard protocols have not been completed for these test methods. CEMS are used both for compliance tests and as permanent systems monitors.

Figure 94 illustrates a comprehensive CEMS. A continuous flue gas sample is withdrawn from the exhaust gas stream. Separate probes are used for the HCl system, the THC system, and the combined O₂, CO₂, SO₂, NO_x, and CO system. The HCl probe incorporates a system which dilutes the sampled gas to prevent moisture condensation. All the probes are built of stainless steel and are heated to prevent condensation. Each probe is fitted with an in-stack filter and calibration gas values.

TABLE 35. MEASUREMENT PROCEDURES THAT MAY BE REQUIRED FOR MEDICAL WASTE INCINERATORS

Material	Procedure
Flue Gas O ₂ , CO, CO ₂ , NO _x , THC	Extractive sampling and CEMS
Particulate matter Total particulate matter Particulate matter smaller than 10 mm Opacity	Method 5 and weighing Method 5 with cascade impactor Method 9 Certified observer
Acid Gases HCl, SO ₂	Extractive sampling and CEMS
Organics Dioxin, PAH, and semivolatiles organics Volatile organics	Modified method 5 and GC/MS VOST and GC/MS
Metals	EPA multiple metals train and AA or ICP analysis
Pathogens	EPA draft spike and analysis

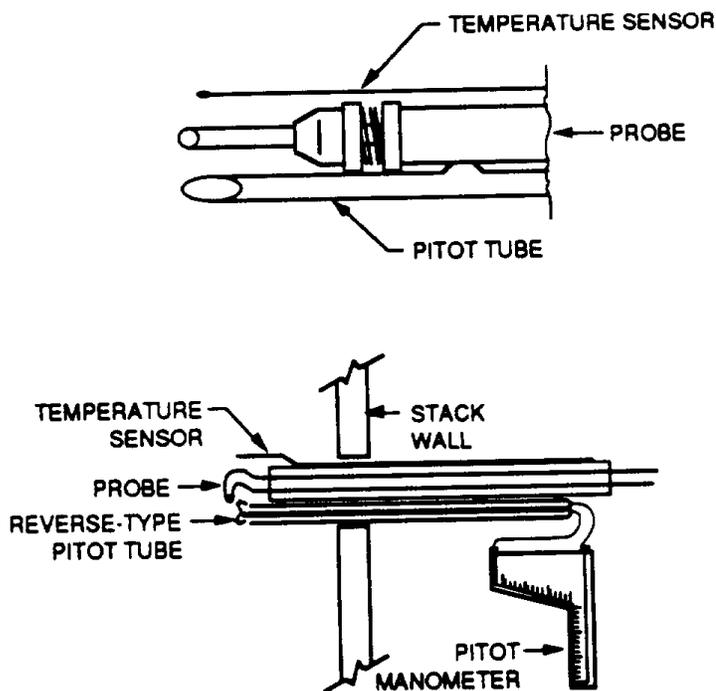


Figure 93. Emissions sampling probe.

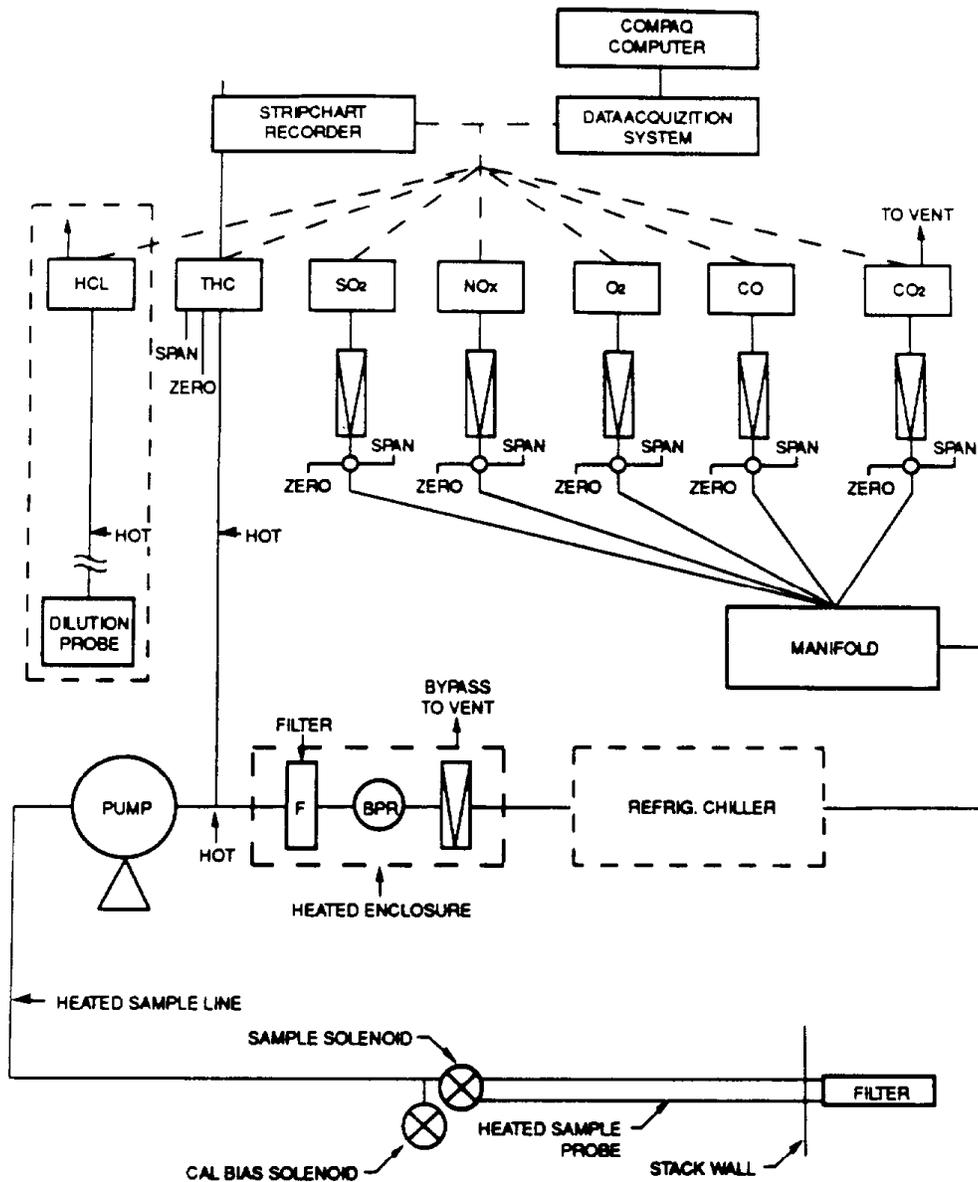


Figure 94: Continuous emissions monitoring system.

In the HCl and THC systems, the sample is introduced directly into the instruments without prior conditioning to remove moisture. This prevents any HCl or THC loss in the moisture removal process. The results must be corrected to account for the moisture in the sampled gas before they can be compared with other data. The HCl and THC analyzers are usually equipped with their own pumps.

A single sample is withdrawn for the O₂, CO₂, SO₂, NO_x, and CO instruments. The gas sample is passed through a conditioning system before it is introduced into these monitors. The conditioning system consists of two filters to remove any condensed material and a chiller. The chiller cools the gas and forces most of the moisture to condense. The condensed moisture is then removed from the gas stream.

To ensure that the results from the CEMS are accurate, careful quality assurance and quality control procedures should be used. These procedures include:

- Regular bias and linearity checks
- Frequent leak checks
- Regular zero and span drift correction
- Periodic response time checks.

During a compliance test, each of the parameters must be within strict guidelines (103). The instrument outputs can be recorded using a computer-based data acquisition system, a strip-chart recorder, or both. Typical instrument specifications for permanent and portable CEMS are shown in Tables 36 and 37.

