

VOLUME II

Part I

GUIDANCE ON REGULATION IMPLEMENTATION

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1.0 SUMMARY

This report provides guidance on complying with the provisions of Section 93104, Title 17, of the California Code of Regulations which addresses potential emissions from medical waste incinerators. The information can be summarized in a series of check lists that can be used to evaluate a given facility.

1.1 EMISSIONS

Emissions testing involves determining the average controlled polychlorodibenzo-p-dioxins and polychlorodibenzofurans (PCDD/PCDF) emission factor for an incinerator system or the PCDD/PCDF removal efficiency achieved by the air pollution control devices used (see section 3.1). The regulations covering dioxin and furan emissions are tiered. The first tier covers facilities burning over 25 tons of waste per year, while the second covers facilities burning between 10 and 25 tons of waste per year, and the third tier exempts those facilities burning less than 10 tons per year from emissions testing. Table 1-1 summarizes the requirements for facilities incinerating more than 25 tons of waste per year. Table 1-2 summarizes the requirements for facilities incinerating between 10 and 25 tons of waste per year.

1.2 TEMPERATURE LIMITS AND RESIDENCE TIMES

The check list shown in Table 1-3 is only applicable to those facilities incinerating more than 25 tons of waste per year. Facilities burning less than 25 tons per year do not have to satisfy the temperature and residence time limits.

1.3 FLY ASH AND APCD RESIDUE HANDLING

All medical waste incineration facilities must set up a system to ensure fly ash, bottom ash, and air pollution control device residuals are not entrained into the air (see section 3.3).

1.4 OWNER OR OPERATOR RESPONSIBILITIES

The responsibilities of incinerator operators vary depending on the size of the facility. Table 1-4 summarizes the responsibilities associated with operation of a facility burning more than 25 tons of waste per year. Facilities which dispose of less than 25 tons of waste per year are required only to maintain equipment for determining and recording the weight of waste charged to the incinerator.

1.5 OPERATOR TRAINING

Owners of facilities incinerating over 25 tons of waste per year are required to ensure that each person who operates or maintains the incinerator obtains either a certificate of training in medical waste incineration by the American Society of Mechanical Engineers, or equivalent training as determined by the air pollution control officer. In addition these facilities must inform operators of medical waste incineration facilities of their duty to promptly report all violations, malfunctions, or upset conditions to the district.

Owners of facilities incinerating less than 25 tons of waste per year are required only to ensure that each person who operates or maintains the incinerator obtains either a certificate of training in medical waste incineration by the American Society of Mechanical Engineers, or equivalent training as determined by the air pollution control officer.

TABLE 1-1. EMISSIONS MEASUREMENT CHECKLIST FOR FACILITIES INCINERATING MORE THAN 25 TONS OF WASTE PER YEAR.

Complete each of the following steps once per year until compliance has been demonstrated over two consecutive years.

Conduct PCDD/PCDF Compliance Source Test at $\pm 10\%$ of Maximum Permitted Capacity

Parameters to be measured in triplicate

Waste feed rate

Standard dry volume of gases collected

Standard dry gas volumetric flow rate

PCDD/PCDF emissions at stack for facilities testing for compliance with the 10 ng/kg-waste burned emission regulation

PCDD/PCDF emissions at stack and before control devices for facilities testing for compliance with the 99% removal efficiency regulation

Characterize waste

Computations

Average PCDD/PCDF removal efficiency

OR

Average PCDD/PCDF emission factor

Compare test results with regulatory limits.

Average PCDD/PCDF emission factor < 10 ng TCDD equivalents/kg waste

OR

Average PCDD/PCDF removal efficiency > 99 percent.

After compliance has been demonstrated twice, the frequency of future tests will be at the discretion of district air pollution control officer.

TABLE 1-2. EMISSIONS MEASUREMENT CHECKLIST FOR FACILITIES INCINERATING BETWEEN 10 AND 25 TONS OF WASTE PER YEAR.

Complete the following steps one time only

Conduct PCDD/PCDF Compliance Source Test at $\pm 10\%$ of Maximum Permitted Capacity

Parameters to be measured in triplicate

Waste feed rate

Standard dry volume of gases collected

Standard dry gas volumetric flow rate

PCDD/PCDF emissions at stack

Characterize waste

Computations

Average PCDD/PCDF emission factor

Note there are no required compliance limits.

**TABLE 1-3. TEMPERATURE AND RESIDENCE TIME CHECKLIST FOR FACILITIES
INCINERATING MORE THAN 25 TONS OF WASTE PER YEAR.**

Required Locations for Gas Temperature Measurements and Regulatory Limits

After last air pollution control device

Limit: Temperature must be less than or equal to 300°F

For two chamber devices

Exit of primary chamber

Limit: Temperature must be 1400°F ± 200°F

Exit of secondary chamber

Limit: Temperature must be 1800°F ± 200°F

Entrance to first air pollution control or quench device.

Limit: None, this parameter is required for residence time calculations and need only be determined once.

For single chamber devices

Exit of combustion chamber

Limit: Temperature must be 1800°F ± 200°F

Entrance of first air pollution control or quench device

Limit: None, this parameter is required for residence time calculations and need only be determined once.

Residence time calculations to be performed once for each device

Compute residence time using Equations 5 and 6, and CARB methods 1, 2, 3, and 4.

Compare residence times with regulatory requirement of 1 second.

TABLE 1-4. MONITORING EQUIPMENT CHECKLIST FOR FACILITIES INCINERATING MORE THAN 25 TONS OF WASTE PER YEAR.

Install and operate a continuous temperature and emissions monitoring system. Monitor and record

Temperatures of gases exiting each combustion chamber

Carbon monoxide emissions at the stack

Opacity of gases at the stack

Determine key air pollution control device operating parameters and set up a continuous monitoring system for each parameter.

Record the weight of waste charged into the incinerator for each hour of operation.

Maintain maintenance records including calibration records where appropriate for

Air pollution control devices

Monitoring equipment,

Incinerator

Equipment for determining and recording the weight of waste charged to the incinerator.

2.0 INTRODUCTION

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 (1). Section 93104 places restrictions on PCDD/PCDF emission levels and several medical waste incinerator operating parameters which may affect PCDD/PCDF emissions. This report was prepared to assist local air pollution management districts implement the regulations. The report 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.

2.1 OBJECTIVES

Part I provides local district personnel with detailed guidance on the implementation of the medical waste incinerator regulations. Specifically, it describes the regulations, provides detailed instructions on the use of any equations, and provides examples of all procedures and calculations.

2.2 SCOPE OF REGULATIONS

The regulations for medical waste incinerators apply to those facilities which incinerate medical waste. These facilities include medical and dental offices, clinics, hospitals, skilled nursing facilities, research facilities, research laboratories, clinical laboratories, all unlicensed and licensed medical facilities, surgery centers, diagnostic laboratories, and other providers of health care. Mortuaries which incinerate only human or animal remains are not covered by the regulations.

The regulations are limited to control of PCDD/PCDF emissions only. Strict PCDD/PCDF emission limits have been established. Because PCDD/PCDF emissions cannot be continuously monitored, the regulation has also placed limits on parameters thought to be related to PCDD/PCDF emissions.

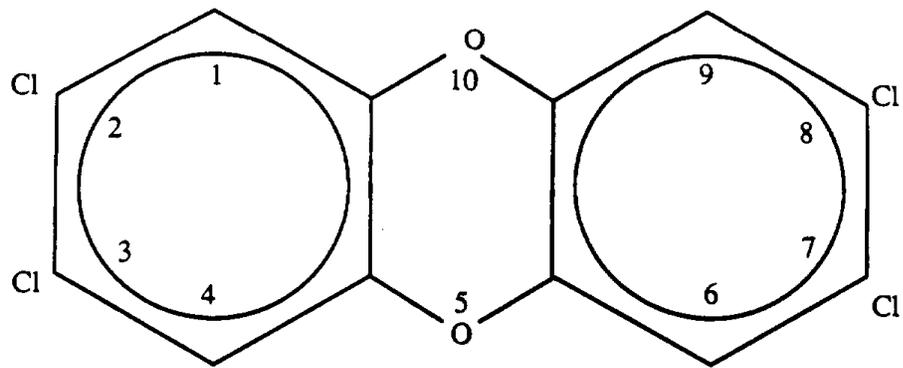
Three classes of facilities are defined based on the yearly quantity of waste incinerated. Facilities which burn over 25 tons of waste per year must comply with the most stringent regulations. Facilities which burn between 10 and 25 tons of waste per year must comply with less stringent limitations. Facilities which burn less than 10 tons of waste per year are only required to comply with limited reporting requirements (1). The specific regulations which apply to the individual facility sizes will be discussed in the section 3.0.

2.3 BACKGROUND

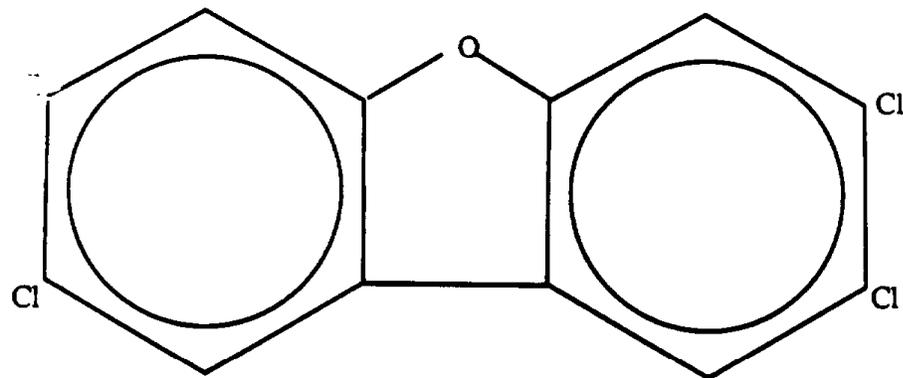
2.3.1 Pollutants of Concern

CARB has implemented regulations to control PCDD/PCDF emissions from medical waste incinerators. These pollutants result from the incomplete oxidation of organic materials and are suspected carcinogens.

Both PCDD and PCDF consist of two chlorinated benzene rings, connected by one oxygen atom in PCDF and two oxygen atoms in PCDD. Figure 2-1 illustrates how the benzene rings are connected and the chlorination sites are filled for 2,3,7,8-Tetrachlorodibenzo-(p)-dioxin (TCDD) and 2,3,7,8-Tetrachlorodibenzofuran (TCDF), respectively. These compounds are suspected of being the most toxic PCDD and PCDF congeners.



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



2,3,7,8-Tetrachlorodibenzofuran

Figure 2-1: Typical dioxin and furan molecule structures.

Those congeners of PCDD and PCDF with four to seven chlorine atoms, and chlorinated in the 2,3,7 and 8 positions have been identified as possible carcinogens by the California Department of Health Services (DHS) (3). Based on this assessment, CARB has identified fifteen PCDD and PCDF congeners (listed in Table 2-1) which will be regulated (3). The toxicity of these compounds decreases as the number of chlorine atoms increases (4).

To reflect the relative toxicity of the various PCDD/PCDF congeners to TCDD, DHS produced the system of toxic equivalency factors shown in Table 2-2 (3). This Table is used to express the emission levels of each PCDD and PCDF congener listed in Table 2-1 as an equivalent TCDD emission level.

2.3.2 PCDD/PCDF Emission Mechanisms

Much research has focused on the formation of PCDD/PCDF in combustion systems. However, no consensus has been reached on the mechanisms responsible for the formation of PCDD/PCDF. The most recent data seem to support the presence of four competing types of mechanisms. The particular mechanism or combination of mechanisms which may dominate PCDD/PCDF formation in a given system is strongly dependent on the facility's operating conditions. The four basic types of emission mechanisms that have been identified are listed below (4):

1. Incomplete combustion of PCDD and PCDF originally present in the waste feed.
2. Incomplete oxidation or pyrolysis of complex organic species like cellulose and polyvinylchloride (PVC).
3. Reactions between precursors such as phenols and chlorobenzenes.
4. Low temperature, fly ash catalyzed reactions.

These four mechanisms are illustrated in Figure 2-2 for a typical combustor. Mechanism 1 is expected to be the smallest contributor to the emission of PCDD/PCDF (4). The strong correlation between particle emissions and the emission of PCDD/PCDF observed in many medical and municipal waste combustion systems indicates that Mechanism 4 is extremely important (4).

Mechanism 4 requires the entrainment of particles into the gas stream, and the reaction of hydrocarbons and HCl on the surfaces these particles. The surface reactions appear to be most rapid between 480 and 660°F.

2.3.3 PCDD/PCDF Emission Control

Emission control strategies for PCDD/PCDF are divided into two main groups: Combustion system based strategies, and air pollution control device based strategies. The combustion based strategies for the removal of PCDD and PCDF involve reducing particle entrainment and assuring the complete destruction of all organic compounds. Reduction of particle entrainment can be accomplished by reducing the velocity of gases through the primary chamber. Organic compounds are destroyed by ensuring uniform temperature distributions and adequate exposure of all materials to sufficient oxygen by increasing the strength of the mixing and the time available for mixing to occur.

TABLE 2-1. LIST OF PCDD AND PCDF CONGENERS OF CONCERN FOR THE CARB REGULATIONS FOR MEDICAL WASTE INCINERATORS (3).

Homologue	Dioxins	Furans
Tetrachloro	2,3,7,8	2,3,7,8
Pentachloro	1,2,3,7,8	1,2,3,7,8 2,3,4,7,8
Hexachloro	1,2,3,4,7,8	1,2,3,4,7,8
	1,2,3,6,7,8	1,2,3,6,7,8
	1,2,3,7,8,9	1,2,3,7,8,9
Heptachloro	1,2,3,4,6,7,8	2,3,4,6,7,8
		1,2,3,4,6,7,8
		1,2,3,4,7,8,9

TABLE 2-2. LIST OF TOXIC EQUIVALENCY FACTORS USED TO EXPRESS THE EMISSION LEVEL OF EACH PCDD AND PCDF CONGENER LISTED TABLE 2-1 IN TERMS OF AN EQUIVALENT TCDD EMISSION LEVEL (3)

Homologue	Dioxins	Furans
Tetrachloro	1.00	1.00
Pentachloro	1.00	1.00
Hexachloro	0.03	0.03
Heptachloro	0.03	0.03
Octachloro	0.00	0.00

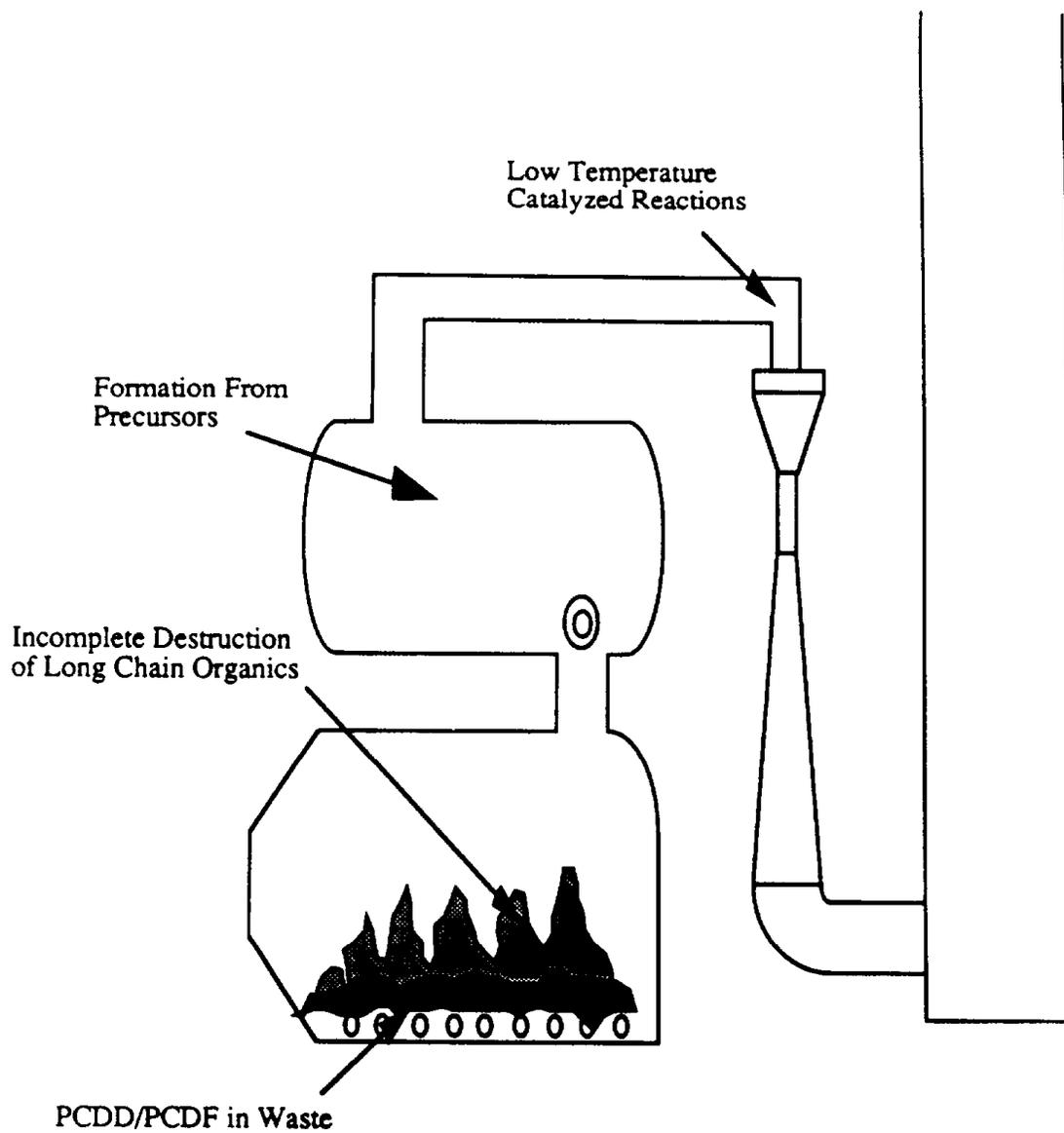


Figure 2-2: Proposed PCDD/PCDF emission mechanisms in waste incinerators.

Most combustion based strategies involve modifying the incinerator, which is often not possible and usually expensive. Thus, flue gas cleaning is most commonly used to reduce the emission of PCDD/PCDF from existing facilities. The most effective technique for removing PCDD/PCDF from flue gases is to first cool the gases to condense the PCDD/PCDF and then capture the condensed material. The vapors can either condense in pure form (homogeneous condensation) or onto particles (heterogeneous condensation). Heterogeneous condensation will favor small particles due to their large surface to volume ratio. This indicates that the technique used to capture the condensed material must be capable of capturing fine particles.

2.3.4 Medical Waste Incinerators

Starved-air modular systems, excess-air modular systems, and rotary kilns are currently the main types of incineration devices used in medical waste incineration facilities (4).

Starved-Air Modular Incinerators

Figure 2-3 illustrates a starved-air modular system which consists of a primary and a secondary chamber. The basic operation modes of each of these chambers are illustrated in Figure 2-4. This Figure gives the chamber temperature as a function of the excess air ratio. The excess air ratio is the ratio of excess air (air supplied in excess of the stoichiometric quantity of air) to the stoichiometric air (air supplied to completely oxidize fuel to CO_2 and H_2O). Figure 2-4 shows that as the quantity of air supplied increases (excess air ratio increasing), the primary chamber's temperature increases. The primary chamber reaches its maximum temperature at the stoichiometric point (no excess air supplied). Figure 2-4 shows that the secondary chamber operates under excess air conditions (excess air ratio greater than zero). Thus, its temperature is increased by reducing the flow rate of air or decreasing the excess air ratio. The temperatures of the primary and the secondary chamber can also be increased by firing the primary and secondary burners (see Figure 2-3).

Excess-Air Modular Incinerators

Excess-air modular incinerators generally have one combustion chamber and a stack afterburner as shown in Figure 2-5. They are usually operated in a batch mode (one load of waste is placed in the chamber, burned and then removed). This is in contrast to starved-air modular incinerators in which waste is automatically introduced into the incinerator at one end while ash is continuously removed from the other (4). In the batch mode, waste is first fed into the incinerator and then the stack afterburner is ignited. After the temperature in the stack reaches a set level, the primary burner is ignited. At the end of the batch cycle the primary burner is turned off and the afterburner is extinguished after a fixed interval. Throughout the cycle, air is supplied at a constant rate, yielding fuel-rich conditions initially and fuel-lean conditions at the later portion of the cycle.

Rotary Kilns

Figure 2-6 illustrates the basic configuration of a rotary kiln. This system features a primary combustion chamber, which rotates to enhance mixing and to move the combustion residuals through the chamber towards the ash dump. As opposed to starved-air incinerators, the primary chamber for rotary kilns operates under excess air conditions (positive excess air ratios as shown in Figure 2-4). Thus, the primary chamber temperature can be increased by lowering the flow rate of air into the chamber. The primary chamber is also equipped with a burner to assist in temperature control. The gases exiting the kiln pass into the secondary chamber, which operates at excess air conditions. The secondary chamber has an auxiliary burner which mainly operates at start-up.

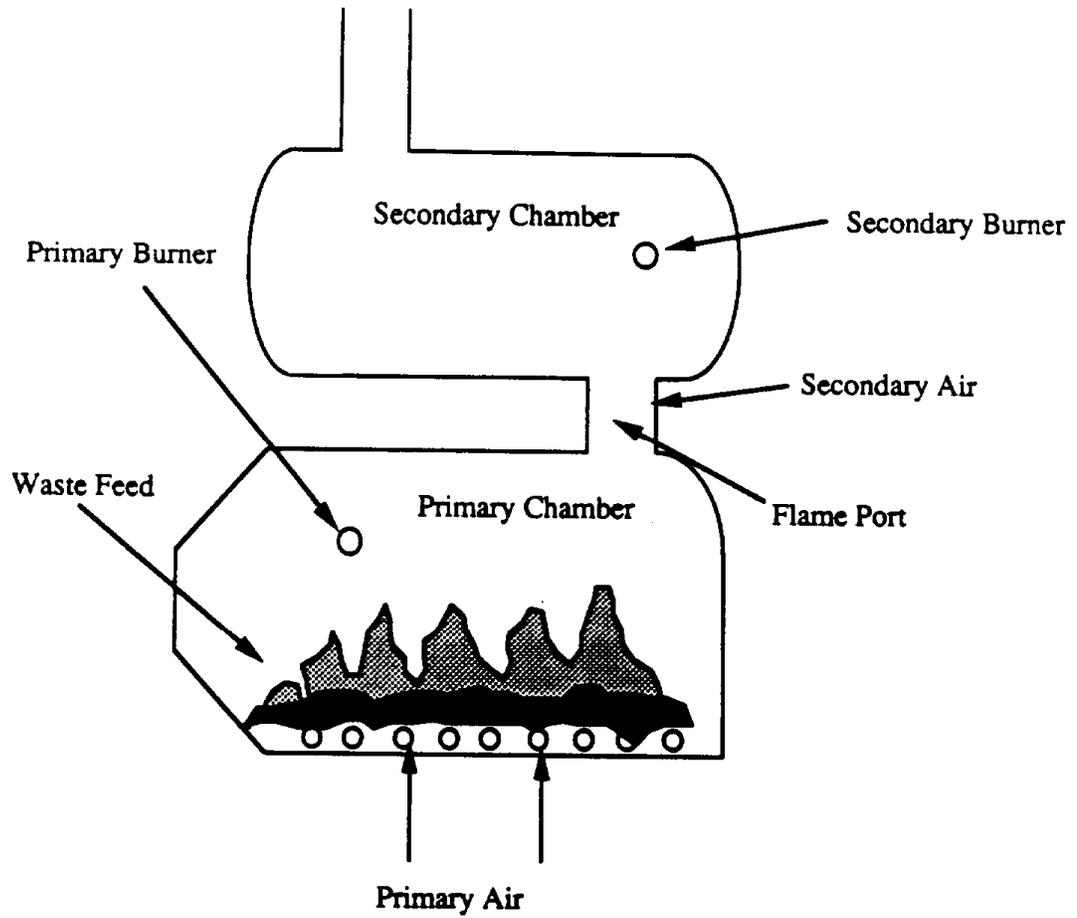


Figure 2-3. Basic configuration of a starved-air modular incinerator.

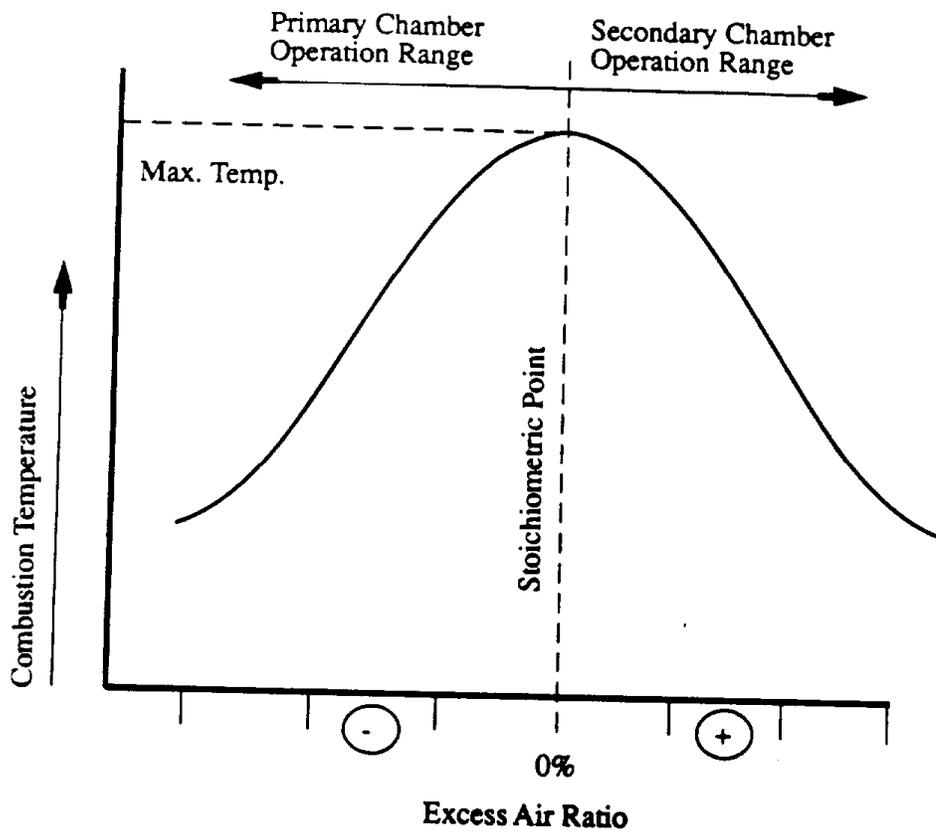


Figure 2-4. Variation of combustion temperature with excess air.

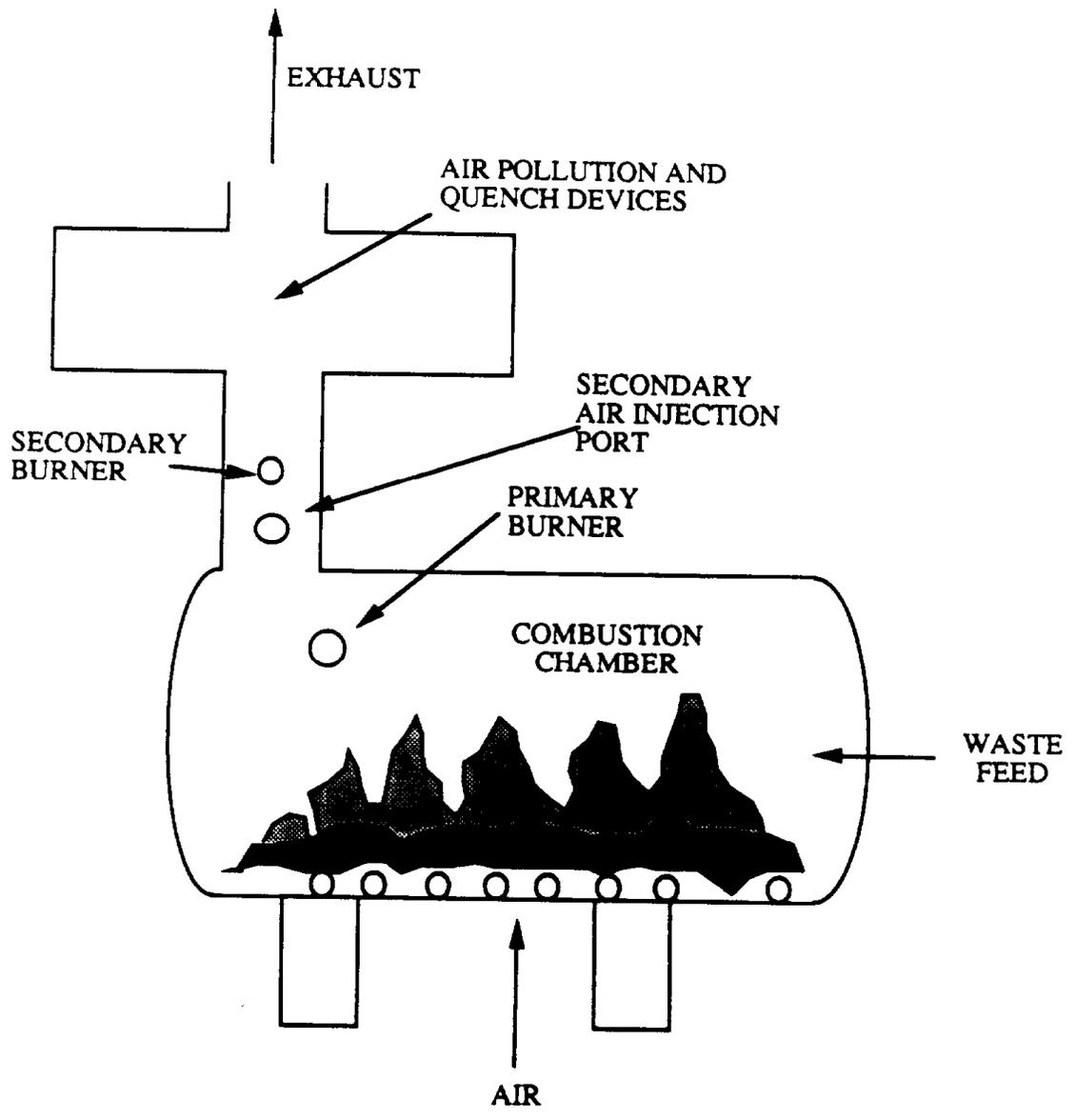


Figure 2-5. Basic configuration of an excess-air modular incinerator

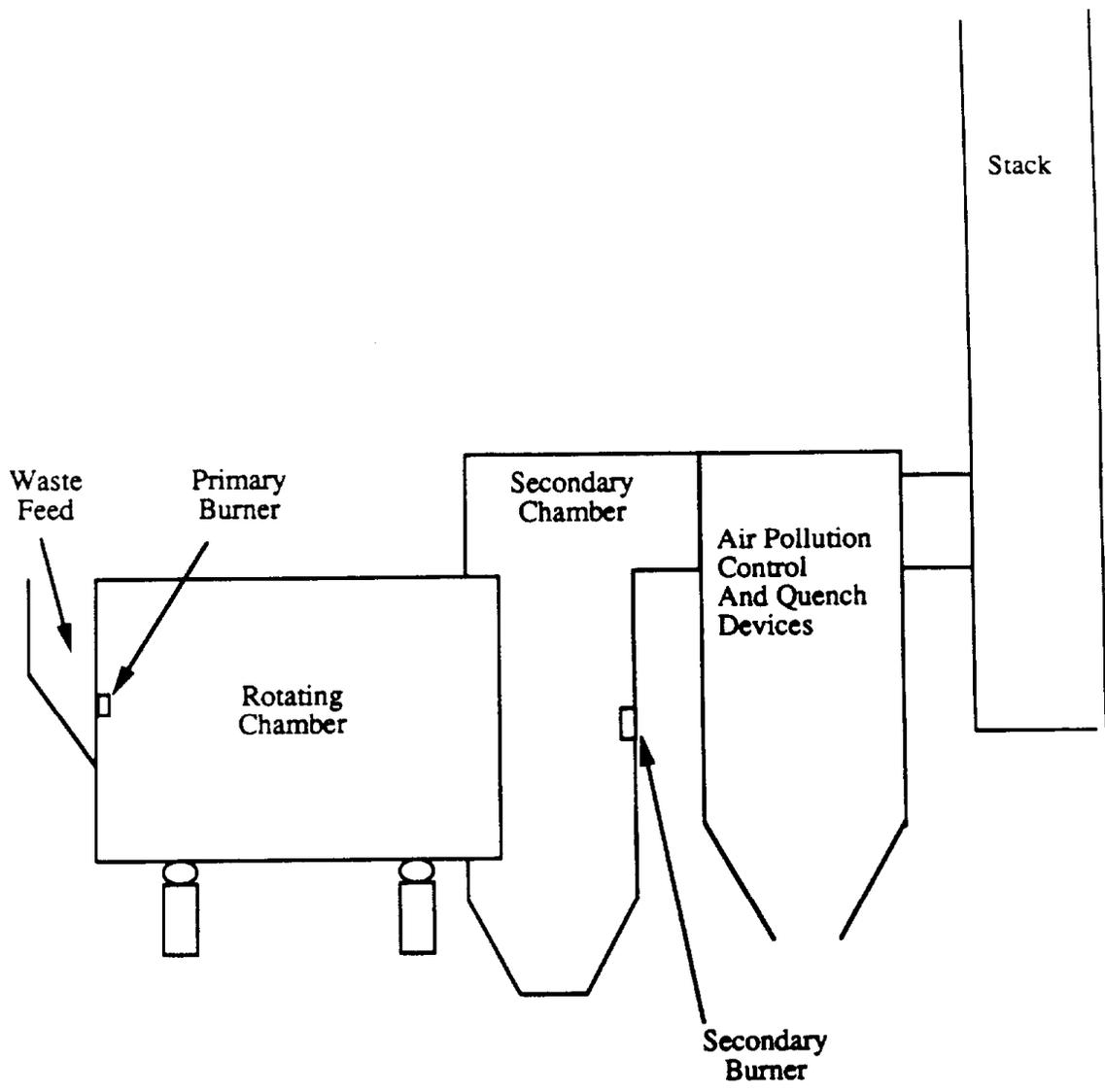


Figure 2-6. Basic Configuration of a Rotary Kiln

2.3.5 Air Pollution Control Devices

At existing facilities, PCDD/ PCDF are usually controlled using flue gas cleaning strategies due to the cost and difficulty of modifying combustors. The most effective flue gas cleaning strategies for the removal of PCDD and PCDF involve cooling the exhaust gases after they exit the combustor and then collecting the condensed material. Some of the devices which are capable of either cooling gases or capturing particle include spray coolers, boilers, fabric filters, electrostatic precipitators (ESPs), and wet scrubbers. The theory of operation, types of equipment, and system capabilities and limitations of each of the devices mentioned previously are discussed in Part II of this report.