TABLE 36. TYPICAL PERMANENT CONTINUOUS EMISSIONS MONITORING SYSTEMS

Species Of Interest	Principle of Operation	Range	Sensitivity ¹ (percent of full scale)
Oxygen	Paramagnetic	0-100%	1.0
Carbon Dioxide	Non-Dispersive Infrared	0-20%	1.0
Carbon Monoxide	Non-Dispersive Infrared	0-500 ppm through 0-5000 ppm	0.4
Nitrogen Oxides	Chemiluminescent	0-2.5 ppm through 0-10,000 ppm	1.0
Sulfur Oxides	Non-Dispersive Ultraviolet	0-100 ppm through 0-1000 ppm	< 1.0
Total Hydrocarbons	Flame ionization detector	0-50 ppm through 0-200,000 ppm	1.0
Hydrogen Chloride	Gas Filter Correlation	0-5 ppm through 0-5000 ppm	0.1 ppm ²

1. Minimum detectable amount
2. Sensitivity independent of instrument scale

TABLE 37. TYPICAL PORTABLE CONTINUOUS EMISSIONS MONITORING SYSTEMS

Species Of Interest	Principle of Operation	Ranges	Sensitivity ¹ (percent of full scale)
Oxygen	Paramagnetic	0-10% 0-25% 0-50% 0-100%	1.0
Carbon Dioxide	Non-Dispersive Infrared	0-20%	1.0
Carbon Monoxide	Non-Dispersive Infrared	0-500 ppm 0-1000 ppm 1-2000 ppm	1.0
Nitrogen Oxides	Chemiluminescent	0-2.5 ppm through 0-10,000 ppm	1.0
Sulfur Oxides	Non-Dispersive Ultraviolet	0-100 ppm through 0-1000 ppm	< 1.0
Total Hydrocarbons	Flame ionization detector	0-50 ppm through 0-200,000 ppm	1.0

1. Minimum detectable amount

- Particulate Matter

Several different manual emissions monitoring techniques are available. These techniques collect key components of the exhaust gas for later analysis. Many manual sampling methods are variations of EPA Method 5 which was designed to determine total particulate matter emissions. Specific sampling equipment and method are dependent on the species of interest. The basic Method 5 train is shown in Figure 95. A gas sample is drawn isokinetically from the flue gas through a heated probe. Downstream of the probe is a filter to collect solid particles. The filter is followed by a series of chilled impingers for the collection of water vapor and condensable matter. Following the impingers is a metering system to measure sample gas flow and a pump. Variations of this standard Method 5 sampling train can be used to determine concentrations of specific organic compounds (as opposed to the total quantity of hydrocarbons determined using CEMS), solid particles, metals, pathogens, hydrochloric acid, and pathogens.

When the quantity of particles in the gas stream is determined using the basic Method 5 equipment, the filter is weighed before and after sampling the gas stream. The weight gained by the filter is assumed to be the weight of the particles which were present in the sampled gas stream. This number is combined with the value for the total volume of gas sampled to determine the concentration of particles in the incinerators exhaust gases.

An older method for determining the approximate concentration of particles in the exhaust gas stream is EPA Method 9, Plume Opacity. Particles scatter the light passing through the plume and make it appear darker than the surrounding air. The percent reduction in visibility is defined as opacity. Plume opacity is determined by a trained and certified observer following specific criteria. The criteria include:

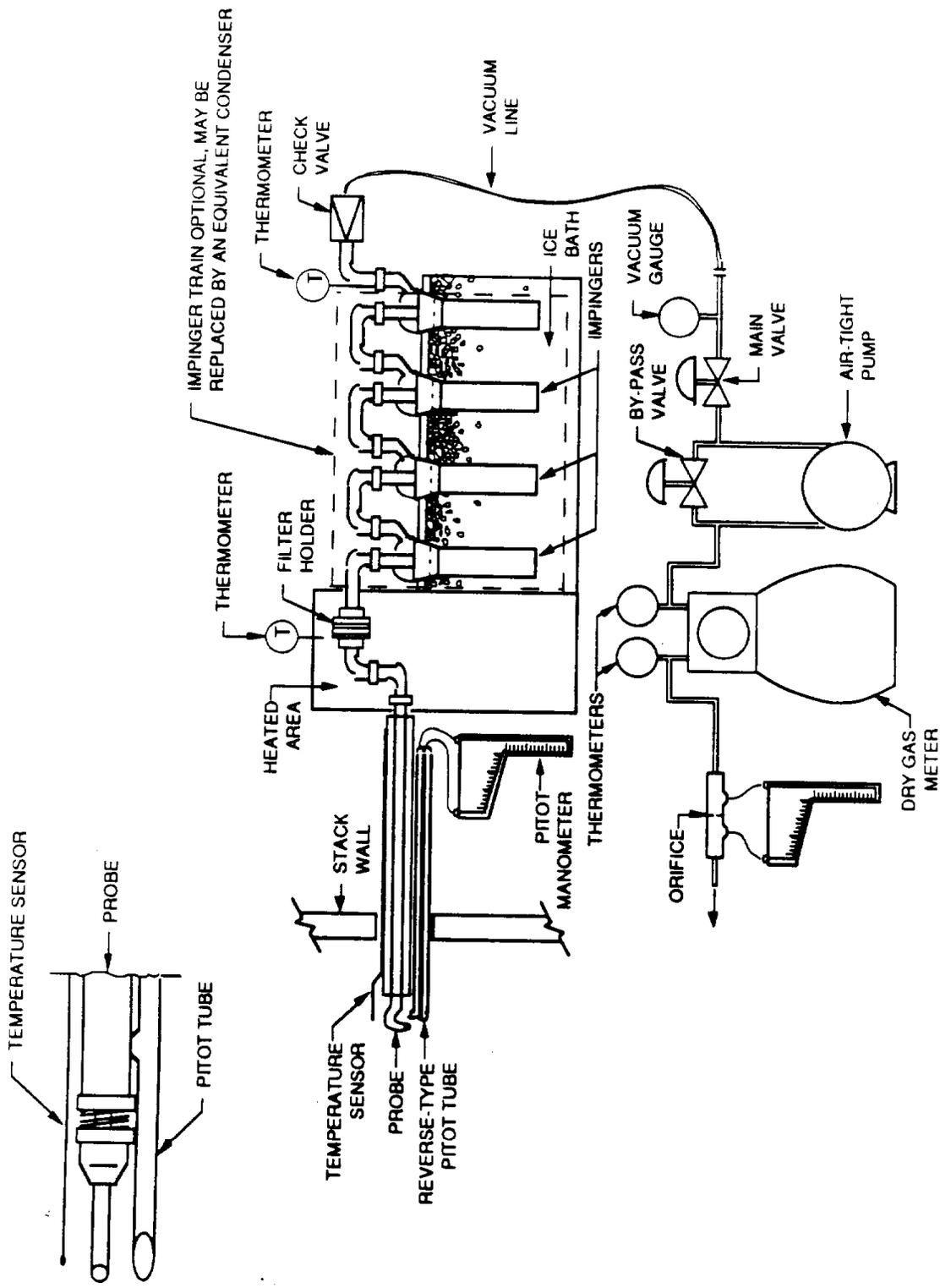


Figure 95. EPA methods sampling train.

- Distance and direction from stack to observer
- Observation frequency and duration
- Adjustment for plume location and potential steam plumes
- Data reduction techniques

Fly ash particle size can be determined in the flue gas if there is interest in the concentration of particulate matter with effective diameters of less than $10\ \mu\text{m}$ (PM_{10}). Particle size is generally determined using an impactor with the Method 5 sampling train discussed previously. There are three major criteria used to choose the proper impactor system for use. These criteria are:

- 1.) The sampling period must be long enough to provide a reasonable averaging of transient conditions in the stack.
- 2.) The loading on a given impactor stage must be low enough to prevent re-entrainment.
- 3.) The sampling rate through the impactor must be low enough to prevent scouring of impacted particles by high gas velocities.

Figure 96 shows a typical inertial cascade impactor that can be used for determining particle size. The complete sample train is shown in Figure 97. Stack gas temperature is measured using a thermocouple attached to the impactor, with the thermocouple junction near the nozzle. Stack gas velocity is determined using an S-type pitot. The gas sample is extracted from the exhaust isokinetically. Each plate of the impactor is covered with a substrate which captures all the particles impinging on it. Glass fiber substrates are typically used. Besides providing a lightweight impaction surface, glass fiber mats greatly reduce re-entrainment resulting from particle bounce. They are superior to greased metal substrates when sampling very hot gas streams but must be handled carefully to prevent fiber loss after weighing. In addition, it has been found that glass fiber materials often exhibit anomalous weight gains resulting from sulfate formation on the substrates when gas streams with high sulfur and HCl concentrations are sampled. HCl and sulfur dioxide in a gas stream react with chemically basic sites on most glass materials and form sulfates. Acid-washed substrates can be used to minimize this problem. It is possible to quantify the sulfate formed by performing a test in which a total filter is placed in the probe before the impactor. Any observed substrate weight gain during this test will be the result of HCl and SO_2 absorption, and should be corrected for in the actual cascade impactor tests. Where possible, the impactor will be oriented vertically in a duct with an upward gas flow to minimize gravity effects on particle re-entrainment.

- Metals

The metals in the exhaust gases are also collected using a modification of the Method 5 sampling equipment (104). A schematic of the "Multiple Metals Sampling Train" is presented in Figure 98. All train components are made of either glass or teflon. No metal is allowed to contact the sample after it has entered the probe. The sample train has a heated quartz glass probe. The probe is followed by a heated glass fiber filter and chilled impingers. The first impinger is empty and used as a water knockout. The second impinger contains 100 ml of a $\text{HNO}_3/\text{H}_2\text{O}_2$ solution. Impingers four and five both contain 100 ml of acidic potassium permanganate solution, and impinger 6 contains 300 g of silica gel. The impingers are followed by a meter box containing a pump, dry gas meter, and a calibrated orifice meter.

Any metals present on solid particles will be captured on the filter. The impinger solutions are designed to capture and retain any gas phase metal species. Acidic potassium permanganate solution is used specifically to capture gaseous mercury. There are specific protocols for preparation of the reagents, train assembly, and sample recovery that can be found in EPA protocol draft reports.

TOP VIEW

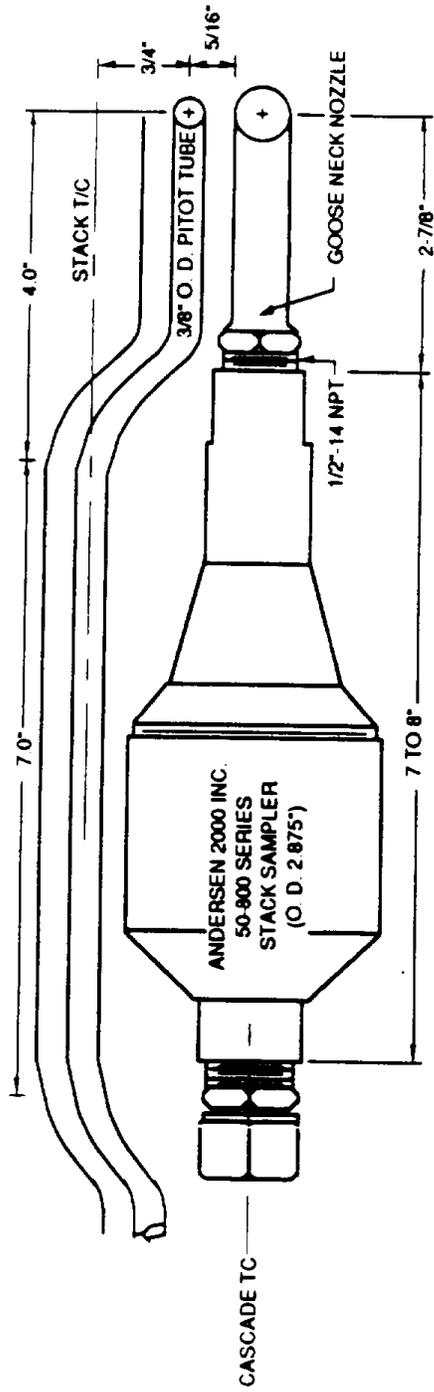


Figure 96 Typical impactor.

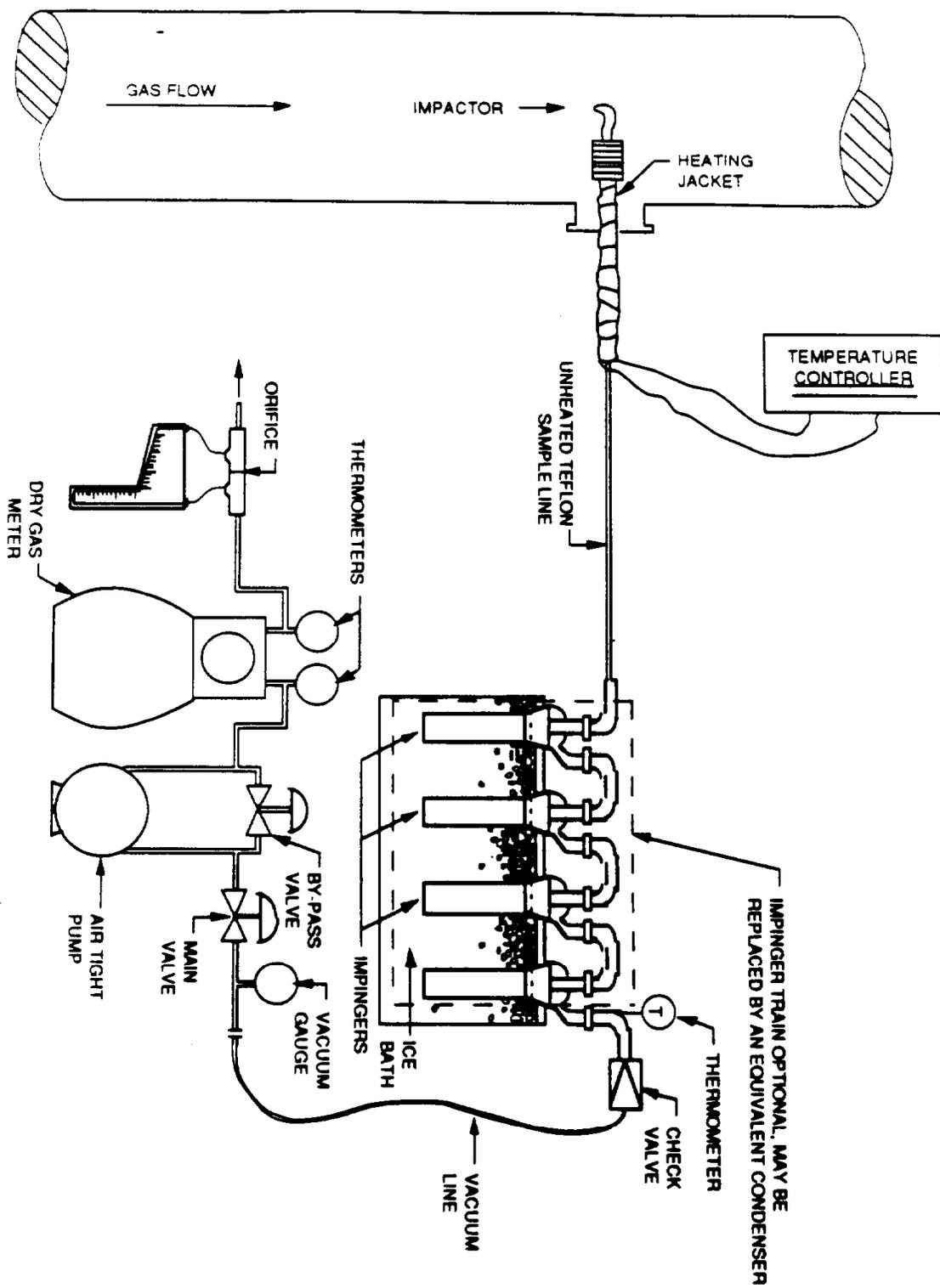


Figure 97. Sampling train used to determine particle size distribution.