3.0 CARB REGULATIONS FOR MEDICAL WASTE INCINERATORS

3.1 EMISSIONS

3.1.1 Regulations

This CARB regulation for medical waste incinerators places restrictions on either the average level of dioxins emitted or the average removal efficiency of dioxins by the APCDs for facilities incinerating over 25 tons of waste per year (1). It also specifies testing requirements for facilities burning between 10 and 25 tons of waste per year.

The level of dioxins emitted and the removal efficiency for a single test are based on the dioxin emission factor (DEF), computed using Equation 1 (3):

Equation 1

$$DEF = \left(\frac{R}{P} \right) \left(\frac{3600}{0.454} \right)$$

DEF = Dioxin emission factor in nanograms per kg of waste burned (ng/kg-waste).

R = Total DHS TCDD toxic equivalent of the fifteen congeners given in Table 2-1 for test run, expressed in nanograms per second (ng/sec).

P = Average waste feed rate for test run, expressed in pounds of waste per hour (lbs-waste/hr).

The removal efficiency for a run is computed using the uncontrolled and controlled DEFs and Equation 2:

Equation 2

$$\text{Removal Efficiency} = \frac{DEF_{\text{unct}} - DEF_{\text{ct}}}{DEF_{\text{unct}}} \times 100$$

DEF_{unct} = DEF computed before the first APCD (heat recovery boilers are not considered to be APCDs).

DEF_{ct} = DEF computed at the stack after the last APCD.

DEF_{unct} and DEF_{ct} must be computed from dioxin measurements taken simultaneously before and after the control equipment. For the uncontrolled and controlled dioxin measurements to be considered simultaneous, they must satisfy the requirement given in Equation 3:

Equation 3

$$\frac{\text{Total Time of Overlap}}{\text{Longest Sample Time}}_{100 > 90}$$

The numerator of Equation 3 is computed by summing up the intervals of time in which the controlled and uncontrolled samples overlap, and the denominator is the longest sampling time.

To satisfy the CARB emission regulations, facilities burning over 25 tons of waste per year must comply with one of the following:

1. The average DEF, derived from a minimum of three DEFs computed from dioxin measurements at the stack, must not exceed 10 ng/kg-waste.

OR

2. The average removal efficiency, derived from a minimum of three removal efficiencies each based on simultaneously measured controlled and uncontrolled DEFs, must exceed 99%. Equation 3 will be used to determine the simultaneity of the controlled and uncontrolled measurements.

To demonstrate compliance with either regulation 1 or 2, facilities burning over 25 tons of waste per year must conduct a minimum of one source test per year until compliance has been demonstrated over two consecutive years. Thereafter, the frequency of future tests will be at the discretion of the district air pollution control officer. During each source test the incinerator must be operated at $\pm 10\%$ of its permitted capacity and the composition of the waste burned must be representative of the facility's average daily waste composition. To determine if the waste is representative, its composition must be reported. The composition breakdown should include the waste's moisture content and the total amount of waste which is infectious, pathological, hazardous, or radioactive. A copy of the results from each source test must be provided concurrently to CARB and the district air pollution control officer.

Facilities incinerating between 10 and 25 tons of waste per year need only conduct one initial source test. During this test the incinerator must be operated at $\pm 10\%$ of its maximum permitted capacity. Compliance with regulations 1 and 2 above is not required, however, the average DEF (derived from a minimum of three DEFs measured at the stack), waste feed rate, and waste composition (see previous paragraph) must be reported concurrently to CARB and the district air pollution control officer.

Facilities incinerating less than 10 tons of waste per year are not required to perform emissions testing.

3.1.2 Implementation

To implement the regulations described in section 3.1.1, source tests must be conducted, samples from these tests must be sent to a laboratory for analysis, and results from the laboratory must be used to compute either the average removal efficiency or the average DEF for the emitted gases. In the following sections, some general background information will be presented describing source tests, laboratory procedures, and data reduction. After these sections, an

example will be presented incorporating many of the steps required to check for compliance with the emission regulations.

Source Tests

For facilities burning over 25 tons of waste per year, source testing at $\pm 10\%$ of the facility's permitted capacity must be conducted at least once per year until two consecutive tests demonstrate compliance with either regulation 1 or 2 in section 3.1.1. During each source test, CARB methods 1, 2, 3, 4, and 428 (see references 5, 6, 7, 8, and 9) must be conducted at the stack during at least three consecutive test runs. If the removal efficiency is computed, these methods must be conducted at locations before (uncontrolled) and after (controlled) the APCDs during at least three consecutive test runs. Sampling at the uncontrolled and controlled locations during each test run must be over approximately the same period of time. The simultaneity of the runs must be demonstrated by satisfying the requirement given in Equation 3. Along with data from the test methods, the waste feed rate in pounds per hour, and the waste composition must be recorded. The composition of the waste burned must be representative of the facility's average daily waste composition.

- CARB Methods 1,2,3,4, and 428

To acquire the data necessary to compute the parameter R in Equation 1, CARB method 3 and 428 sample trains must set up, calibrated, and checked. A CARB method 428 sample train is shown in Figure 3-1. This sample train has a thermocouple for temperature measurements, a pitot tube for velocity measurements, a probe to draw the sample, a cyclone (optional) and filter for particle collection, a condenser, a sorbent module and impingers for PCDD/PCDF capture and stack gas moisture determination, and a dry gas meter. The CARB method 3 train is used to measure the fractions of CO₂ and O₂ present in the stack gases. CARB method 3 and 428 trains must be operated by or under the supervision of a skilled professional. Methods 2 and 4 provide computational procedures for the determination of the stack gas velocity and moisture content.

To use CARB method 428, an acceptable sampling location must be found using the guidelines given in CARB method 1. Such a location must meet the following criteria:

- the flow must not be cyclonic or swirling,
- the stack or ducting diameter must be greater than or equal to 12 inches,
- the measurement location must be over 2 stack or duct diameters downstream from all flow disturbances,
- the measurement location must be over 1/2 stack or duct diameter upstream from all flow disturbances,

Flames, bends, contractions, expansions, and nearby sampling trains are considered flow disturbances. The effects of these disturbances can be dampened by installing straightening vanes. Installing these vanes can be costly and difficult, thus they should only be used when it is impossible to locate an acceptable location.

Once an acceptable measurement site is found, CARB method 1 must be used to determine the number of sampling points within the duct. This number is a function of the duct geometry and size, and the distances from the measurement location to the nearest upstream and downstream

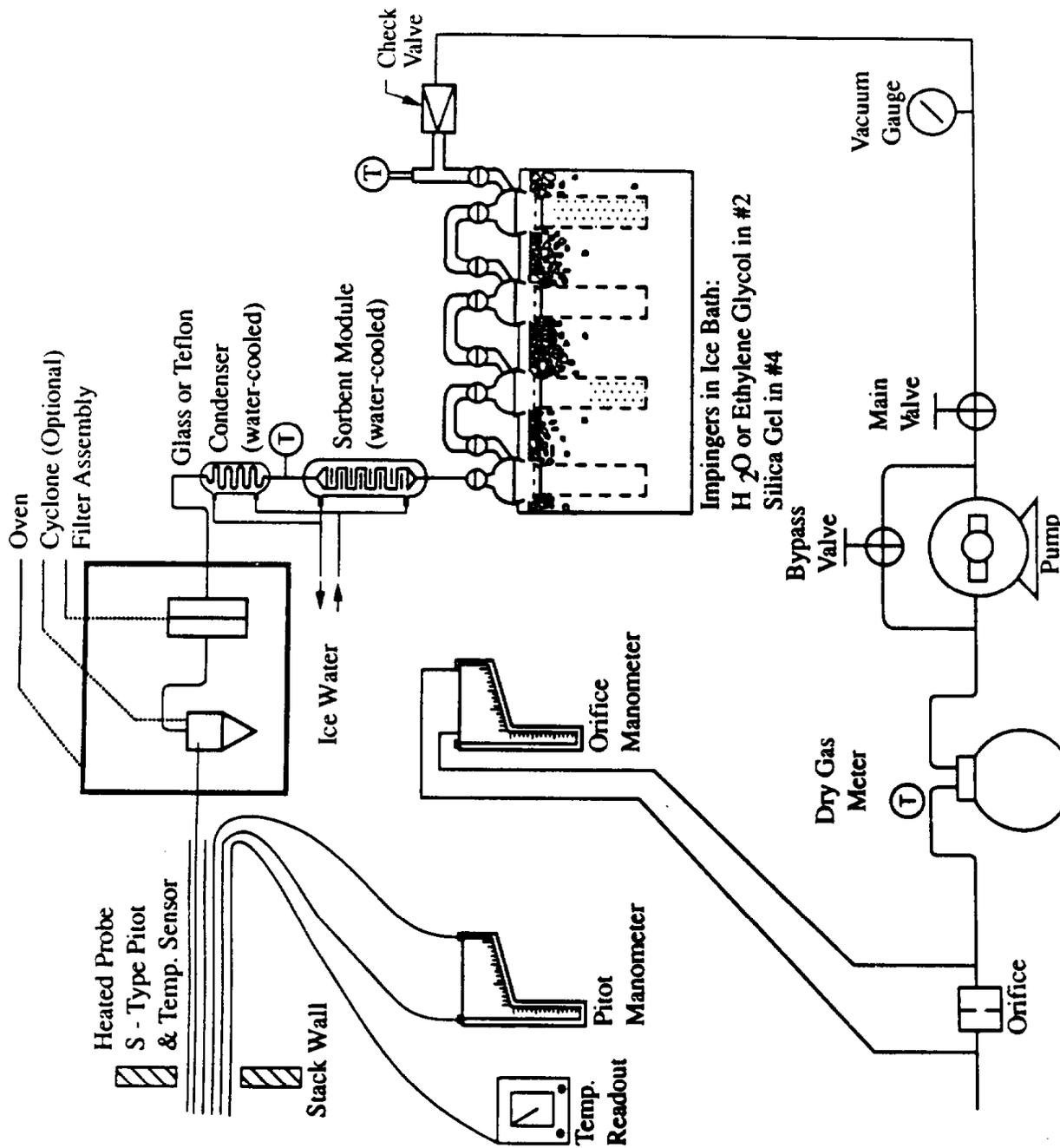


Figure 3-1: PCDD/PCDF Sampling Train.

flow disturbances. Charts are given in CARB method 1 to determine the number of traverse points. Once the number of traverse points is selected, these points must be distributed over two perpendicular diameters within the duct. The exact locations are given by CARB method 1.

After the measurement locations and sampling points are selected, the system components for CARB method 3 and 428 sample trains must be calibrated and checked according to the procedures given in the individual methods. During the testing, the trains must be operated simultaneously over a period of at least 3 hours.

Along with the test runs, various quality assurance (QA) and quality control (QC) procedures should be following both internally and externally. These procedures involve performing leak checks on the sample trains, obtaining reagent blanks, recovery blanks, lab proof blanks and field blanks, inspecting internal standards and surrogate recoveries, and carrying out duplicate analyses and method blanks. Method 428 should be consulted for a complete listing of QA and QC procedures.

- Waste Feed Rate

The waste feed rate for each test run (lasting at least 3 hours) can be determined by weighing and recording in pounds the total amount of waste feed burned in the incinerator over the test and dividing this quantity by total sample time in hours. If waste feed rate is less than ± 10 percent of the incinerator's maximum permitted waste firing capacity, the test should be terminated. This could be expensive, thus, before the test is started enough waste should be present to complete the run.

- Waste Characterization

During each of the test runs, representative samples must be taken from the waste to determine the waste's moisture content. The samples should be extracted from each of the waste streams (for example red bag or infectious wastes, and municipal wastes) leaving each department at the facility. The samples should only contain those items which are burnt in the incinerator. Furthermore, the amount of each sample taken should be proportional to the quantity actually burnt in the incinerator. This step should be performed with extreme caution, since the waste could contain infectious organisms and hazardous chemicals (cytotoxic and radioactive compounds). The moisture content analysis can be performed using ASTM method D 3176, 3180 (12).

To determine the total amount of waste which is infectious, pathological, hazardous, or radioactive, one of three methods can be used. In the first method, the waste can be categorized before it is placed in the contaminated waste stream. The moisture content sample, discussed above, might also be obtained by this method. In the second method, the waste can be categorized by opening the containers in a central location. This method is more dangerous than the first because in the process of sifting through the waste a worker might be cut and possibly infected. Infectious organisms might also be dispersed into the air during the sorting process. Finally, the waste could be characterized by questioning the facility staff. This method is the safest, but it is also the least accurate.

Laboratory Analysis

The samples (each sample includes the filter, cyclone catch, probe rinse, sorbent module, and impinger catches) obtained from the stack and uncontrolled sampling locations during each of the test runs, must be sent to a qualified laboratory for analysis. The laboratory results must include the total quantity in nanograms of each chlorinated class (TCDD through OCDD and TCDF through OCDF) and of each of the fifteen congeners listed in Table 2-1. A separate set of results must be provided for each run at each sampling location. The reported quantities for the fifteen

congeners will be used to compute the parameter R in Equation 1 for each test run. The total quantity in each chlorinated class can be used for facility comparisons.

When requesting analyses, either high or low resolution mass spectrometry must be specified. The choice of mass spectrometry option will determine the lower detection limit for the PCDD/PCDF compounds of concern, and the price of the analysis.

Data Reduction

After completing the source test and receiving the quantities in ng/sample of each congener listed in Table 2-1 at each sample location for each test run, the following steps can be used to compute the average removal efficiency and the average DEF at the stack.

1. Divide the amount of each congener listed in Table 2-1 by the standard volume of dry gas collected during the corresponding sampling run and at the corresponding sample location to obtain the congener concentrations. The standard volume of dry gas is calculated using the data from the source test and the analysis given in CARB method 428.
2. Multiply each of the congener concentrations determined in step 1 by the standard volumetric flow rate of dry stack gases for the corresponding sampling run and at the corresponding sample location to obtain the congener mass flow rates. The standard volumetric flow rate of dry gas is calculated using the data from the source test and the analysis given in CARB method 2.
3. Multiply each of the congener mass flow rates determined in step 2 by the corresponding toxic equivalency factors in Table 2-2 to obtain the TCDD toxic equivalent mass flow rates.
4. At the stack and uncontrolled (if applicable) measurement locations for each test run, add the TCDD toxic equivalent mass flow rates determined for each congener in step 3 to obtain the total TCDD toxic equivalent mass flow rates. This step should yield three stack and three uncontrolled TCDD toxic equivalent mass flow rates for facilities seeking to comply with regulation 2 in section 3.1.1. For facilities testing for compliance with regulation 1 in section 3.1.1, this step should yield three stack TCDD toxic equivalent mass flow rates.
5. Using the total TCDD toxic equivalent mass flow rates determined in step 4 and the waste feed rates for each test run, compute the DEF for each run at the stack and uncontrolled (if applicable) measurement locations using Equation 1.
6. For those facilities testing for compliance with regulation 1 in section 3.1.1, average the three stack DEFs obtained in step 5. This average DEF at the stack must not exceed 10 ng/kg of waste.
7. For those facilities testing for compliance with regulation 2 in section 3.1.1, calculate the removal efficiency for each test run using Equation 2 and the corresponding simultaneously measured controlled (stack) and uncontrolled DEFs computed in step 5. Average the three removal efficiencies to determine the average removal efficiency for the source test. This value must exceed 99%.

Emissions Example

To demonstrate the procedures necessary to determine compliance with the emission regulations, an example based on the incinerator pictured in Figure 3-2 will be constructed. This incinerator is a starved-air modular incinerator with primary and secondary chambers. A boiler is present for energy recovery and cooling purposes, and emissions are controlled using a baghouse.