Sampling time is based on the expected concentration of the metals in the gas stream and the desired sensitivity. Longer sampling times allow greater sensitivity. 2 - 4 hours are typically required to collect sufficient quantities to achieve acceptable sensitivity. However, the test protocol specifies that the testing time should not exceed 4 hours. Testing for longer than 4 hours may significantly change the composition of the impinger solutions.

Samples collected using the multiple metals sampling train can be analyzed for particulate and target metals. Particulate is determined gravimetrically using Method 5 procedures. All metals except mercury can be effectively analyzed by inductively coupled argon plasma atomic emission spectroscopy (ICAP). Mercury is determined using Method 6010 of EPA SW-846.

- Trace Organics

Method 5 can also be modified to collect trace organic species which may be present in the exhaust gases. Figure 99 illustrates the "Modified Method 5" train. As in the method used to capture metals, a gas sample is withdrawn isokinetically from the stack. The sample is passed through a heated filter to remove any condensed material. The gases are then passed through a condenser and a container filled with XAD-2 resin. This resin strongly absorbs many organic species including dioxins, furans, and polynuclear aromatic hydrocarbons (PAHs).

Standard analytical procedures described in EPA SW-846, "Test Methods for Evaluating Solid Waste," (101) are used to determine target organic compounds levels in organics train samples. The organic compounds will be extracted from the particles collected on the filter, the resin, and the impinger fluids using soxlet or liquid/liquid methods depending on sample matrix. Extractions are divided into equal parts for as many analytical methods as required. Polynuclear aromatic hydrocarbons (PAHs) can be measured using Method 80980, a gas chromatographic method. Gas chromatograph/mass spectroscopy (GC/MS) methods should be used for PCDD/PCDF and other semi-volatile organic compounds analyses according to EPA proposed Method 23, "Determination of Polychlorinated Dibenzo-p-Dioxins and Polychlorinated Dibenzofurans from Stationary Sources." These procedures parallel Method 8280 from SW-846. Types of compounds that can be measured are tabulated in Table 38.

An alternate method for collecting samples of organic compounds is illustrated in Figure 100. In this method, all the gases sampled are collected in a Tedlar bag. Tedlar is a well characterized material which is highly impervious to organic gases. Once filled, the bag is taken to a laboratory where the compounds of interest are concentrated and quantified.

- HCl

HCl concentrations in the exhaust can be determined using a modification of Method 5 in addition to the CEMS method mentioned earlier in this section (105). In the train for hydrogen chloride, all components are of glass, stainless steel or teflon construction. Downstream of the probe is a teflon filter maintained at a temperature of $250^{\circ}\text{F} \pm 25^{\circ}\text{F}$. After the sample gas passes through the filter, it is bubbled through an absorbing solution, 15 ml of 0.1 N sulfuric acid (H_2SO_4). Impingers three and four contain a chlorine scrubbing solution consisting of 0.1 N sodium hydroxide (NaOH). If long sampling times are needed or the exhaust gas contains high levels of water, a midjet impinger with a shortened stem may be used as a water knockout before the first standard impinger.

The hydrogen chloride (HCl) sampling train has impingers containing dilute acid. In the dilute acid, HCl gas is dissolved and forms chloride (Cl^-) ions. The Cl^- is analyzed by ion chromatography (IC). Analytical procedures from Method 26 "Determination of Hydrogen Chloride Emissions from Stationary Sources (8.4/89)" (105) are used.

TABLE 38. METHOD 8280 TARGET COMPOUNDS

DIOXINS

Total trichlorinated dibenzo-p-dioxins (TrCDD)
Total tetrachlorinated dibenzo-p-dioxins (TCDD)
2378-TCDD
Total pentachlorinated dibenzo-p-dioxins (PeCDD)
2378-PeCDD
Total hexachlorinated dibenzo-p-dioxins (HxCDD)
2378-HxCDD (isomers)
Total Heptachlorinated dibenzo-p-dioxins (HpCDD)
2378-HpCDD
Total octachlorinated dibenzo-p-dioxins (OCDD)

FURANS

Total trichlorinated dibenzofurans (TrCDF)
Total tetrachlorinated dibenzofurans (TCDF)
2378-TCDF
Total pentachlorinated dibenzofurans (PeCDF)
2378-PeCDF isomers
Total hexachlorinated dibenzofurans (HxCDF)
2378-HxCDF isomers
Total heptachlorinated dibenzofurans (HpCDF)
2378-HpCDF isomers
Total octachlorinated dibenzofurans (OCDF)

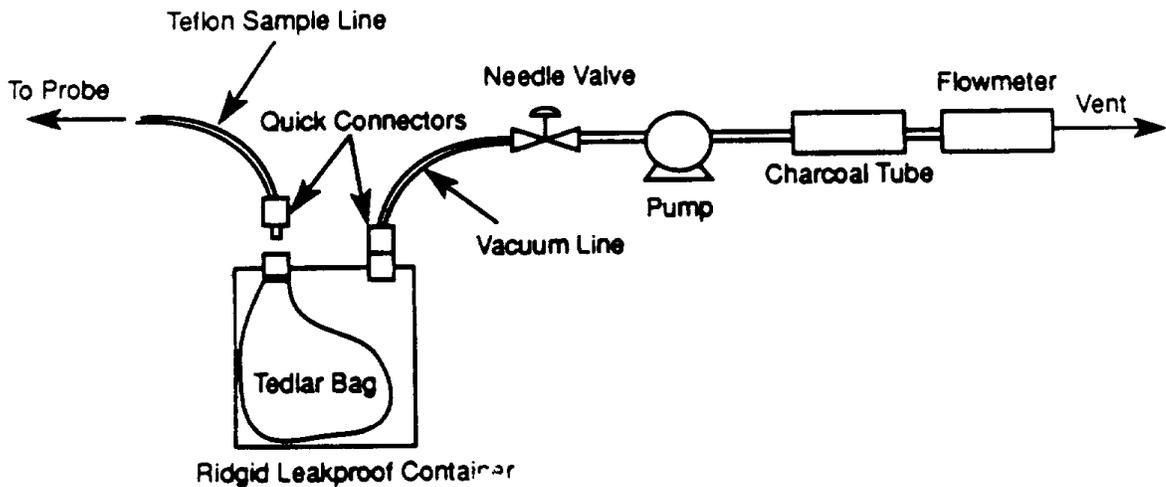


Figure 100. Simple sampling train used to collect volatile organic compounds for analysis.

With all the manual test methods described above, sampling time plays an important role in determining the procedures' sensitivity. Longer sampling times allow the collection of larger quantities of the material of interest and greater sensitivity.

- Pathogens

The detection of microorganisms in the exhaust gases warrants special attention. A standard protocol has not yet been developed by the EPA. However, a method is being developed which calls for the use of a modification of the Method 5 train. The waste is spiked with *Bacillus Stearothermophilus* (an extremely heat-resistant, spore-forming bacteria). The exhaust gases are then tested for the presence of any of the bacteria which may have escaped destruction. Gas samples are drawn isokinetically into the sampling train shown in Figure 101. The probe is glass lined and water cooled to reduce spore mortality in the hot environment upstream of the impingers. The impingers contain a phosphate buffer solution to prevent the acids present in the sample gases from reducing the pH of the impinger solutions, which would kill spores. Spores and particulate matter are captured in the buffered solutions in the first two impingers.

Samples from the indicator spore train will be analyzed according to newly developed procedures. The samples are briefly exposed to high temperatures to kill any vegetative spore which will interfere with the *Bacillus Stearothermophilus* analysis. Sterile procedures must be observed during the analysis. Sample analysis is completed within 24 hours of sample collection. The method involves making an agar plate upon which viable colonies can grow. The filtration apparatus from the sample probe is placed onto the individual agar plate and aerobically incubated in air (65°C for 24 hrs.). Following incubation, the colonies on each plate are counted.

SOLID EFFLUENT SAMPLING AND ANALYSIS

Solids effluents usually consist of ash from the incinerator. Some flue gas cleaning systems produce additional solids effluents. Because of the variety of system characteristics, it is difficult to define standard solids sampling techniques. The EPA has developed guidelines for obtaining representative solid samples (101).

Ash components of potential interest include:

- PCDD/PCDF
- Toxic metals
- Carbon

In addition, the weight the ash would lose when completely burned, loss on ignition (LOI), is of interest. It is unlikely that these parameters would be measured in routine compliance testing. However, they are potentially important.

The PCDD/PCDF concentration in the ash is determined in much the same way that the concentration in particles in the air emissions is determined. PCDD/PCDF are extracted from a prepared ash sampling using soxlet. The extract is then analyzed using a combination of gas chromatography and mass spectrometry. The detailed procedures are described in EPA Method 23 (draft-modified). The concentrations of all metals except mercury is determined using Inductively Coupled Argon Plasma (ICAP) spectroscopy. The analysis is described in EPA Method 6010. Cold Vapor Atomic Adsorption Spectroscopy (CVAAS) is used to determine the concentration of mercury (EPA Method 7470). Loss on Ignition can be determined by exposing the sample to a uniform, high temperature with an excess of oxygen available until the weight has stabilized. The procedures are described in more detail in ASTM Method D2795. Ash carbon content is generally determined using ASTM Method D3172.

Metals leachability is also a concern. The EPA has developed two techniques for estimating the quantity of toxic metals that would be removed from the ash under conditions typically found in landfills. These techniques are the Extraction Procedure (EP) and the Toxicity Characteristic Leaching Procedure (TCLP). The EP was promulgated in 1980 (106) and involves the use of a dilute solution of acetic acid to leach metals from the ash. The TCLP was developed in response to criticism of the EP. TCLP was promulgated in 1986 (107). TCLP calls for use of either a buffered or a dilute acetic acid solution depending on the pH of the initial slurried solid.

LIQUID EFFLUENT SAMPLING

Liquid effluents are produced by some flue gas cleaning equipment. There is a current trend to minimize or eliminate liquid effluents. Characteristics of liquid effluents that may be of concern include:

- Solution pH
- PCDD/PCDF concentration
- Toxic metals concentration
- Chlorine concentration

pH is commonly determined with specific ion electrodes. PCDD/PCDF, metals and chlorine concentrations are all determined using techniques like those used to analyze the impinger solutions in the manual sampling trains discussed previously.

OPERATING PARAMETERS

The operation of an incinerator is controlled by many factors. As medical waste combustion equipment becomes more sophisticated, more of these parameters are being monitored and controlled. Parameters of potential interest are identified in EPA publications describing good combustion practices for municipal solid waste incineration (108) and EPA guidance manuals for hazardous waste incinerator permitting (109). These parameters include:

- Feed rate
- Chamber temperatures (characteristic temperatures of each chamber.)
- Combustion air flow rates
- Auxiliary fuel feed rate
- Flue gas cleaning device specific parameters
- Ash production rate

No system now manufactured is equipped with devices to measure all these parameters. However, as more sophisticated incineration control equipment is developed, more of the parameters are typically monitored and controlled.

As described in other sections of this report, feed rate has a strong effect on system operation. Because of this, many incineration systems are equipped with devices to monitor waste feed rate. These systems involve the use of a scale (either attached to the incinerator feed system or separate) and a timer. The charge frequency and charge size are also monitored.

Chamber temperatures are the most commonly monitored parameters. Temperatures are typically determined by placing a thermocouple in contact with the gas stream. Care must be taken in choosing the location of the thermocouple to ensure that the temperature measured is characteristic of the incinerator's performance. Measurements produced by a fixed thermocouple are subject to two major limitations. They cannot measure the temperature distribution across a chamber and they may not accurately reflect the temperature of the gases. All thermocouples radiate heat to the incinerator walls and receive radiated heat from the burning materials. To avoid both problems, a suction pyrometer is used for more accurate temperature measurements. As shown in Figure 102, a suction pyrometer consists of a thermocouple contained within a ceramic sheath. Gases are pulled through a hole in the outside of the sheath and passed over the thermocouple. The thermocouple is exposed to the gas temperature but is not exposed to the radiative environment of the combustion chamber. The suction pyrometer is typically introduced into the chamber through a port and is used to determine the gas temperatures at many different locations in the chamber. Suction pyrometers are usually used only during periodic characterization tests.

Gas velocities are not typically measured in medical waste incinerators. Analogy to hazardous and municipal waste incinerators indicates there are several methods available for the measurement of gas velocities. The most common is the pitot tube. Figure 103 illustrates the pitot tube arrangement used with the manual sampling trains described previously. Gas velocity is determined by measuring the difference in pressures between the two openings in the probe. Many other techniques are available from commercial vendors.

Auxiliary gas feed rate is infrequently measured. This has been due primarily to a lack of interest. Metering techniques for natural gas and other fuels are well-defined and precise.

Flue gas cleaning device operation is controlled by many different parameters specific to the devices of interest. The definition of these factors and the techniques used to measure them is beyond the scope of this report.

Ash production rate is almost never directly measured in medical waste incinerators. However, ash may contribute significantly to treatment costs. Ash must be disposed of. Local requirements vary, but generally ash is sent to a landfill.

MONITORING SYSTEM COST

The costs of continuous emission monitoring systems for medical waste incinerators (like those for municipal waste incinerators) are substantially greater than the cost of the type of analyzers routinely used by combustion research laboratories or field testing teams. The systems must be rugged, must pass stringent EPA certification standards, must be self-calibrating, must provide for continuous recording and averaging and must be capable of prolonged operation without intervention by a skilled technician. During a recent workshop on medical waste incineration (Cincinnati, Ohio, February 15-16, 1989), incinerator equipment vendors suggested that the installed cost of a certified CO monitor with automatic correction for dilution (e.g., corrected to 7 percent O₂ or 12 percent CO₂) was approximately \$100,000. An opacity monitor was estimated to cost about \$20,000 (installed) while NO_x and SO_x monitors would add about \$50,000 each to the total monitoring cost. Certification costs were estimated to run as high as \$20,000. Combining these systems, such an incinerator with certified continuous emission monitoring and reporting of opacity, CO, CO₂, SO_x and NO_x is estimated to cost about \$250,000. Thus, a complete CEMS was estimated to have a total cost approximately equal to the capital cost of a 450 kg/hr (1000 lb/hr) incinerator.