- Source Test

To check for compliance with regulation 2 in section 3.1.1, two sampling locations were selected. One location was between the boiler and the baghouse (uncontrolled location) and the other location was after the baghouse (controlled location). The approximate positions of the CARB method 3 and 428 sample trains are given at the controlled and uncontrolled sample locations in Figure 3-2. The distances between the trains and the distances between the CARB Method 428 trains and the downstream disturbances were set at minimum distances required by CARB Method 1. These minimum distances were used to avoid the large upstream disturbances caused by the baghouse and the pipe bend. Swirl checks conducted in accordance with CARB method 1, indicated that the flow at each sample train location was not cyclonic.

The number of sample points were selected in accordance with CARB Methods 1 and 3. The number of sample points for each train at each location are shown in Table 3-1.

TABLE 3-1. REQUIRED NUMBER OF SAMPLE POINTS AT THE CONTROLLED AND UNCONTROLLED SAMPLE LOCATIONS FOR THE EMISSION TESTING EXAMPLE.

Train	Number of Sample Points
Method 3 Controlled	8
Method 3 Uncontrolled	8
Method 428 Controlled	24
Method 428 Uncontrolled	24

The traverse points for each method were spaced in agreement with the requirements of CARB method 1.

The required test time was selected based on the lowest cost per run at which the congener 2,3,7,8 - Tetrachlorodibenzo - (p) - dioxin (TCDD) could be detected. TCDD was used because it is usually detected at lower levels than the other congeners in Table 2-1. Equation 4 was used to determine the combined cost of sampling and laboratory analysis for a test run with controlled and uncontrolled emissions sampling.

Equation 4

$$\text{Cost} = \text{LC} + \text{STC} * \text{T}$$

LC = Total cost for the laboratory analysis of controlled and uncontrolled samples (\$).
STC = Total cost for the simultaneous operation of controlled and uncontrolled sample trains (\$/hr).
T = Time of test run (hrs).

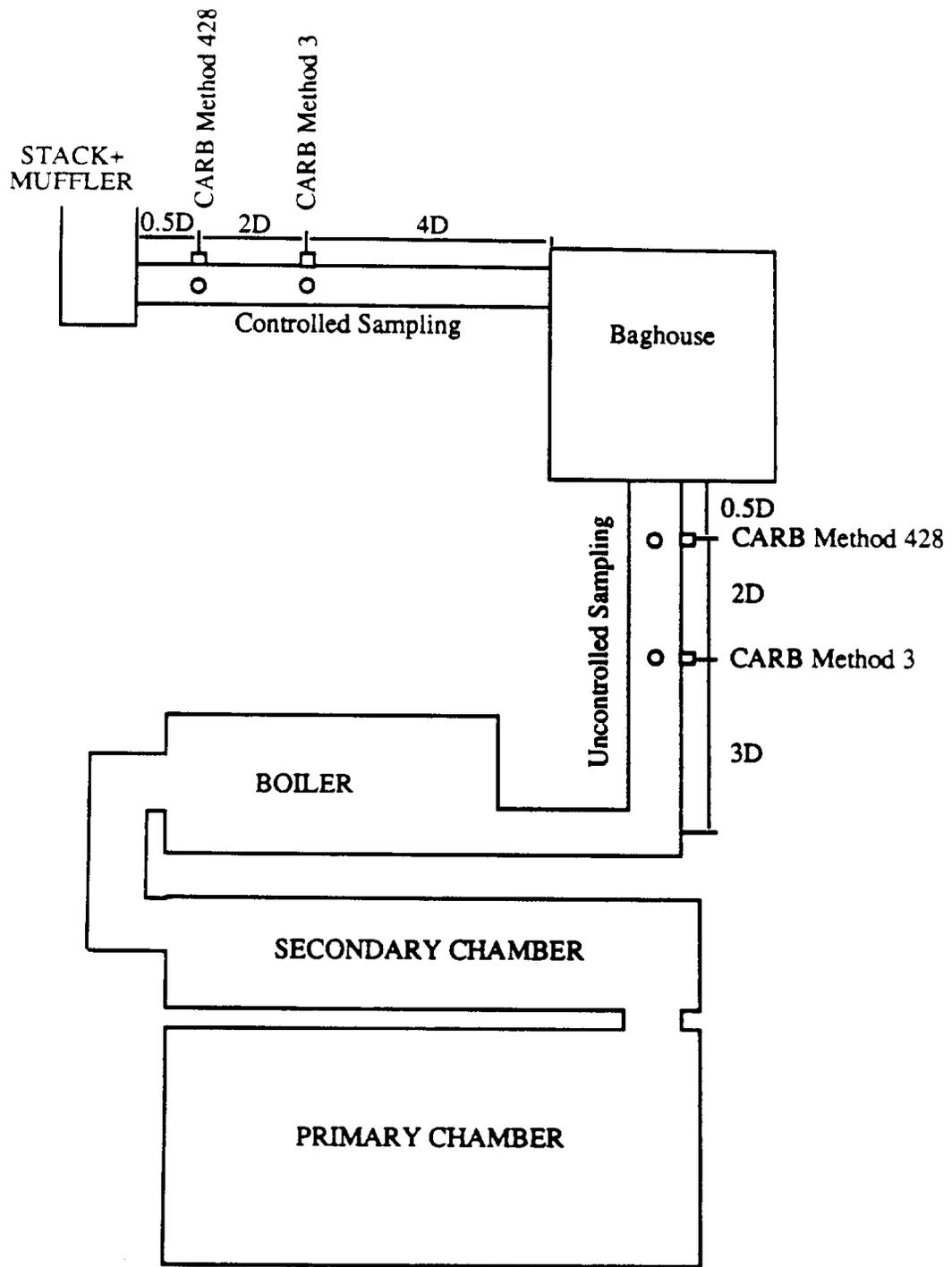


Figure 3-2. CARB method 3 and 428 sample train locations for emission testing example.

The run time required to detect TCDD can be estimated based on Equation 5.

Equation 5

$$T = \frac{A}{S * W * EF * IF}$$

- A= Target detection limit of the method for TCDD (ng/sample)
- S= Emissions Standard (10 ng TCDD toxic equivalents/kg-waste)
- W= Waste feed rate (kg-waste/hr)
- EF= Fraction of total source emissions collected in the sampling train.
- IF= Fraction of total toxic equivalent emissions attributed to target isomer.

Table 3-2 shows the parameters used to estimate the run time and the combined sampling and lab analysis costs using high resolution mass spectrometry (HRMS) and low resolution mass spectrometry (LRMS). The parameter EF was computed by dividing the estimated flow rate of gases through the sampling system by the flow rate of stack gases, while IF was based on CARB source test data. The cost per test run was 3,895 and 4,297 using HRMS and LRMS, respectively. Aside from the cost benefit the HRMS technique was selected because:

- The smaller sampling time allowed by HRMS over LRMS will lead to fewer problems during the sampling period. Leakage, contamination, probe and other train component failures, and plugging are some of the primary problems that could arise during the extended sampling time.
- The longer sampling time for LRMS could result in increased interference from other compounds in the gas sample, thus negating some of the gains obtained with the larger sample.
- Compared to LRMS, HRMS has improved selectivity which means that isomers may be identified more accurately and precisely. Improved selectivity also allows detection of low levels of analytes in complex matrices such as found from incinerators. Therefore, at low concentrations, matrix effects lead to less variability among test with HRMS than with LRMS.

As required by CARB Method 428, the sampling time was set at the minimum allowable time of 3 hours. With the sampling locations, number of traverse points, traverse point location, and sampling time selected, the trains were calibrated and checked according to the requirements in CARB methods 3 and 428. Three consecutive sampling runs were then conducted at approximately 3 hours apiece with the incinerator operating at $\pm 10\%$ of its permitted capacity. QC and QA procedures such as pre and post test leak checks were conducted, and field, lab, and reagent/recovery were collected for analysis.

During each of the runs the waste feed rate was determined by dividing the total quantity of waste burned in the incinerator by the total sample time. The waste was characterized by interviewing key facility personnel and observing disposal practices in each department.

TABLE 3-2. MARCH OF 1991 COMPARISON OF THE LABORATORY AND SAMPLING COSTS PER TEST RUN USING HRMS AND LRMS FOR THE EMISSION TESTING EXAMPLE.

Parameter	High Resolution Mass Spectrometry (HRMS)	Low Resolution Mass Spectrometry (LRMS)
Laboratory Costs, LC (\$) (1)	3670	2050
Cost of Test Run, STC (\$/hr) (2)	100	100
Target Detection Limit for TCDD, A (ng/sample)	0.2	2
Emission Standard, S (ng/kg-waste)	10	10
Waste Feed Rate, W (kg/hr)	445	445
Fraction of Source Emissions Collected in Sample Train, EF	0.0004	0.0004
Fraction of TCDD Equivalent Attributed to Target Congener, IF	0.05	0.05
Time of Test Run (hrs)	2.25	22.47
Total Cost for One Run and Associated Lab Work, (\$)	3895	4297

(1) Total cost required for the analysis of controlled and uncontrolled samples for a single test run.

(2) Total cost per hour required to operate simultaneous controlled and uncontrolled CARB method 428 trains.

After each run was completed, the requirement in Equation 3 was used to assure that the controlled and uncontrolled samples were measured simultaneously. The filter, cyclone catch, probe rinse, sorbent module, and impinger catches for each train were then recovered following the procedures of CARB Method 428. The samples from each train were then sent to the laboratory. Analyses were carried out for the fifteen congeners listed in Table 2-1 and the total amounts in each chlorinated class.

- Data Analysis

Tables 3-3a-c show the amount detected in ng/sample of each of the fifteen congeners listed in Table 2-1 at the controlled and uncontrolled measurements locations (see Figure 3-2) for each test run. Only those congeners required to compute the TCDD toxic equivalent mass flow rates are listed. Other congeners commonly reported by laboratories such as OCDD and OCDF should also be included in the results presentation. The results of the application of steps 1 through 3 in the data analysis section are given under the Step 1, 2, and 3 columns in Tables 3-3a-c. A less than sign indicates that the dioxin congener was not detected. In these cases, one half the reported detection limit was used to compute the TCDD toxic equivalent mass flow rate according to CARB guidelines.

The results of the application of step 4 in the data analysis section are given in Tables 3-3a-c as sums at the end of the Step 3 columns. Step 4 yields three uncontrolled and three controlled TCDD toxic equivalent mass flow rates.

Step 5 is carried out in the set of computations illustrated in Figure 3-3. The average waste feed rates for test runs 1, 2, and 3 were 970, 980, and 990 lbs/hr, respectively. The total TCDD toxic equivalent mass flow rates in Equation 1 were taken from Step 4 in Tables 3-3a-c.

As instructed in step 6 of the data analysis section, the three controlled DEF values from step 5 were averaged to produce an average controlled DEF of 164.67 ng/kg-waste. Since the average controlled DEF is well above 10 ng/kg-waste limit, step 7 was carried out, yielding removal efficiencies of -16.42%, 11.75%, and 77.38 for test runs 1, 2, and 3, respectively. Averaging these removal efficiencies, gives an overall removal efficiency is 24.23 %. This average removal efficiency is well below the limit of 99 percent given in the regulations. Thus, this incinerator will have to be modified or shut down.

3.1.3 Retrofit Options

If either the maximum DEF of 10 ng/kg-waste or the minimum removal efficiency of 99 percent cannot be met, the incinerator must either be shut down, or a combustion or an air pollution control device based control strategy (the general concepts behind these strategies are given in sections 2.3) must be implemented. Since major modifications on existing combustors are expensive, combustion strategies are economically viable in special cases only. Furthermore, since most incinerators are already designed to run at their maximum organic destruction capabilities, nonstructural modifications such as reductions in the air flow rate will have little effect on the destruction rate of PCDD and PCDF compounds. Even though combustion strategies are difficult and costly, some minor tactics will be discussed for starved-air modular (controlled air), excess-air modular (batch), and rotary kiln incinerators (see section 2.3.4 for more information on these incinerators).

Starved-Air Modular Incinerators

The first strategy to reduce PCDD/PCDF emissions in controlled air incinerators is to reduce the flow rate of air into the primary chamber when the chamber temperature exceeds 1400°F (minimum primary chamber temperature). This strategy will reduce the entrainment of particles in

TABLE 3-3. COMPUTATION OF THE CONTROLLED AND UNCONTROLLED TOTAL TCDD TOXIC EQUIVALENT MASS FLOW RATES FOR THE EMISSION TESTING EXAMPLE.

TEST RUN #1		UNCONTROLLED		CONTROLLED					
DATA ENTRY		UNCONTROLLED		CONTROLLED					
Standard Dry Gas Volume, Vmsid (dscm)		3,8961		7,9514					
Standard Dry Gas Volumetric Flow Rate, Qstd (dscm/sec)		1.1331		1.2794					
PCDD/PCDF Congeners	TCDD Factor TF	UNCONTROLLED EMISSIONS				CONTROLLED EMISSIONS			
		Source Test Lab Analysis Amount Found (ng/sample) AF	Step 1*** Concentration (ng/dscm) Ct**	Step 2 Mass Flow Rate (ng/sec) Ms**	Step 3 TCDD Toxic Equivalent (ng/sec) TE**	Source Test Lab Analysis Amount Found (ng/sample) AF	Step 1*** Concentration (ng/dscm) Ct**	Step 2 Mass Flow Rate (ng/sec) Ms**	Step 3 TCDD Toxic Equivalent (ng/sec) TE**
Dioxins									
2,3,7,8 - TCDD	1.00	0.70	0.18	0.20	0.20	2.00	0.25	0.32	0.32
1,2,3,7,8 - PeCDD	1.00	2.30	0.59	0.67	0.67	10.20	1.28	1.64	1.64
1,2,3,4,7,8 - HxCDD	0.03	10.00	2.57	2.91	0.09	10.50	1.32	1.69	0.05
1,2,3,6,7,8 - HxCDD	0.03	9.20	2.36	2.68	0.08	17.20	2.16	2.77	0.08
1,2,3,7,8,9 - HxCDD	0.03	8.00	2.05	2.33	0.07	11.80	1.48	1.90	0.06
1,2,3,4,6,7,8 - HpCDD	0.03	125.00	32.08	36.35	1.09	177.00	22.26	28.48	0.85
Furans									
2,3,7,8 - TCDF	1.00	4.40	1.13	1.28	1.28	12.20	1.53	1.96	1.96
1,2,3,7,8 - PeCDF	1.00	20.40	5.24	5.93	5.93	43.40	5.46	6.98	6.98
2,3,4,7,8 - PeCDF	1.00	22.00	5.65	6.40	6.40	43.70	5.50	7.03	7.03
1,2,3,4,7,8 - HxCDF	0.03	38.50	9.88	11.20	0.34	69.90	8.79	11.25	0.34
1,2,3,6,7,8 - HxCDF	0.03	36.90	9.47	10.73	0.32	73.70	9.27	11.86	0.36
1,2,3,7,8,9 - HxCDF	0.03	<*	< 0.24	< 0.28	< 0.01	8.20	1.03	1.32	0.04
2,3,4,6,7,8 - HxCDF	0.03	52.00	13.35	15.12	0.45	99.60	12.53	16.03	0.48
1,2,3,4,6,7,8 - HpCDF	0.03	266.00	68.27	77.36	2.32	488.00	61.37	78.52	2.36
1,2,3,4,7,8,9 - HpCDF	0.03	46.20	11.86	13.44	0.40	66.40	8.35	10.68	0.32
				Step 4	19.65			Step 4	22.88

* < - Indicates a nondetected value. One half the detection limit is used to compute toxic equivalent in accord with CARB guidelines.

***Equations

Ct=AF/Vmsid

Ms=Ct*Qstd

TE=TF*Ms

***Description of each step given in Data Analysis Section

TABLE 3-3. CONTINUED.

TEST RUN #2	UNCONTROLLED	CONTROLLED
DATA ENTRY		
Standard Dry Gas Volume, V _{std} (dscm)	4.4967	6.4789
Standard Dry Gas Volumetric Flow Rate, Q _{std} (dscm/sec)	1.2035	1.2738

PCDD/PCDF Congeners	TCDD Factor TF	UNCONTROLLED EMISSIONS				CONTROLLED EMISSIONS			
		Source Test Lab Analysis Amount Found (ng/sample) AF	Step 1*** Concentration (ng/dscm) C1**	Step 2 Mass Flow Rate (ng/sec) Ms**	Step 3 TCDD Toxic Equivalent (ng/sec) TE**	Source Test Lab Analysis Amount Found (ng/sample) AF	Step 1*** Concentration (ng/dscm) C1**	Step 2 Mass Flow Rate (ng/sec) Ms**	Step 3 TCDD Toxic Equivalent (ng/sec) TE**
Dioxins									
2,3,7,8 - TCDD	1.00	1.80	0.40	0.48	0.48	2.60	0.51	0.51	0.51
1,2,3,7,8 - PeCDD	1.00	9.30	2.07	2.49	2.49	9.80	1.93	1.93	1.93
1,2,3,4,7,8 - HxCDD	0.03	8.20	1.82	0.07	0.07	14.90	2.93	2.93	0.09
1,2,3,6,7,8 - HxCDD	0.03	14.90	3.31	0.12	0.12	17.50	3.44	3.44	0.10
1,2,3,7,8,9 - HxCDD	0.03	10.50	2.34	0.08	0.08	14.80	2.91	2.91	0.09
1,2,3,4,6,7,8 - HpCDD	0.03	167.00	37.14	1.34	1.34	157.00	30.87	30.87	0.93
Furans									
2,3,7,8 - TCDF	1.00	10.40	2.31	2.78	2.78	14.20	2.79	2.79	2.79
1,2,3,7,8 - PeCDF	1.00	41.90	9.32	11.21	11.21	51.50	10.13	10.13	10.13
2,3,4,7,8 - PeCDF	1.00	41.00	9.12	10.97	10.97	51.10	10.05	10.05	10.05
1,2,3,4,7,8 - HxCDF	0.03	64.80	14.41	17.34	0.52	76.80	15.10	15.10	0.45
1,2,3,6,7,8 - HxCDF	0.03	62.50	13.90	16.73	0.50	77.60	15.26	15.26	0.46
1,2,3,7,8,9 - HxCDF	0.03	<*	< 0.47	< 0.56	< 0.02	< 4.40	0.87	0.87	0.03
2,3,4,6,7,8 - HxCDF	0.03	90.40	20.10	24.19	0.73	92.70	18.23	18.23	0.55
1,2,3,4,6,7,8 - HpCDF	0.03	381.00	84.73	101.97	3.06	392.00	77.07	77.07	2.31
1,2,3,4,7,8,9 - HpCDF	0.03	55.70	12.39	14.91	0.45	56.30	11.07	11.07	0.33

Step 4 34.82 Step 4 30.73

* < - Indicates a nondetected value. One half the detection limit is used to compute toxic equivalent in accord with CARB guidelines.

**Equations

C1=AF/V_{std}

Ms=C1*Q_{std}

TE=TF*Ms

***Description of each step given in Data Analysis Section

TABLE 3-3. CONTINUED.

TEST RUN #3		UNCONTROLLED	CONTROLLED
DATA ENTRY			
Standard Dry Gas Volume, Vmsid (dscm)		3.6877	6.932
Standard Dry Gas Volumetric Flow Rate, Qstd (dscm/sec)		1.1492	1.2837

PCDD/PCDF Congeners	TCDD Factor TF	UNCONTROLLED EMISSIONS			CONTROLLED EMISSIONS				
		Source Test Lab Analysis Amount Found (ng/sample) AF	Step 1*** Concentration (ng/dscm) Ct***	Step 2 Mass Flow Rate (ng/sec) Ms**	Step 3 TCDD Toxic Equivalent (ng/sec) TE**	Source Test Lab Analysis Amount Found (ng/sample) AF	Step 1*** Concentration (ng/dscm) Ct***	Step 2 Mass Flow Rate (ng/sec) Ms**	Step 3 TCDD Toxic Equivalent (ng/sec) TE**
Dioxins									
2,3,7,8 - TCDD	1.00	1.10	0.30	0.34	< 0.06	< 0.01	< 0.01	< 0.01	< 0.01
1,2,3,7,8 - PeCDD	1.00	4.60	1.25	1.43	< 1.55	< 0.22	< 0.29	< 0.29	< 0.29
1,2,3,4,7,8 - HxCDD	0.03	7.70	2.09	2.40	< 2.60	< 0.38	< 0.48	< 0.01	< 0.01
1,2,3,6,7,8 - HxCDD	0.03	14.50	3.93	4.52	< 4.35	< 0.63	< 0.81	< 0.02	< 0.02
1,2,3,7,8,9 - HxCDD	0.03	9.80	2.66	3.05	5.80	0.84	1.07	0.03	0.03
1,2,3,4,6,7,8 - HpCDD	0.03	169.00	45.83	52.67	73.40	10.59	13.59	0.41	0.41
Furans									
2,3,7,8 - TCDF	1.00	6.80	1.84	2.12	3.40	0.49	0.63	0.63	0.63
1,2,3,7,8 - PeCDF	1.00	28.10	7.62	8.76	13.50	1.95	2.50	2.50	2.50
2,3,4,7,8 - PeCDF	1.00	35.40	9.60	11.03	11.60	1.67	2.15	2.15	2.15
1,2,3,4,7,8 - HxCDF	0.03	56.20	15.24	17.51	21.50	3.10	3.98	0.12	0.12
1,2,3,6,7,8 - HxCDF	0.03	53.40	14.48	16.64	26.70	3.85	4.94	0.15	0.15
1,2,3,7,8,9 - HxCDF	0.03	2.05	< 0.56	< 0.64	< 0.16	< 0.02	< 0.03	< 0.00	< 0.00
2,3,4,6,7,8 - HpCDF	0.03	95.80	25.98	29.85	34.20	4.93	6.33	0.19	0.19
1,2,3,4,6,7,8 - HpCDF	0.03	426.00	115.52	132.75	118.00	17.02	21.85	0.66	0.66
1,2,3,4,7,8,9 - HpCDF	0.03	74.70	20.26	23.28	19.90	2.87	3.69	0.11	0.11

Step 4 32.18 Step 4 7.28

• < - Indicates a nondetected value. One half the detection limit is used to compute toxic equivalent in accord with CARB guidelines.
 ***Equations
 Ct=AF/Vmsid
 Ms=Ct*Qstd
 TE=TF*Ms
 ***Description of each step given in Data Analysis Section

<p>Test Run #1</p> <p>Uncontrolled: $DEF=(19.65/970)(3600/0.454)=160.63$ Controlled: $DEF=(22.88/970)(3600/0.454)=187.04$</p>
<p>Test Run #2</p> <p>Uncontrolled: $DEF=(34.82/980)(3600/0.454)=281.74$ Controlled: $DEF=(30.73/980)(3600/0.454)=248.65$</p>
<p>Test Run #3</p> <p>Uncontrolled: $DEF=(32.18/990)(3600/0.454)=257.75$ Controlled: $DEF=(7.28/990)(3600/0.454)=58.31$</p>

Figure 3-3. Computation of the controlled and uncontrolled dioxin emission factors (DEFs) for the emission testing example.

the gas stream. Reduced entrainment may decrease the rate of production of PCDD/PCDF congeners from surface catalyzed reactions in the temperature range from 480 to 660°F (see section 2.3.2).

To increase the destruction rate of PCDD/PCDF congeners in the secondary chamber, the flow rate of air into the flame port can be reduced. This strategy should only be used if the secondary chamber temperature is less than the maximum chamber temperature imposed by material limitations.

The final strategy to reduce PCDD/PCDF emissions is to increase the residence time of gases in the system by adding another secondary chamber or by increasing the length of the stack to the first quench device or air pollution control device. This strategy would be expensive due to the cost of equipment modifications and could be limited by available space.

Excess-Air Modular Incinerators

Since batch incinerators are simple units, very little can be done to modify their PCDD/PCDF destruction capabilities. Additional afterburners can be added to the stack to increase the destruction rate of the PCDD/PCDF compounds, and the residence time can be increased by increasing the length of the stack before the first air pollution control device or quench device. The temperature in the extended stack should remain above 1600°F if the extended stack volume is to be included in the residence time computation (see section 3.2.1).

Rotary Kilns

The secondary chamber temperature and residence time strategies for reducing PCDD/PCDF emissions from rotary kilns are exactly the same as the corresponding strategies given for controlled air incinerators. Like controlled air facilities, reducing the flow rate of air will reduce particle entrainment in the rotary kiln (reducing particle entrainment reduces surface catalyzed PCDD/PCDF formation), but the kiln's primary chamber temperature will increase as the flow rate of air is decreased. Thus, the rotary kiln's primary chamber temperature might exceed the maximum chamber temperature imposed by material limitations.

Air Pollution Control Devices

As stated previously, combustion based strategies are expensive and difficult to implement. Thus, air pollution control device based strategies are often the best way to reduce emissions of PCDD/PCDF from existing facilities. The basic concepts behind these air pollution control device strategies are simple and consist of cooling the exhaust gases and then capturing the resulting condensate. Boilers and spray coolers are common cooling devices, while wet scrubbers (venturi scrubbers and acid gas absorbers), dry scrubbers (cyclones and impingers), wet and dry electrostatic precipitators (ESPs), and fabric filters (baghouses) are the primary particle removal devices.

- Cooling Devices

Cooling devices must be capable of quenching the gases quickly to reduce the amount of time that the exhaust gases are exposed to temperatures between 480 and 660°F (see section 2.3.2). Furthermore, these devices should be made from corrosion resistant materials due to the concentrations of acid gases, such as HCl, typically present in incinerator exhaust gases. Finally, the cooling devices should be located far enough from the incinerator to allow the gases to reach the required residence times of 1 sec (if not longer).

- Particle Collection Devices

Particle collection devices must be able to capture small particles (see section 2.3.5). Like the cooling devices, particle collection devices must also be resistant to the effects of acid gases. Finally, when one or more of these particle collection devices and any of the quench devices are used together, the effect of one device on the other device should be considered. Space limitations and scaling should also be considered.

This section has only touched on some of the complex issues involved with air pollution control devices. For more information, consult Part II of this document which discusses the theory of operation, types of equipment, system capabilities and limitations, and economics of commonly used air pollution control devices.

3.2 TEMPERATURE LIMITS AND RESIDENCE TIMES.

3.2.1 Regulations

This CARB regulation for medical waste incinerators controls the temperatures of the exhaust gases and combustion chambers, and the amount of time combustion gases have to mix and react. It states that the temperature of the gases exiting the last air pollution control device must be less than or equal to 300°F. If the air pollution control devices operate more effectively (have higher PCDD/PCDF removal efficiencies) at higher temperatures, this limit can be changed if the district air pollution control officer and the CARB agree.

The regulation also states that the primary and secondary chamber temperatures must be greater than or equal to 1400 and 1800°F (± 200°F), respectively. This restriction would affect both starved-air modular incinerators and rotary kilns (see section 2.3.4). The combustion chamber temperature for single chamber incinerators (excess-air modular incinerators, see section 2.3.4) must be greater than or equal to 1800°F (± 200°F).

The final restriction specifies a residence time of 1 second or greater. The residence time, t_{res} , is computed using Equation 5 (1):

Equation 5

$$t_{res} = \frac{V}{Q_c}$$

V = the residence volume, which is equal to the volume in cubic feet (ft³) of the incinerator from the location where a temperature of 1800°F has been reached to a location where the temperature has dropped to 1600°F.

Q_c = the volumetric flow rate in actual cubic feet per second (acfs) of combustion gases through the residence volume. The combustion gas volumetric flow rate is computed using CARB test method 2 (6). Once measured, the flow rate must be adjusted to the maximum temperature within the residence volume. If conditions exist within the system making direct measurement impossible, alternate methods can be used. This determination of acceptability shall be within the guidelines of the method and at the discretion of the district air pollution control officer and CARB.

If the temperature and residence time requirements are not met and the incinerator burns more than 25 tons of waste per year, it must be shut down.

3.2.2 Implementation

Stack Temperature Measurement

The flue gas temperature should be measured after the last air pollution control device. This measurement can be obtained using a thermocouple with a low temperature range. Since the flue gas temperature is low, radiation, stem conduction, and gas convection corrections will probably be unnecessary.

Incinerator Temperature Measurements

Since the temperatures in the combustion chambers of starved-air modular incinerators, excess-air modular incinerators and rotary kilns are high, a heat resistant thermocouple must be used. Radiation, stem conduction, and gas convection corrections may be required due to the high temperatures and large gas flow rates present in combustion chambers.

The response time of thermocouples used in the incinerator should be on the order of 1 second to resolve bulk changes in system conditions, such as those occurring at startup and when waste is fed into the system. The thermocouples must also be resistant to the highly corrosive conditions present in the incinerator. A ceramic shield can be placed over the thermocouple to prevent corrosion problems and reduce radiation errors. The temperature measurement locations for the combustion chambers will vary depending on the type of incinerator.

- Rotary Kilns and Starved-Air Modular Incinerators Thermocouple Placement

For starved-air modular incinerators and rotary kilns, temperature measurement devices must be placed at the exit of the primary and the secondary chamber, and at the entrance to the first air pollution control device or quench device. The temperature measurement before the first air pollution control device or quench device is necessary if the stack volume between the incinerator exit and the first air pollution control device or quench device is used in the residence time computation. If the temperature in this volume drops below 1600°F, it cannot be used in the residence time computation (see section 3.2.1). The measurement locations, including the stack temperature measurement location, are illustrated in Figure 3-4 for a typical starved-air modular incinerator.

- Excess-Air Modular Incinerators Thermocouple Placement

Two combustion temperature measurement devices are required for an excess-air modular incinerator, one at the exit of the combustion chamber and one at the entrance to the first air pollution control device or quench device as shown in Figure 3-5 (includes stack temperature measurement device location). The need for a temperature measurement before the first air pollution control device is discussed in the previous paragraph.

Residence Time Computation

To solve Equation 5 for the residence time, t_{res} , the combustion gas volumetric flow rate, Q_c , and the residence volume, V , must be determined. The required method of computing Q_c is by CARB method 2.

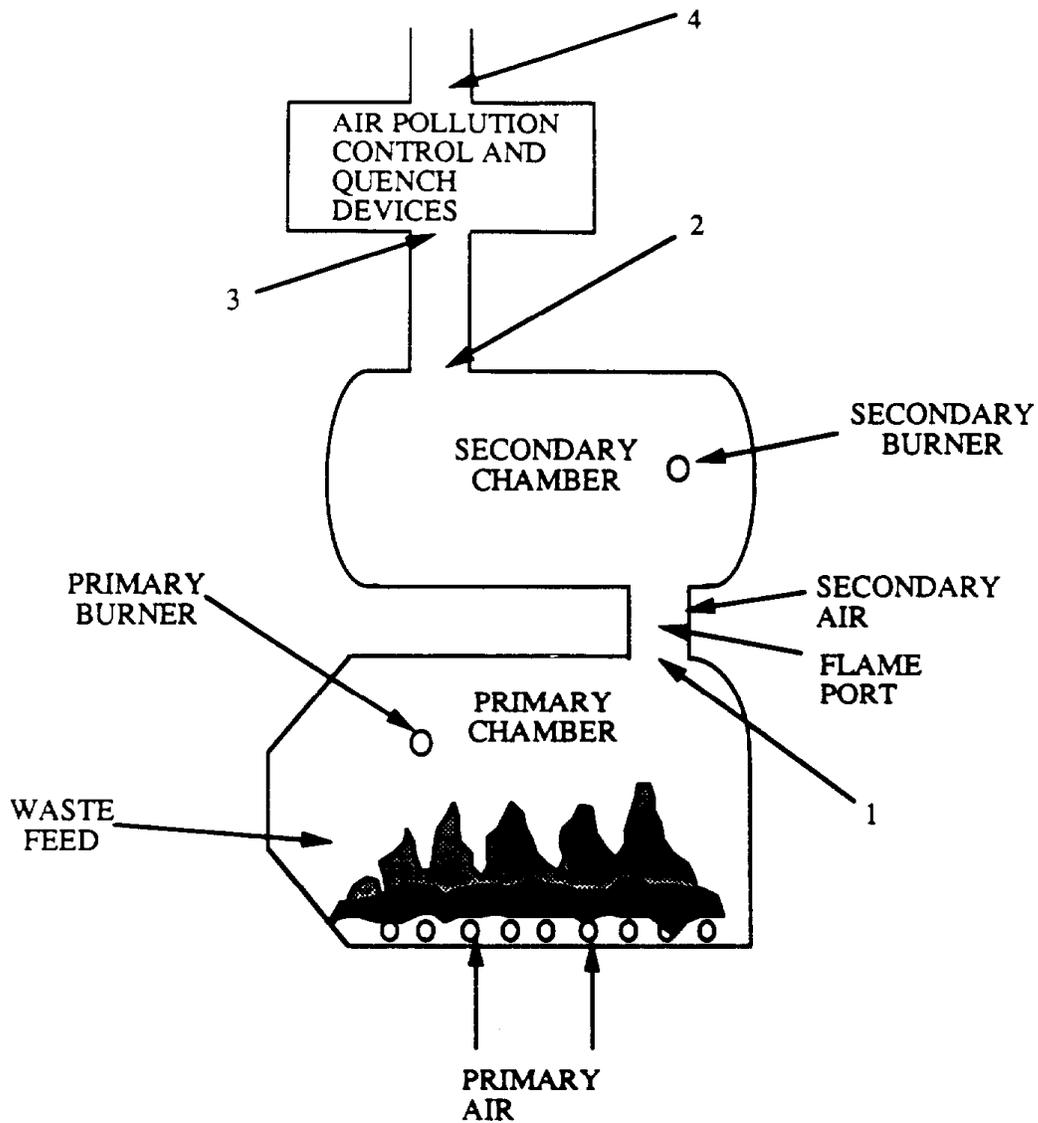


Figure 3-4. Starved-air modular incinerator thermocouple locations required to check CARB temperature limits.