It should be stressed that the CEMS costs were estimated by incinerator equipment manufacturers who are uniformly opposed to installation of such equipment. However, EPA measurement specialists who attended this conference agreed with the manufacturers on the general magnitude of the cost. As a final note, EPA's Office of Air Quality Planning and Standards has recently (June 2, 1989) issued a work assignment to

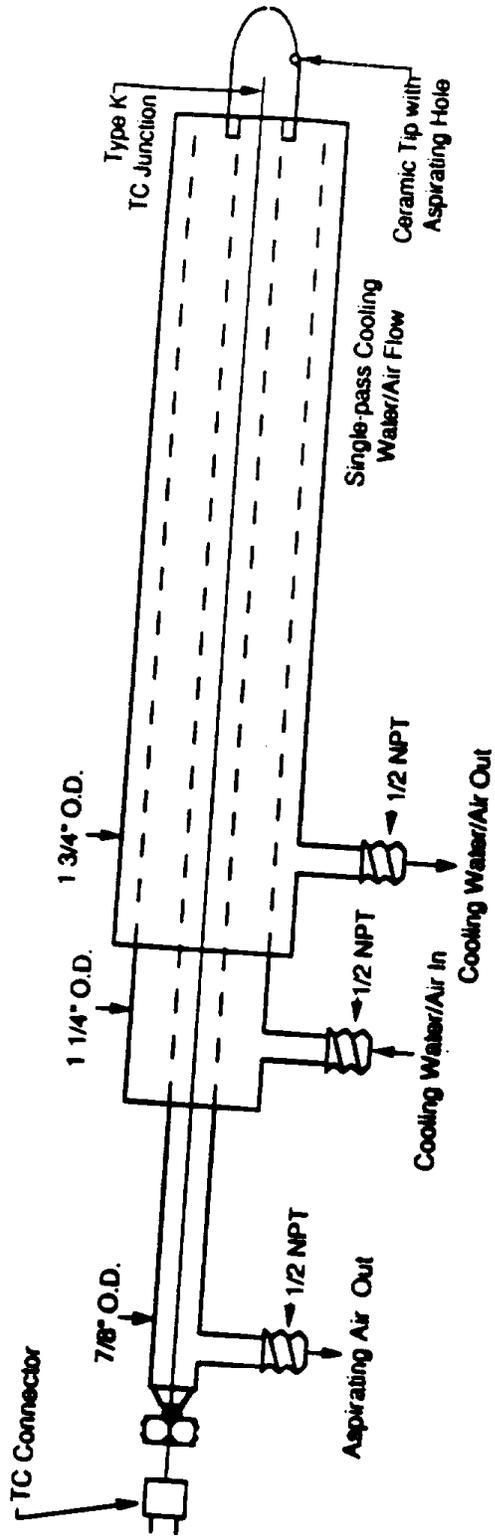


Figure 102. Suction pyrometer with shielded tip.

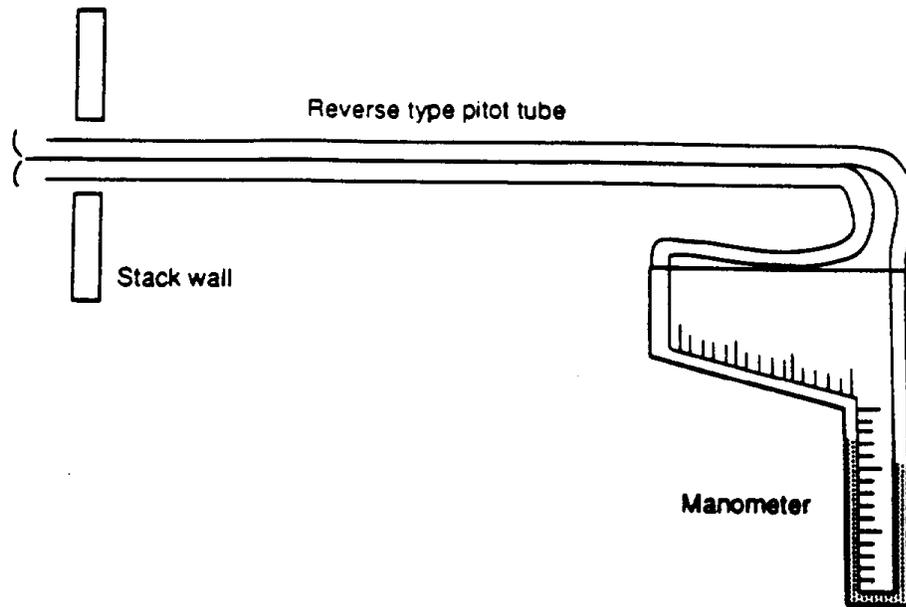


Figure 103. Pitot tube arrangement used to determine stack gas velocities.

Entropy Environmentalists, Inc., to perform a study entitled "CEMS Cost Estimates for Municipal Waste Combustors." The final report on this task is projected to include results from a survey of CEMS vendors and users.

REFERENCES

1. "EPA Releases Estimates on Infectious Wastes Generation for This Week's Meeting. Infectious Waste News. November 17, 1988.
2. Rutala, W. "Management of Infectious Waste by United States Hospitals," In: Proceedings: Twenty-Eighth ICAAC, Los Angeles, 1988.
3. Acurex Corp. Guidance on Setting Permit Conditions and Reporting Trial Burn Results, EPA/625/6-89/019, January 1989.
4. Santolevi, J. J. and R. L. Kratz. "Medical Waste Incineration Requirements for System Design Modifications," In: Proceedings: Third National Symposium on Infectious Waste Management: Incinerator Retrofit for Hospitals and Industry, Chicago, IL, April 1989.
5. U.S. Congress. H.R. 3515. January 1988.
6. Rutala, W. American Journal of Infectious Control, 13, 1984, p. 218.
7. U.S. Congress, Office of Technology Assessment. Issues in Medical Waste Management: Background Paper, OTA-BP-O-49, October 1988.
8. U.S. EPA, Office of Solid Waste and Emergency Response Policy Directive No. 9401.00-2 EPA Guide for Infectious Waste Management, EPA/530-SW-86-014, May 1986.
9. Federal Register. 54, 56, March 24, 1989. pp. 12340-2.
10. Doucet, L. Hospital/Infectious Waste Incineration Dilemmas and Resolutions. Doucet and Manika, P.C., 1988.
11. Doyle, B. W., D. A. Drum, and J. D. Lauber. Pollution Engineering, July 1985.
12. Hickman, D. C. Cadmium and Lead in Bio-Medical Waste Incinerators. Master of Science Thesis, University of California, Davis, 1987.
13. Thompson, T. K., and J. S. Vavruska. "Design Features of the New Los Alamos Low Level Waste/Mixed Waste Incinerator." In: Proceedings: The 1989 Incineration Conference, Knoxville, TN. May 1989.