1. Primary Chamber Exit
2. Secondary Chamber Exit
3. First APCD or Quench Device Entrance
4. Stack Exit

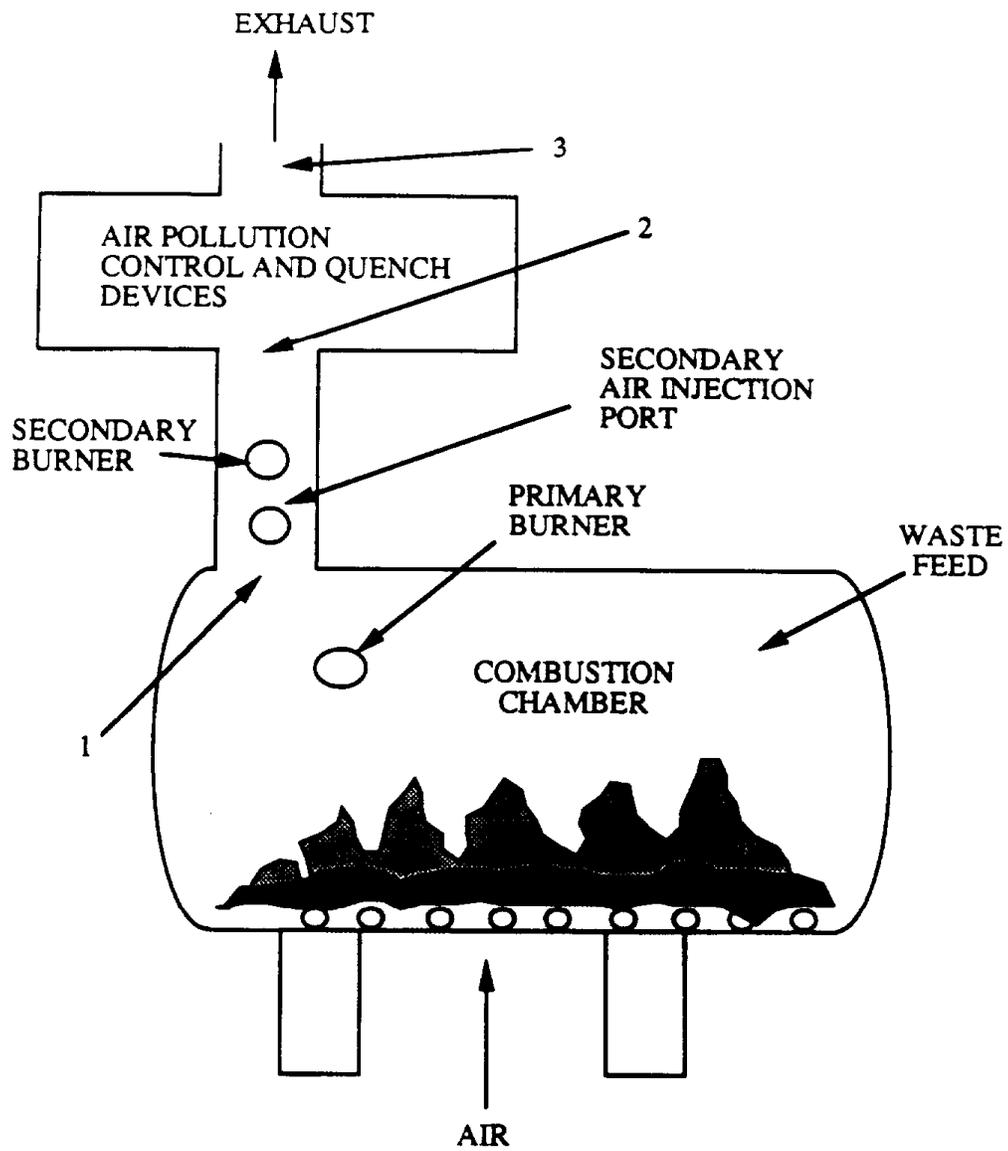


Figure 3-5. Excess-air modular incinerator thermocouple locations required to check CARB temperature limits

1. Combustion Chamber Exit
2. APCD or Quench Device Entrance
3. Stack Exit

- Combustion Gas Volumetric Flow Rate, Q_c , By CARB Method 2

CARB Method 2 (6) involves the use of a S type pitot tube and a differential pressure gauge to measure and indicate the dynamic pressure at several locations along two perpendicular diagonals in the stack. A thermocouple is attached to the pitot tube to measure the flue gas temperature, while a barometer and pressure probe are used to measure the local atmospheric and stack static pressures. In addition to CARB method 2, CARB methods 3 and 4 (see references 7 and 8) must be run simultaneously with CARB method 2. These methods are required to determine the molecular weight of the gases at the CARB method 2 measurement location.

To use CARB method 2 an acceptable sampling location must be found. Such a location must meet the following criteria:

- the flow must not be cyclonic or swirling,
- the stack or ducting diameter must be greater than or equal to 12 inches,
- the measurement location must be over 2 stack or duct diameters downstream from all flow disturbances,
- the measurement location must be over 1/2 stack or duct diameter upstream from all flow disturbances,
- the system must remain closed (constant mass flow rate) from the point where the maximum temperature was attained to the measurement location,
- and the absolute pressure and gas composition at the measurement location and the location of maximum system temperature should be similar.

Flames, bends, contractions, expansions, and nearby sampling trains (methods 3, 4, and 428 (9) have sampling trains) are considered flow disturbances. The effects of these disturbances can be dampened by installing straightening vanes, which can be costly and time consuming. Thus, when an acceptable measurement location cannot be found for CARB method 2, another method is usually required to measure the volumetric flow rate. One such method is the stoichiometric method. This method involves several assumptions and complications, which make it less desirable than CARB method 2 (the stoichiometric method will be discussed in detail in a subsequent section).

Once an acceptable measurement site is found, CARB method 1 (5) must be used to determine the number of sampling points within the duct. This number is a function of the duct geometry and size, and the distances from the measurement location to the nearest upstream and downstream flow disturbances. Charts are given in CARB method 1 to determine the number of traverse points. Once the number of traverse points is selected, these points must be distributed over two perpendicular diameters within the duct. The exact locations are given by CARB method 1.

With the measurement site and traverse points selected and the system instruments calibrated and checked, CARB methods 2, 3 and 4 can be conducted. With the data from these methods, and assuming the combustion gas mass flow rate, composition, and absolute pressure do not change significantly from the measurement location to the location of the maximum temperature, Equation 6 can be used to compute the combustion gas volumetric flow rate, Q_c , in actual cubic feet per second (acfs):

Equation 6

$$Q_c = T_c A_s K_p C_p (\sqrt{\Delta p})_{avg} \sqrt{\frac{1}{(T_s)_{avg} P_s M_s}}$$

A_s = Cross sectional area of stack, ft²

K_p = Pitot Tube Constant, 85.49

C_p = Pitot Tube Coefficient, dimensionless (From calibration)

T_s = Absolute Stack Temperature at Traverse Point, °R

P_s = Absolute Stack Pressure, in. Hg

Δp = Dynamic Pressure at Traverse Point, in. H₂O

M_s = Molecular weight of stack gas, wet (From Methods 3 and 4)

T_c = The maximum temperature within the residence volume, °R

In most incinerators the gas molecular weight and pressure will remain relatively constant throughout the system due to the large percentage of diatomic nitrogen in the flue gas and the absence of high flow rates. Thus, the uniformity of the combustion gas pressure and molecular weight from the measurement location to the location of the maximum temperature is not a major concern in most cases. The mass flow rate of combustion gases can change, however, as a result of air leakage and APCDs. To assure that the mass flow rate is approximately the same at the measurement location and at the location of the maximum temperature, the measurement device should not be placed after APCDs such as wet scrubbers, spray coolers, baghouses, ESPs, and dry injectors which can add significantly to the mass flow rate of the flue gases.

To save time and reduce costs, results from the dioxin CARB method 3 and 428 runs (see section 3.1) can be used to compute the combustion gas volumetric flow rate. These results cannot be used to compute the residence time if the mass flow rate changes from the location of the CARB method 3 and 428 runs to the location of the maximum temperature. Stack dioxin emission test results will probably be unacceptable for residence time computations for systems with APCDs (see previous paragraph).

- Residence Volume, V

For starved-air modular systems and rotary kilns, the residence volume is equal to the volume of the secondary chamber plus the volume of the stack section extending from the secondary chamber exit to the entrance of the first cooling device or air pollution control device. The cross-hatched section in Figure 3-6 illustrates this volume for a typical starved-air modular incinerator. The volume extending from the incinerator exit to the first air pollution control device or quench device can be included in the residence volume as long as the temperature remains above 1600°F (see section 3.2.1).

The cross-hatched section in Figure 3-7 illustrates the residence volume for an excess-air modular incinerator. This volume includes the volumes of the combustion chamber and the volume of the stack to the first quench device or air pollution control device. The temperature in the stack volume must remain above 1600°F.

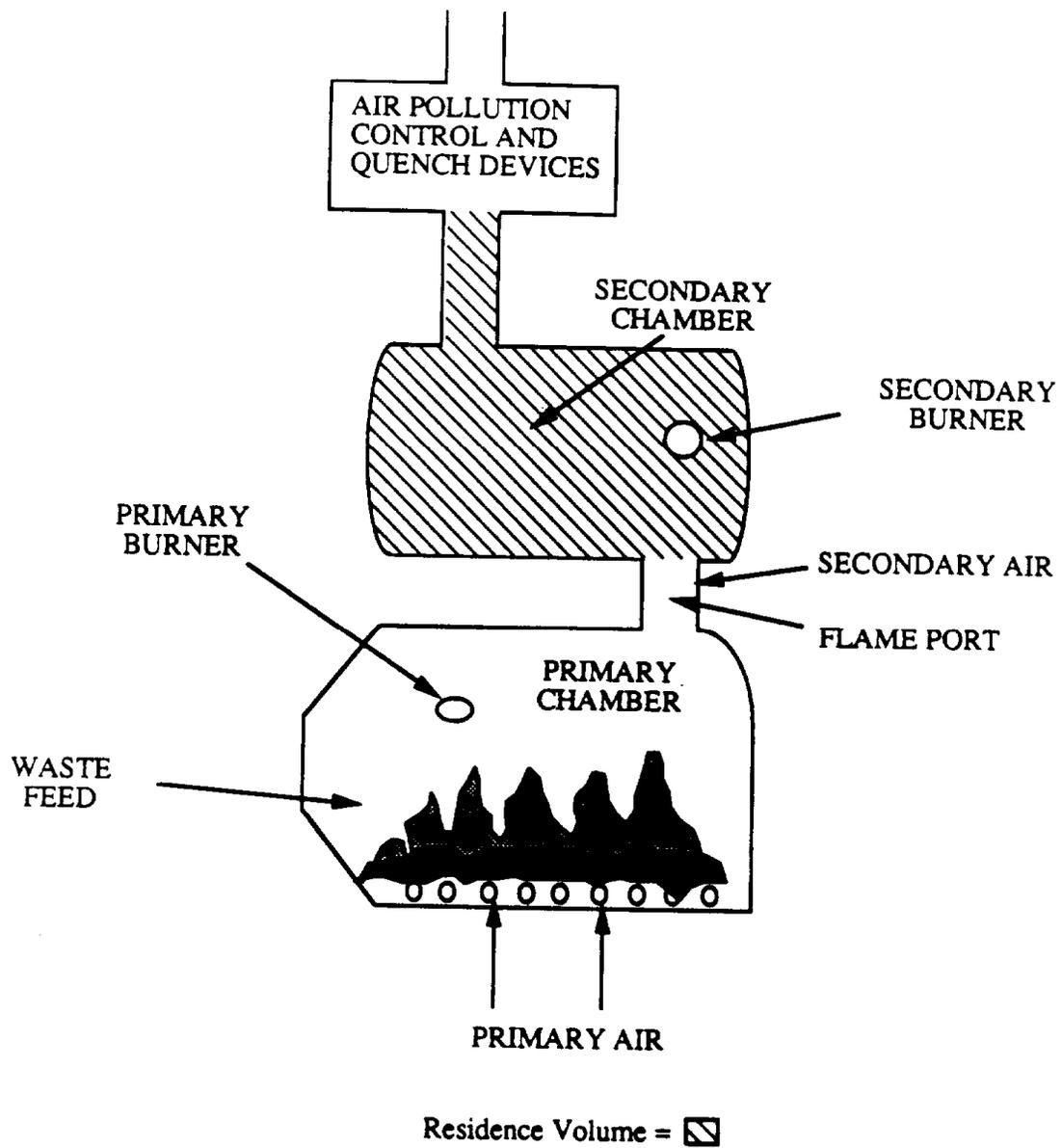


Figure 3-6. Starved-air modular incinerator residence volume for CARB residence time computation. The temperature at the entrance to this volume must be at least 1800 F and the temperature at the exit must be greater than 1600 F.

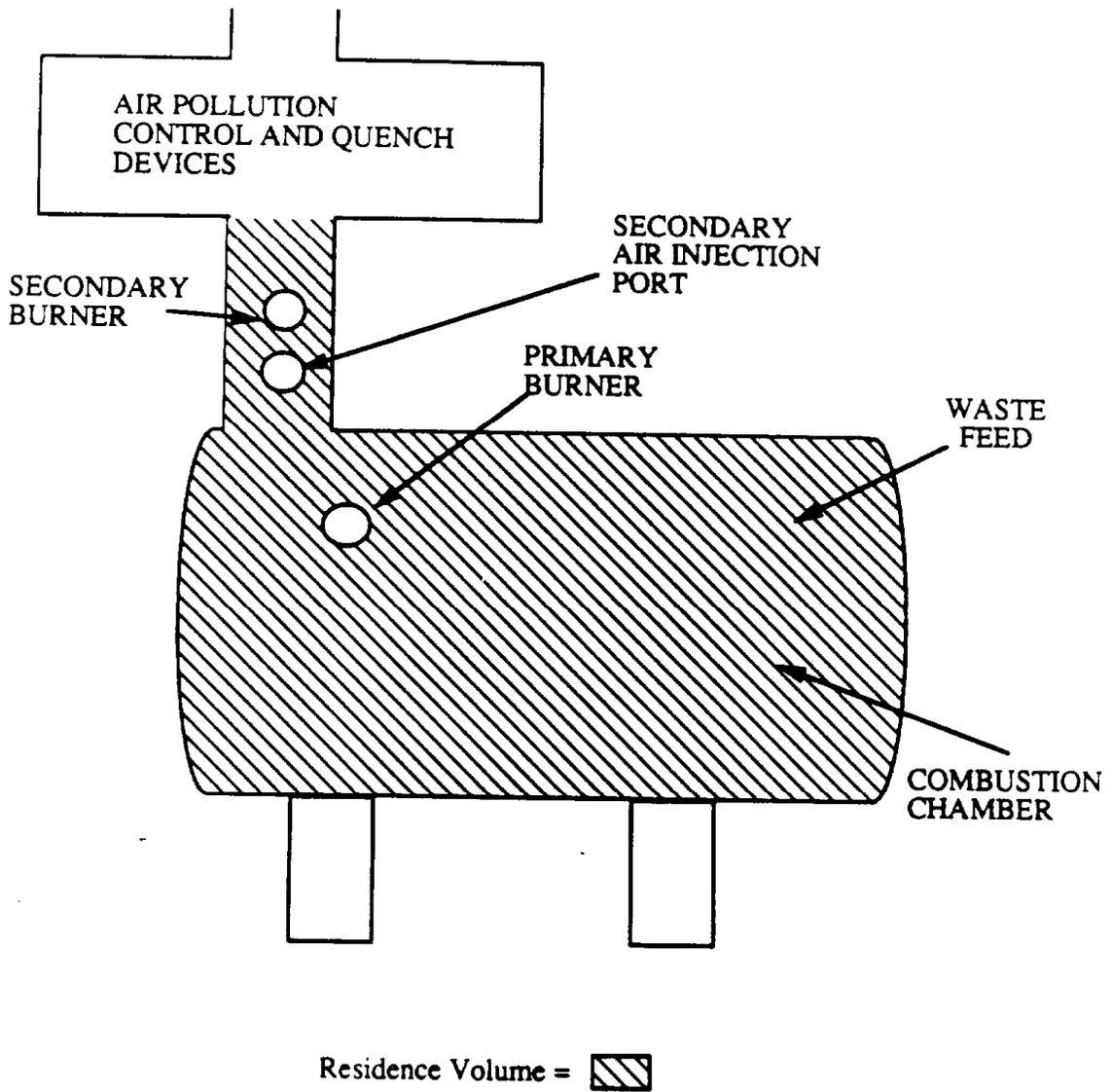


Figure 3-7: Excess-air modular incinerator residence volume for CARB residence time computation. The temperature within the combustion chamber must exceed 1800 F and the temperature at the exit of the volume must be greater than 1600 F.

- Summary of Residence Time Determination Procedures

While computing the residence time is a complicated process, several important steps can be summarized to make the process less confusing. These steps include the following:

1. Select suitable measurement sites for CARB methods 2, 3, and 4 in accordance with CARB method 1. The mass flow rate from the measurement locations to the location of the maximum system temperature should be constant. No mass should be added or subtracted from the system over this path.
2. If suitable sampling locations cannot be found, consult with the district to see if an alternate method can be used. One such method is the stoichiometric method discussed in this paper. Another method uses straightening vanes to dampen the effects of disturbances.
3. Compute the number of traverse points for CARB method 2 using the guidelines of CARB method 1. The traverse points for CARB method 3 and 4 are given in the guidelines for these methods.
4. Locate the traverse points within the stack or duct in accordance with CARB method 1.
5. Calibrate and check the measurement system's components in accordance with the requirements given in CARB methods 2, 3, and 4.
6. Place thermocouples at the exit of the first and last combustion chamber and before the first quench device or APCD.
7. Complete the sampling run or runs.
8. Compute the residence volume according to the guidelines given in this document and compute the combustion gas volumetric flow rate using Equation 6.
9. Compute the residence time using Equation 5.

- Example Computation of the Residence Time Using CARB Method 2

To demonstrate the computations and procedures involved in determining the residence time using CARB methods 2, 3, and 4, an example was carried out using the incinerator shown in Figure 3-8. This system has two combustion chambers including a primary chamber and a thermal reactor. The thermal reactor is 7.77' long and 3' in diameter. A 10.17' long and 5' diameter retention chamber is also present to increase the mixing and reaction times. A boiler is present for heat recovery. The boiler is separated from the retention chamber by a duct which is 11.75' long and 1.75' in diameter.

The residence volume of 283 ft³ includes the thermal reactor, retention chamber, and duct volumes. Each volume is indicated in Figure 3-8. A thermocouple was placed after the thermal reactor to record the system's maximum temperature and a thermocouple was located in the duct system just before the boiler to assure that the temperature remained above 1600 °F in the duct. The approximate locations of the thermocouples are given in Figure 3-8.

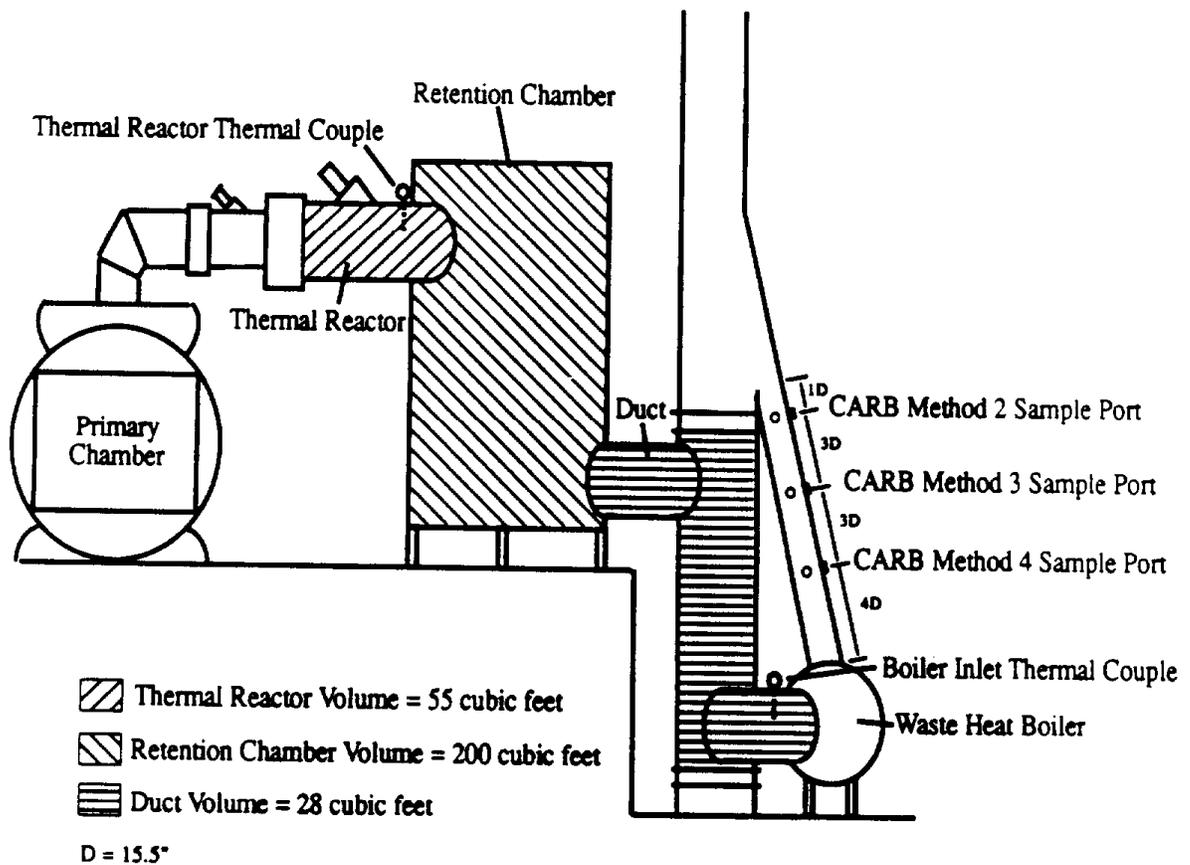


Figure 3-8: Residence volume, thermocouple locations, and CARB Method 2, 3, and 4 train locations for the residence time computation example using CARB method 2.

The approximate locations of the CARB method 2, 3, and 4 are illustrated in Figure 3-8. The distances between the method ports were chosen to be as large as possible within the overall space requirements. A slightly larger distance was provided between the boiler exit and the CARB method 4 port because the boiler probably disrupted the flow more than the sample trains. The CARB method 2 sample port was placed only 1 duct diameter from the stack/duct connection because downstream disturbances generally cannot penetrate very far upstream. Swirl checks performed in accordance with CARB method 1 at the CARB method 2 port indicated the absence of cyclonic flow.

At each measurement location two perpendicular ports were constructed. The number of points at each location are given below in Table 3-4.

TABLE 3-4. REQUIRED NUMBER OF SAMPLE POINTS FOR CARB METHOD 2, 3, AND 4 SAMPLE TRAINS FOR THE RESIDENCE TIME COMPUTATION EXAMPLE USING CARB METHOD 2.

CARB Method	Number of Sample Points
2	16
3	8
4	8

The traverse points for each method were spaced in agreement with the requirements of CARB method 1.

After calibrating the systems and performing the checks required by CARB methods 2, 3, and 4, three 3 hour runs were carried out with the incinerator running at ± 10 percent of its maximum permitted capacity. The results pertaining to the residence time are given in Table 3-5. The combustion gas volumetric flow rate and the residence time were computed using Equations 6 and 5, respectively. The residence times for each run are clearly above the 1 second limit, thus this system satisfies the residence time requirements.

Alternate Residence Time Computation By The Stoichiometric Method

If it is not possible or practical to use CARB method 2 to compute the residence time and the district air pollution control officer is in agreement, then the stoichiometric method can be used to estimate the residence time. The stoichiometric method involves performing a mass balance on the system and making the following assumptions:

- the combustion gases have the same properties as air,
- the ideal gas law is valid,
- and the fuel burns completely to CO₂ and H₂O.

These assumptions are usually valid under the conditions present in typical incineration units because the temperatures are high, diatomic nitrogen is a predominate species, and excess air is usually used to assure complete combustion. With these assumptions, Equation 7 can be used to compute the combustion gas volumetric flow rate, Q_c , in actual cubic feet per second (acfs).

TABLE 3-5. PARAMETERS USED FOR THE RESIDENCE TIME COMPUTATION EXAMPLE USING CARB METHOD 2.

PARAMETER	RUN 1	RUN 2	RUN 3
Maximum Chamber Temperature, Tc (R)	2566	2561	2572
Pitot Tube Coefficient, Cp	0.829	0.829	0.829
Average Stack Temperature, Ts(avg) (R)	836	824.6	823.9
Absolute Stack Pressure, Ps (in Hg)	28.531	28.901	28.961
Average Root Squared Dynamic Pressure, Dp (in H2O) ^{0.5}	0.526	0.51	0.522
Molecular Weight of Stack Gas, wet	28.109	27.998	28.011
Stack Area (ft ²)	1.31	1.31	1.31
Residence Volume, V (ft ³)	283	283	283
Combustion Gas Volumetric Flow Rate, Qc (acfs) see EQ. 6	153.04	148.45	152.47
Residence Time (sec) see EQ. 5	1.85	1.91	1.86

Equation 7

$$Q_c = \left[\frac{m_{\text{waste}}}{\text{TFAR}_{\text{wf}}} \left(\text{TFAR}_{\text{wf}} \left(1 + \frac{\text{AWR}}{100} \right) + 1 + \frac{\text{EA}_{\text{wf}}}{100} \right) + \frac{m_{\text{fuel}}}{\text{TFAR}_{\text{af}}} \left(\text{TFAR}_{\text{af}} + 1 + \frac{\text{EA}_{\text{af}}}{100} \right) + m_{\text{Qwater}} \right] \left[\frac{53.55(T_c + 460)}{P} \right]$$

- EA = the ratio of excess air in pounds to required air in pounds times 100 (100*lbs-excess-air/lbs-required-air),
- T_c = the maximum combustion chamber temperature in degrees Fahrenheit (°F),
- TFAR = the theoretical fuel air ratio in pounds of fuel per pounds of required air (lbs-fuel/lb-required-air),
- m_{waste} = mass flow rate of waste in pounds of waste per second (lb-waste/sec),
- m_{fuel} = mass flow rate of fuel in pounds of fuel per second (lbs-fuel/sec),
- m_{Qwater} = mass flow rate of quench water and under fire steam to the primary chamber in pounds of water per second (lbs-water/sec),
- AWR = the ratio of ash in pounds to waste in pounds times 100 (100*lbs-ash/lbs-waste),
- P = the absolute pressure at the maximum combustion chamber temperature T_c expressed in pounds per foot squared (lbs/ft²).

Equation 7 was derived using a mass balance and the ideal gas law. The subscripts "wf" and "af" refer to the waste feed and auxiliary fuel feed, respectively. Equation 7 only applies to incinerators burning one waste type and one auxiliary fuel type, which is the industry norm. To compute a worst case scenario, the maximum auxiliary fuel loading should be used in the Equation 7.

To solve equations 5 and 7 for the residence time, t_{res} , the residence volume, V, maximum combustion chamber temperature, T_c, absolute pressure at the maximum combustion chamber temperature, P, theoretical fuel air ratios for the waste feed, TFAR_{wf}, and auxiliary fuel feed, TFAR_{af}, excess air ratios for the waste feed, EA_{wf}, and auxiliary fuel feed, EA_{af}, ratio of ash to waste, AWR, and the mass flow rates of auxiliary fuel, m_{fuel}, waste, m_{waste}, and quench water and steam, m_{Qwater}, must be determined. The determination V and T_c were discussed in the section describing CARB method 2 (see Residence Time Computation Using CARB Method 2). m_{Qwater} can be computed using flow meters which are usually part of the system. The computation of EA_{wf}, EA_{af}, TFAR_{wf}, TFAR_{af}, m_{waste}, and m_{fuel} will be discussed in the following sections.

- Excess Air Ratios For The Waste Feed, EA_{wf} , and Auxiliary Fuel Feed, EA_{af}

The excess air ratios for the waste feed, EA_{wf} , and auxiliary fuel Feed, EA_{af} , can be computed by measuring the total mass flow rate of air to the auxiliary burners, m_{airaf} , and the total mass flow rate of air to the waste feed, m_{airwf} , and then using Equations 8 and 9:

Equation 8

$$EA_{wf} = \frac{m_{airwf} \frac{m_{waste}}{TFAR_{wf}}}{\frac{m_{waste}}{TFAR_{wf}}}$$

Equation 9

$$EA_{af} = \frac{m_{airaf} \frac{m_{fuel}}{TFAR_{af}}}{\frac{m_{fuel}}{TFAR_{af}}}$$

- TFAR = the theoretical fuel air ratio in pounds of fuel per pounds of required air (lbs-fuel/lb-required-air),
- m_{waste} = the mass flow rate of waste in pounds of waste per second (lb-waste/sec),
- m_{fuel} = the mass flow rate of fuel in pounds of fuel per second (lb-fuel/sec),
- m_{airaf} = the total mass flow rate of air to the auxiliary fuel in pounds of air per second (lb-air/sec),
- m_{airwf} = and the total mass flow rate of air to the waste feed in pounds of air per second (lb-air/sec).

Equations 8 and 9 were derived using a mass balance and wf and af refer to the waste feed and auxiliary fuel feed, respectively. The computation of $TFAR_{wf}$, $TFAR_{af}$, m_{waste} , and m_{fuel} will be discussed in the following sections.

- Waste Feed Rate, m_{waste} , and Auxiliary Fuel Feed Rate, m_{fuel}

The fuel mass flow rate for the waste feed, m_{waste} , can be determined by weighing the waste fed into the incinerator over a period and then dividing this quantity by the elapsed interval. The fuel mass flow rate for the auxiliary fuel, m_{fuel} , is equal to the combined burner heating rate in Btu/sec divided by the heating value of the fuel in Btu/lb. Natural gas has a higher heating value of 23,877 Btu/lb (11). The combined burner heating rate is usually supplied by the manufacturer, and should include all burners.

- Theoretical Fuel Air Ratio For The Waste Feed, $TFAR_{wf}$, and Auxiliary Fuel Feed, $TFAR_{af}$

To compute the theoretical fuel air ratio for the waste feed, $TFAR_{wf}$, an ultimate analysis of the waste feed must be performed or a representative ultimate waste composition must be found. An ultimate analysis gives the weight percentage of each of the following components: moisture, carbon, hydrogen, oxygen, nitrogen, sulfur, chlorine, and ash (noncombustibles). All of these percentages are determined using ASTM method D 3176, 3180 (12), except the weight percentage of chlorine, which is found using ASTM method D 2361 (12).

Instead of analytically determining the ultimate waste composition, results from a prior ultimate analysis which are representative of the waste stream can be used. Table 3-6 illustrates the results from two ultimate analyses, one taken from a document prepared by Andersen 2000 Inc. (10) and one taken from Santolevi and Kratz (13). Each of these ultimate waste compositions will yield significantly different residence times in a given incinerator. For instance, in a 1700 lb/hr Joy Energy Systems Model 2500 TESI Controlled Air Incinerator (10), the Santolevi and Kratz waste composition produces a residence time of 1.15 sec, while the Andersen 2000 Inc. waste composition produces a residence time of 1.52 sec. Thus, if one cannot find ultimate waste composition data which is representative of the facility's waste stream (a representative facility would be one which has similar specialties and waste handling policies), an ultimate analysis of the waste feed should be performed. Since, an ultimate analysis of medical waste can be hazardous and obtaining a representative sample is difficult, CARB method 2 is clearly a better alternative for computing the combustion gas volumetric flow rate.

Computing the theoretical fuel air ratio for the auxiliary fuel, $TFAR_{af}$, also requires a knowledge of the amount of carbon, hydrogen, and oxygen present in auxiliary fuel. Natural gas, the fuel most commonly used in incinerators, is composed of 74.87 percent carbon and 25.13 percent hydrogen by weight.

- Table For Residence Time Determination

Knowing the weight percentages of moisture, carbon, hydrogen, oxygen, nitrogen, sulfur, chlorine, and ash in the waste feed and auxiliary fuel streams, and the residence volume, V , maximum combustion chamber temperature, T_c , excess air ratio for auxiliary fuel, EA_{af} , and waste feed, EA_{wf} , the mass flow rates of auxiliary fuel, m_{fuel} , and waste feed, m_{waste} , and the flow rate of quench water, m_{Qwater} , Table 3-7 can be used to compute the residence time. This table has five subsections, including Waste Fuel Stream Input Data, Auxiliary Fuel Stream Input Data, General Input Data, Results, and Equations. The input parameters listed in the sections titled Waste Fuel Stream Input Data, Auxiliary Fuel Stream Input Data, and General Input Data must have the units given in the third column. The output rows 21-25 in the Results section are computed with equations 21-25, respectively, in the Equations section. The item numbers in the Equations section correspond to a particular item number in the input sections.

- Example of Residence Time Computation For Starved-Air Modular Incinerator

To demonstrate the procedure given in Table 3-7, an example will be carried out using the 1700 lb/hr Joy Energy Systems Model 2500 TESI Controlled Air Incinerator (10) pictured in Figure 3-9. In the residence time computation which follows, the Joy incinerator is assumed to run at full capacity. Thus, its two natural gas, 3,700,000 Btu/hr, primary burners and its single natural gas, 7,000,000 Btu/hr, secondary burner will be fired. The input parameters are given in rows 1-20 in Table 3-8, and were taken from a document prepared by ANDERSEN 2000 INC. (10). The computed residence time is 1.52 seconds (see row 25), which is well above the CARB residence time regulation. If the primary and secondary burners are extinguished (this is

TABLE 3-6. ANDERSEN 2000 INC. (10), AND SANTOLEVI AND KRATZ (13)
 ULTIMATE WASTE COMPOSITIONS FOR THE
 STOICHOIMETRIC RESIDENCE TIME COMPUTATION.