14. University of California, Irvine. Draft Low Level Radioactive Waste Handbook - Low Level Radioactive Waste Management in Medical & Biomedical Research Institutions. U.S. Department of Energy, 1981.
15. Radian Corp. Hospital Waste Combustion Study, Data Gathering Phase, Final Draft. U.S. Environmental Protection Agency, October 1987.
16. Campbell, D. "Hospital Waste Management in Canada." In: Proceedings: National Workshops on Hospital Waste Incineration and Hospital Sterilization. U.S. EPA, OAQPS, San Francisco, May 1988.
17. Cross, F. L. "The Case For Regional Incineration of Hospital Waste," In: Proceedings: First National Symposium On Incineration of Infectious Wastes, Washington, D.C., May 1988.
18. Milburn, T. "Biomedical Waste Incineration BACT Application Considerations," In: Proceedings: Third National Symposium on Infectious Waste Management, Chicago, IL, April 1989.
19. Van de Velde, J. M. A. "Aspects of the Disposal of Hospital Waste in the Netherlands," Recycling International: Recovery of Energy and Material From Residues and Waste, K. J. Thome-Kozmiensky ed., 1982.
20. Nini, M., M. Bellotto, and V. Lamarca. "The Role of Waste Thermal Destruction in the Waste Disposal Plan for the Region Puglia, Italy." Proceedings of the Incineration Conference, Knoxville, Tennessee, May 1989.
21. Kremer, J. G., F. D. Dryden, and S. J. Hyland. Disposal of Hospital Infectious Solid Wastes to the Sewerage System." L.A. County Sanitation Districts, 1975.
22. Yandell, J. "Session I: Overview of the Problem, Summary of Discussion," In: Proceedings National Workshops on Hospital Waste Incineration and Hospital Sterilization. U.S. EPA, OAQPS. San Francisco, May 1988.
23. Brunner, C. A., and C. H. Brown. Journal of the Air Pollution Control Association (JAPCA). 38, 10, October 1988.
24. U.S. Census Bureau. 1988 Statistical Abstract of the United States. U.S. Government Printing Office, Washington, D.C., 1988.
25. I.I.A. Incinerator Standards. Incinerator Institute of America, November 1968, reprinted 1970
26. Neulicht, R. M., M. B. Turner, J. A. Eddinger, K. R. Durkee. Operation and Maintenance of Hospital Medical Waste Incinerators. EPA-450/3-89-008.
27. Federal Register. July 6, 1987.
28. Sedman, C. B., and T. G. Brna. Municipal Waste Combustion Study: Flue Gas Cleaning Technology. EPA/530-SW-87-021d, June 1987.

29. Wark, K. and C. F. Warner. *Air Pollution: Its Origins and Control*. Harper and Row, New York, 1978.
30. Frame, G. B. *Journal of Air Pollution Control Association (JAPCA)*. 38, 8, August 1988.
31. Brady, J. D. *Economically and Operationally Attractive Incinerator Emissions Controls*. Anderson 2000 Technical Report, 1989.
32. Shuler, S. "Controlled Air Incineration of Biohazardous Waste: Technology and Regulatory Economic Impacts." In: *Proceedings: Hospital Waste Incineration and Hospital Sterilization Workshops*, EPA-450/4-89-002, January 1989.
33. Lee, C. C., W. S. Lanier, and W. R. Seeker. *Medical Waste Incinerator Workshop, Summary Report*. Workshop held at U.S. EPA Risk Reduction Engineering Laboratory, Cincinnati, OH, February 1989.
34. Jenkins, A. C. *Evaluation Test on a Hospital Refuse Incinerator at Saint Agnes Medical Center, Fresno, CA*. California Air Resources Board, ARB/SS-87-01, January 1987.
35. Jenkins, A., C. Castronovo, G. Lindner, P. Ouchida, and D.C. Simeroth. *Evaluation Test on a Hospital Refuse Incinerator at Cedars-Sinai Medical Center, Los Angeles, CA*. California Air Resources Board, ARB/SS-87-11, April 1987.
36. Jenkins, A., P. Ouchida, and G. Lew. *Evaluation Test on a Refuse Incinerator at Stanford University Environmental Safety Facility, Stanford, CA*. California Air Resources Board, ARB/SS-88-025, August 1988.
37. Jenkins, A., P. Ouchida, and G. Lew. *Evaluation Test on a Hospital Refuse Incinerator at Sutter General Hospital, Sacramento, CA*. California Air Resources Board, ARB/SS-88-026, April 1988.
38. McCormack, J. E. *Evaluation Test on a Small Hospital Refuse Incinerator, Saint Bernadines Hospital, San Bernardino, Sacramento, CA*. California Air Resources Board, Draft Report C-87-092 1988.
39. Midwest Research Institute. *Emission Data Base for Municipal Waste Combustors*. EPA/530-SW-87-021b, June 1987.
40. Ollie, et al. *Chemosphere*. 6, 1977.
41. Ozvacic, F., G. Wong, H. Tosine, R. E. Clement, and J. Osborne. *Journal of the Air Pollution Control Association (JAPCA)*. 35, 8, 1985. p. 849.
42. Shaub, W. M., and W. Tsang. *Environmental Science and Technology*. 17, 12, 1983. p. 721.
43. Ballschmiter, K., W. Zoller, C. Scholtz, and A. Nottrodt. *Chemosphere*. 12, 4/5, 1983. p. 585.
44. Benefenanti, E., F. Gizzi, R. Reginato, R. Fanelli, M. Lodi, and R. Tagliatferri. *Chemosphere*. 12 3 10, 1983. p. 1151.

45. Vogg, H., and L. Stieglitz. *Chemosphere*, 15, 1986. p. 1373.
46. Karesek, F. W., and L. C. Dickson. *Proceedings of the Municipal Waste Incineration Conference*. Montreal, Canada, October 1987.
47. Barton, R. G., et al. *Draft Topical Report: Analysis of Quebec City Incineration Tests*. EPA Contract 68-03-3365, April 1988.
48. Environment Canada. *National Incinerator Testing and Evaluation Program: Environmental Characterization of Mass Burning Incinerator Technology at Quebec City; Summary Report*. Report EPS 3/UP/5, June 1988.
49. Seeker, W. R., M. P. Heap, and W. S. Lanier. "Combustion Control of Organic Emissions." EPA/530-SW-87-02/C. See also J. D. Kilgroe, L. P. Nelson, P. S. Schindler, and W. S. Lanier. "Combustion Control of Organic Emissions from Municipal Incinerator." In: *Proceedings: First International Congress on Toxic Combustion Byproducts: Formation and Control*. Submitted for Publication. *Combustion Science and Technology*, 1990.
50. Dellinger, B., P. Taylor, and D. Tirey. "Gas Phase Formation - Mechanisms of Chlorinated Aromatic Compounds From the Thermal Degradation of Simple Chloro Carbon Precursors." In: *Proceedings: First International Congress on Toxic Combustion By-Products: Formation and Control*. Submitted for Publication. *Combustion Science and Technology*, 1990.
51. Moyeda, D. "The Formation and Control of PCDD/PCDF From RDF Fired Combustion Systems." In: *Proceedings: Dioxin 1989*, Toronto, September 1989.
52. Allen, R. J, G. R. Brenniman, R. R. Logue, V. A. Strand. *Bacterial Emissions From Incineration of Hospital Waste*. Illinois Department of Energy and Natural Resources, ILENR/RE-AQ-88/17, July 1988.
53. Burchinal, J. C. *A Study of Institutional Solid Wastes*. EPA-670/2-73-083, 1973.
54. Gordon, J. G., et al. *Disposal of Hospital Wastes Containing Pathogenic Organisms*. The MITRE Corporation, Publication No. MTR-79W00098, 1980.
55. Dixon, R. E. *Annals Internal Medicine*. 89 (Part 2), 1978. p. 749.
56. Barbiato, M. S., and G. G. Gremillion. *Applied Microbiology*, 16, 1968.
57. Barba, P. D. "Test Results From Bacterial Sample Burns From Nine Infectious Waste Incinerators." In: *Proceedings: Mid-Atlantic States Section, Air Pollution Control Association*, 1987.
58. Barbiato, M. S., and M. Shapiro. *Journal Medical Primatology*. 6, 1977.
59. Barbiato, M. S., L. A. Taylor, and R. W. Seiders. *Applied Microbiology*, 16, 1968.

60. U.S. Environmental Protection Agency. Pathogens Associated With Solid Waste Processing. EPA-SW-49r, 1970.
61. Kelly, N., R. Allen, G. Brenniman, and J. Kusek. "Evaluation of Bacterial Emissions From a Hospital Incinerator." In: Proceedings: The Sixth World Congress on Air Quality, Vol. 2, 1983.
62. Brenniman, G. R., and R. J. Allen. "Hospital Incineration of Infectious Waste and Airborne Emissions." In: Proceedings: Third National Symposium on Infectious Waste Management, Chicago, IL, April 1989.
63. Merryman, E. L., and A. Levy. Enhanced SO₃ Emissions from Staged Combustion. EPA-600/7-79-002, January 1979.
64. Kirtcher, J. F., A. A. Putnam, D. A. Ball, H. H. Krause, J. M. Genco, R. W. Coutant, J. O. L. Wendt, and A. Levy. A Survey of Sulfate, Nitrate, and Acid Aerosol Emissions and Their Control. EPA-600/7-77-041, 1977.
65. Chen, S. L., M. P. Heap, D. W. Pershing, and G. B. Martin. "Influence of Coal Combustion on the Fate of Volatile and Char Nitrogen During Combustion." In: Proceedings: Nineteenth Symposium (International) on Combustion, The Combustion Institute, Pittsburgh, 1982. p. 1271.
66. Versar, Inc. Guidance on Metals and Hydrogen Chloride Controls for Hazardous Waste Incinerators. U.S. EPA/OSW, March 1988.
67. U.S. EPA. Health Assessment Document for Chromium, Final Report. EPA-600/8-83-014F, August 1984.
68. Neville, M. and A. F. Sarofim. "The Stratified Composition of Inorganic Submicron Particles Produced During Coal Combustion." In: Proceedings: Nineteenth International Symposium on Combustion, The Combustion Institute, 1982. p. 1441.
69. Law, S. L., and G. E. Gordon. Environmental Science and Technology, 13, 4, 1979. p. 432.
70. Quann, R. J., and A. F. Sarofim. "Vaporization of Refractory Oxides During Pulverized Coal Combustion." In: Proceedings: Nineteenth International Symposium on Combustion, The Combustion Institute, 1982. p. 1429.
71. Li, K. W. AIChE Journal. 20, 1974. p. 1017.
72. Goldstein, H. W., and C. W. Siegmund. Environmental Science and Technology, 10, 12, 1976. p. 1109.
73. Peterson, H. H. "Electrostatic Precipitators for Resource Recovery Plants." In: Proceedings: 1984 National Waste Processing Conference, ASME, Orlando, FL, 1984.
74. Vogg, H., H. Braun, M. Metzger, and J. Schneider. Waste Management and Research, 4, 1986. p. 65-74.

75. Flagan, R. C. "Submicron Particles from Coal Combustion." In: Proceedings: Seventeenth International Symposium on Combustion, The Combustion Institute, 1978. p. 97.
76. Friedlander, S. K. Smoke, Dust, and Haze. John Wiley and Sons, New York, 1977.
77. Senior, C. L., and R. C. Flagan. Environmental Science and Technology, 1, 1982. p. 371.
78. Barton, R. G., P. M. Maly, W. D. Clark, W. R. Seeker, and W. S. Lanier. Prediction of the Fate of Toxic Metals in Hazardous Waste Incinerators. A Final Report under EPA Contract 68-03-3365, EER Corp., Irvine, CA, 1989.
79. Vaccari, P. L., K. Tonat, R. DeChristoforo, J. F. Gallelli, and P. F. Zimmerman. American Journal of Hospital Pharmacy, 41, 1984. p. 87.
80. La Fond, R. K., J. C. Kramlich, W. R. Seeker, and G. S. Samuelsen. Evaluation of Continuous Performance Monitoring Techniques for Hazardous Waste Incinerators. Journal of Air Pollution Control Association, 35, 6, June 1985.
81. Rogers, H. W. Journal Hospital SPD, July/August, 1985. p. 40.
82. Gershon, R. M., and K. A. Strauss. "Thermal Destruction of Radiolabeled Biohazardous Waste Materials." In: Proceedings: The 1989 Incineration Conference, Knoxville, TN, May 1989.
83. Lauber, J. D. "The Incineration of Low Level Radioactive Wastes." In: Proceedings: 1988 Conference on Toxic Substances Sponsored by the Air Pollution Control Association, Montreal, Canada, April 1988.
84. Davidson, R. L., D. F. S. Natusch, J. R. Wallace, and C. A. Evans, Jr. Environmental Science and Technology, 8, 13, 1974.
85. Konheim, C. S., and F. Hasselriis. "Characterization of Hospital Waste Emissions." In: Proceedings: Eighty-First Annual Meeting, Air Pollution Control Association, Dallas, TX, June 1988.
86. Entropy Environmentalists, Inc. Stationary Source Sampling Report. EEI Ref. No. 5286-B, Signal Resco Pinellas County Resource Recovery Facility St. Petersburg, Florida, CARB/DER Emissions Testing, 1987.
87. Tsaveras, T., M. Gaskin, and J. Maidhof. "Hospital Waste Incineration And Emissions Test Results." In: Proceedings: Mid-Atlantic States Section of the Air Pollution Control Association, Atlantic City, NJ, November 1987.
88. Powell, F. C. Journal of the Air Pollution Control Association (JAPCA), 37, 7, 1987.
89. Milburn, T. J. "Biomedical Waste Incineration BACT Application Considerations." In: Proceedings: Third National Symposium on Infectious Waste Management, Chicago, IL, April 1989.

90. Pinder, S.N. "Incineration of Pre-densified Hospital Waste." In: Proceedings: The 1989 Incineration Conference, Knoxville, TN, May 1989.
91. Klafka, S. and M. Tierney. "Pathogen Survival at Hospital/Infectious Waste Incinerators." In: Proceedings: Hospital/Infectious Waste Incineration and Hospital Sterilization Workshops, San Francisco-Baltimore, May 1988.
92. Manufacturer Interview - Thermtec, July 1989.
93. Clapp, T.L., D.S. Kosson, and R.C. Ahlert. "Leaching Characteristics of Residual Ashes from Incineration." In: Proceedings: International Conference on Incineration of Hazardous, Radioactive and Mixed Wastes, San Francisco, CA, May 1988.
94. Classic, K., G. Gross, and R.J. Vetter. *Health Physics*, 49, 6, 1985.
95. Brunner, C. R. and C. H. Brown. *Journal of the Air Pollution Control Society (JAPCA)*, Vol. 38, No. 10.
96. *Infectious Waste News*, 4,17, August 17, 1989.
97. *Infectious Waste News*, 4,1, January 5, 1989.
98. Pettit, C. L. *Waste Age*, April 1987.
99. Jones, M. R. *Index to EPA Test Methods*. National Technical Information Service, Springfield, Illinois, 1988.
100. 40 CFR: Federal Regulations, Chapter 40, Part 60.
101. *Test Methods for Evaluating Solid Waste*. U.S. EPA Office of Solid Waste, SW-846, 3rd edition, 1986.
102. *Annual Book of ASTM Standards*. American Society of Testing and Materials, 1980 - 1990.
103. *Quality Assurance Handbook for Air Pollution Measurement Systems*. Vol. I - III, U.S. EPA, Office of Research and Development, EPA/600/9-76/005, 1976.
104. *Methodology for the Determination of Metals Emissions in Exhaust Gases From Hazardous Waste Incineration and Similar Combustion Processes*. U.S. EPA Draft Method, August 28, 1990.
105. *Determination of Hydrogen Chloride Emissions from Stationary Sources*. EPA Draft Method 26, August 4, 1989.
106. *Federal Register*. 45(98), 33127-33129, May 19, 1980.
107. *Federal Register*. 51(9), 1750-1758, January 14, 1986.

108. Shindler, P., and L. P. Nelson. "Municipal Waste Combustion Assessment: Technical Basis for Good Combustion Practice. EPA 600/8-89-063, August, 1989.

109. Guidance on Setting Permit Conditions and Reporting Trial Burn Results. U.S. EPA, Office of Research and Development, EPA/625/6-89/019, January, 1989.