Component	ANDERSEN 2000 INC. (WT. %)	Santolevi and Kratz (WT. %)
Moisture	12.080	9.000
Ash	10.920	7.620
Hydrogen	4.288	6.230
Sulfur	0.692	0.170
Oxygen	28.276	21.310
Chlorine	2.836	4.120
Nitrogen	0.000	0.450
Carbon	40.908	51.100
	100.00	100.00

TABLE 3-7. TABLE FOR THE COMPUTATION OF THE RESIDENCE TIME USING THE STOICHIOMETRIC METHOD.

WASTE FUEL STREAM INPUT DATA (Input each item with the specified units)			
ITEM #	ITEM DESCRIPTION	UNITS	VALUE
1	% Carbon	lb-C/lb-waste	
2	% Hydrogen	lb-H/lb-waste	
3	% Oxygen	lb-O/lb-waste	
4	% Nitrogen	lb-N/lb-waste	
5	% Chlorine	lb-Cl/lb-waste	
6	% Sulfur	lb-S/lb-waste	
7	% Moisture	lb-H ₂ O/lb-waste	
8	% Ash, AWR	lb-Ash/lb-waste	
9	Waste Feed Rate, m_{waste}	lb-waste/sec	
10	% Excess Air, EA_{af}	lb-excess-air/ lb-required-air	

AUXILIARY FUEL STREAM INPUT DATA (Input each item with the specified units)			
ITEM #	ITEM DESCRIPTION	UNITS	VALUE
11	% Carbon	lb-C/lb-fuel	
12	% Hydrogen	lb-H/lb-fuel	
13	% Oxygen	lb-O/lb-fuel	
14	Heating Value	Btu/lb-fuel	
15	Heating Rate	Btu/hr	
16	% Excess Air, EA_{af}	lb-excess-air/ lb-required-air	

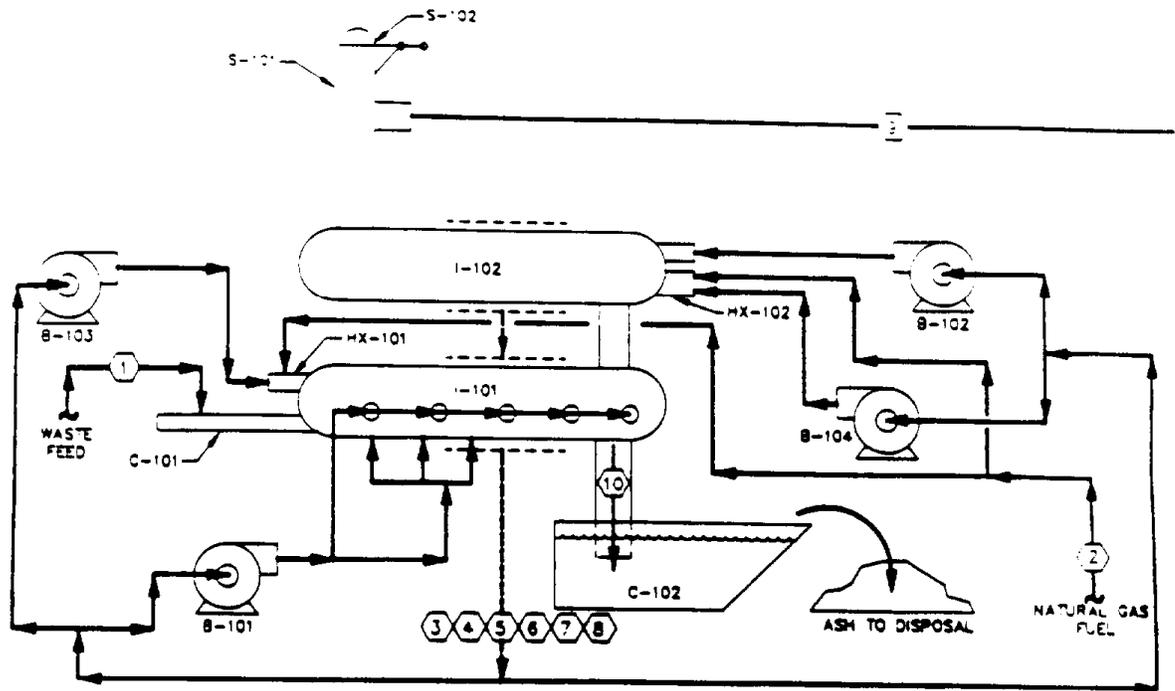
TABLE 3-7. CONTINUED

GENERAL INPUT DATA (Input each item with the specified units)			
17	Maximum Combustion Chamber Temperature, T_c	$^{\circ}\text{F}$	
18	Residence Volume, V	ft^3	
19	Absolute Combustion Chamber Pressure, P	lb/ft^2	
20	Total Mass Flow Rate of Quench Water and Steam, m_{water}	$\text{lb-water}/\text{sec}$	

RESULTS (Use the corresponding equation number in the equation section on the next page to calculate each item in this table.)			
ITEM #	ITEM DESCRIPTION	UNITS	VALUE
21	Auxiliary Fuel Feed Rate, m_{fuel}	$\text{lb-fuel}/\text{sec}$	
22	Theoretical Fuel Air Ratio for Waste Feed, TFAR_{wf}	$\text{lb-waste}/\text{lb-required-air}$	
23	Theoretical Fuel Air Ratio for Auxiliary Fuel Feed, TFAR_{af}	$\text{lb-fuel}/\text{lb-required-air}$	
24	Combustion Gas Volumetric Flow Rate, Q_c	ft^3/sec	
25	Residence Time, t_{res}	sec	

TABLE 3-7. CONTINUED

EQ. #	EQUATION
21	$m_{fuel} = \frac{Item15}{3600 * Item14}$
22	$TFAR_{wt} = \frac{1.45631}{2 \left(\frac{Item1}{12.01} \right) + 0.5 \left(\frac{Item2}{1.008} - \frac{Item5}{35.45} \right) + 2 \left(\frac{Item6}{32.06} \right) - \frac{Item3}{16.0}}$
23	$TFAR_{si} = \frac{1.45631}{2 \left(\frac{Item11}{12.01} \right) + 0.5 \left(\frac{Item12}{1.008} \right) - \frac{Item13}{16.0}}$
24	$Q_c = \left[\left(\frac{Item9}{Item22} \left(Item22 \left(1 - \frac{Item8}{100} \right) + 1 + \frac{Item10}{100} \right) \right) + \left(\frac{Item21}{Item23} \left(Item23 + 1 + \frac{Item16}{100} \right) \right) + Item20 \right] \frac{53.55 * (Item17 + 460)}{Item19}$
25	$t_{res} = \frac{Item18}{Item24}$



EQUIPMENT LIST

C-101	RAW FEEDER
I-101	PRIMARY COMBUSTION CHAMBER
I-102	SECONDARY COMBUSTION CHAMBER
B-101	PRIMARY AIR FAN
B-102	SECONDARY AIR FAN
B-103	PRIMARY BURNER FAN
B-104	SECONDARY BURNER FAN
HE-101	PRIMARY GAS BURNER
HE-102	SECONDARY GAS BURNER
C-102	WET ASH REMOVAL
S-101	BYPASS STACK
S-102	STACK CAP

Figure 3-9. Configuration of the Joy Energy Systems Model 2500 TESI controlled air incinerator used for the residence time computation example using the stoichiometric method (10).

TABLE 3-8. EXAMPLE COMPUTATION OF THE RESIDENCE TIME USING THE STOICHIOMETRIC METHOD FOR A JOY ENERGY SYSTEMS MODEL 2500 TEST CONTROLLED AIR INCINERATOR. CASE ONE: PRIMARY AND SECONDARY BURNERS FIRED.

Waste Fuel Stream Input Data			
Item #	Item Description	Units	Value
1	% Carbon	lb-C/lb-waste	40.908
2	% Hydrogen	lb-H/lb-waste	4.288
3	% Oxygen	lb-O/lb-waste	28.276
4	% Nitrogen	lb-N/lb-waste	0.000
5	% Chlorine	lb-Cl/lb-waste	2.836
6	% Sulfur	lb-S/lb-waste	0.692
7	% Moisture	lb-H ₂ O/lb-waste	12.080
8	% Ash, AWR	lb-Ash/lb-waste	10.920
9	Waste Feed Rate, M _{waste}	lb-waste/sec	0.47
10	% Excess air, EA _{wf}	lb-excess-air/ lb-required-air	250.00

Auxiliary Fuel Stream Input Data			
Item #	Item Description	Units	Value
11	% Carbon	lb-C/lb-fuel	74.866
12	% Hydrogen	lb-H/lb-fuel	25.134
13	% Oxygen	lb-O/lb-fuel	0.000
14	Heating Value	Btu/lb-Fuel	23,877.0
15	Heating Rate	Btu/hr	10,700,000.0
16	% Excess Air, EA _{af}	lb-excess-air/ lb-required-air	20.00

General Input Data			
Item #	Item Description	Units	Value
17	Maximum Combustion Chamber Temperature, T _c	Degrees F	1,856.3
18	Residence Volume, V	Cubic Feet	1,000.0
19	Absolute Combustion Chamber Pressure, P	lb/ft ²	2,116.2
20	Total Mass Flow Rate of Quench Water and Steam, m _{Qwater}	lb-water/sec	0

Results			
Item #	Item Description	Units	Value
21	Auxiliary Fuel Feed Rate, m _{fuel}	lb-fuel/sec	0.12
22	Theoretical Fuel Air Ratio For Waste Feed, TOFR _{wf}	lb-waste/ lb-required-air	0.2030
23	Theoretical Fuel Air Ratio For Auxiliary Fuel Feed, TOFR _{af}	lb-fuel/ lb-required-air	0.0584
24	Combustion Gas Volumetric Flow Rate, Q _c	cubic feet/sec	659.13
25	Residence Time, t _{res}	sec	1.5171

accomplished by setting the heating rate in row 15 to zero), the residence time increases to 2 seconds as shown in Table 3-9. The differences in the computed residence time with and without auxiliary fuel clearly demonstrate the need to include auxiliary fuel loading in the computation.

3.2.3 Retrofit Options

Stack Temperatures

If the temperature at the outlet of the last air pollution control device exceeds 300°F, a quench device should be added to the system or any existing quench devices should be adjusted to produce the desired temperature. If the existing air pollution control devices operate more efficiently (have better emissions control) at the current temperature, the air pollution control officer should be contacted to inquire if the temperature limit can be increased. Changing the existing temperature requirement would involve detailed testing and documentation, and could be expensive. It is also doubtful that the air pollution control devices would operate more efficiently at higher temperatures, since a greater portion of the PCDD/PCDF would be present in vapor form above 300°F.

Incinerator Temperatures

The strategies for increasing the temperatures in the combustion chambers vary depending on the type of incinerator present.

- Starved-Air Modular Incinerators

If the temperature in the primary chamber of a starved-air modular incinerator drops below 1400°F, the flow rate of air into the chamber should be increased or the primary burner should be ignited (see Figure 2-3). If the secondary chamber temperature is less than 1800°F, the flow of air to the flame port (see Figure 2-3) should be reduced. If this tactic is unsuccessful, the afterburner should be turned on. The temperature correction actions for the primary and secondary chambers should occur automatically for most starved-air modular incinerator designs. Thus, if the system temperatures are consistently dropping below the CARB limits, the control system should be readjusted or the manufacturer should be contacted.

- Rotary Kilns

The temperature control techniques in the rotary kiln's secondary chamber are exactly the same as those discussed for the starved-air modular incinerator's secondary chamber. If the kiln's primary chamber temperature drops below 1400°F, the flow rate of air to the chamber should be reduced. If this tactic is unsuccessful, the primary burner should be ignited (see Figure 2-6). Most rotary kilns have automatic temperature controllers. Thus, if the desired temperatures are not being maintained, the manufacturer should be consulted.

- Excess-Air Modular Incinerators

Since excess-air modular incinerators are simple devices, very little can be done to control their temperature. If the temperature in the primary chamber drops below 1800°F, the flow rate of air into the chamber can be reduced throughout the batch cycle. The composition of the waste stream must also be monitored to ensure that materials with low heating values (glass and sharps) are mixed with materials with high heating values (plastics). This technique can also work to ensure consistent temperatures in the primary and secondary chambers of starved-air modular incinerators and rotary kilns.

TABLE 3-9. EXAMPLE COMPUTATION OF THE RESIDENCE TIME USING THE STOICHIOMETRIC METHOD FOR A JOY ENERGY SYSTEMS MODEL 2500 TEST CONTROLLED AIR INCINERATOR. CASE TWO: PRIMARY AND SECONDARY BURNERS OFF.

Waste Fuel Stream Input Data			
Item #	Item Description	Units	Value
1	% Carbon	lb-C/lb-waste	40.908
2	% Hydrogen	lb-H/lb-waste	4.288
3	% Oxygen	lb-O/lb-waste	28.276
4	% Nitrogen	lb-N/lb-waste	0.000
5	% Chlorine	lb-Cl/lb-waste	2.836
6	% Sulfur	lb-S/lb-waste	0.692
7	% Moisture	lb-H ₂ O/lb-waste	12.080
8	% Ash, AWR	lb-Ash/lb-waste	10.920
9	Waste Feed Rate, M _{waste}	lb-waste/sec	0.47
10	% Excess air, EA _{wf}	lb-excess-air/ lb-required-air	250.00

Auxiliary Fuel Stream Input Data			
Item #	Item Description	Units	Value
11	% Carbon	lb-C/lb-fuel	74.866
12	% Hydrogen	lb-H/lb-fuel	25.134
13	% Oxygen	lb-O/lb-fuel	0.000
14	Heating Value	Btu/lb-Fuel	23,877.0
15	Heating Rate	Btu/hr	0.0
16	% Excess Air, EA _{af}	lb-excess-air/ lb-required-air	20.00

General Input Data			
Item #	Item Description	Units	Value
17	Maximum Combustion Chamber Temperature, T _c	Degrees F	1,856.3
18	Residence Volume, V	Cubic Feet	1,000.0
19	Absolute Combustion Chamber Pressure, P	lb/ft ²	2,116.2
20	Total Mass Flow Rate of Quench Water and Steam, m _{Qwater}	lb-water/sec	0

Results			
Item #	Item Description	Units	Value
21	Auxiliary Fuel Feed Rate, m _{fuel}	lb-fuel/sec	0.00
22	Theoretical Fuel Air Ratio For Waste Feed, TOFR _{wf}	lb-waste/ lb-required-air	0.2030
23	Theoretical Fuel Air Ratio For Auxiliary Fuel Feed, TOFR _{af}	lb-fuel/ lb-required-air	0.0584
24	Combustion Gas Volumetric Flow Rate, Q _c	cubic feet/sec	501.93
25	Residence Time, t _{res}	sec	1.9923

Residence Times

The primary strategy for increasing the residence time is to increase the residence volume. This can be accomplished in rotary kilns and starved-air modular systems by adding another secondary chamber or by lengthening the current secondary chamber. The length of the stack to the first air pollution control device or quench device can also be increased. In excess-air modular incinerators, the residence volume can also be increased by lengthening the stack. Increasing the residence time by lengthening the stack in excess-air modular, starved-air modular, and rotary kilns is only possible if the stack temperature remains above 1600°F (see section 3.2.1). If the stack temperature drops below 1600°F, the stack volume cannot be included in the residence volume computation.

In all three incineration systems, the maximum temperature can be reduced if it exceeds the minimum temperature requirement. This strategy will reduce the volume flow rate and thus the residence time will increase.

3.3 FLY ASH AND AIR POLLUTION CONTROL DEVICE RESIDUE HANDLING

3.3.1 Regulation

This CARB regulation for medical waste incinerators states that ash particles from the bottom of the incinerator's main combustion chamber (bottom ash), small ash particles (fly ash), and scrubber residuals must be handled and stored in a manner which prevents their entrainment into the air. If this section of the regulation is not satisfied, then the incinerator must be shut down, regardless of its size or load capacity (1).

3.3.2 Implementation

Implementation of this regulation requires that incinerator operators and owners know the principle types of equipment which emit bottom ash, fly ash, and scrubber residuals into the air. Bottom ash can be emitted from all types of incinerators. Excess air modular incinerators, however, are of primary concern since they are usually operated in batch mode (see section 2.3.4). In batch mode, bottom ash can easily be entrained into the air during the discharge cycle.

All APCDs and quench devices emit fly ash in varying degrees. The primary devices of concern, however, are fabric filters and electrostatic precipitators (ESPs). These particulate removal devices will have a greater tendency to emit fly ash and scrubber residuals into the air, especially during cleaning cycles.

Spray dryers are the main emitters of solid salt products and other dry scrubber residuals. Venturi scrubbers and acid gas absorbers are not as important since they emit liquid scrubber residuals, which are not entrained into the air as easily as solid scrubber residuals.

3.3.3 Retrofit Options

There are several collection systems available to assist incineration facilities which do not satisfy the regulation described in section 3.3.1. These systems are classified by the manner in which ash and scrubber residuals are transferred from collection hoppers to the central storage silo (see Figure 3-10). In the three main collection systems, pneumatic, hydraulic and mechanical, the residuals are transported from the collection hoppers to the storage silo by air, water, and mechanical conveyors, respectively (14). Mechanical systems require less energy than pneumatic and hydraulic systems (14), while hydraulic systems are least likely to disperse particles into the air.

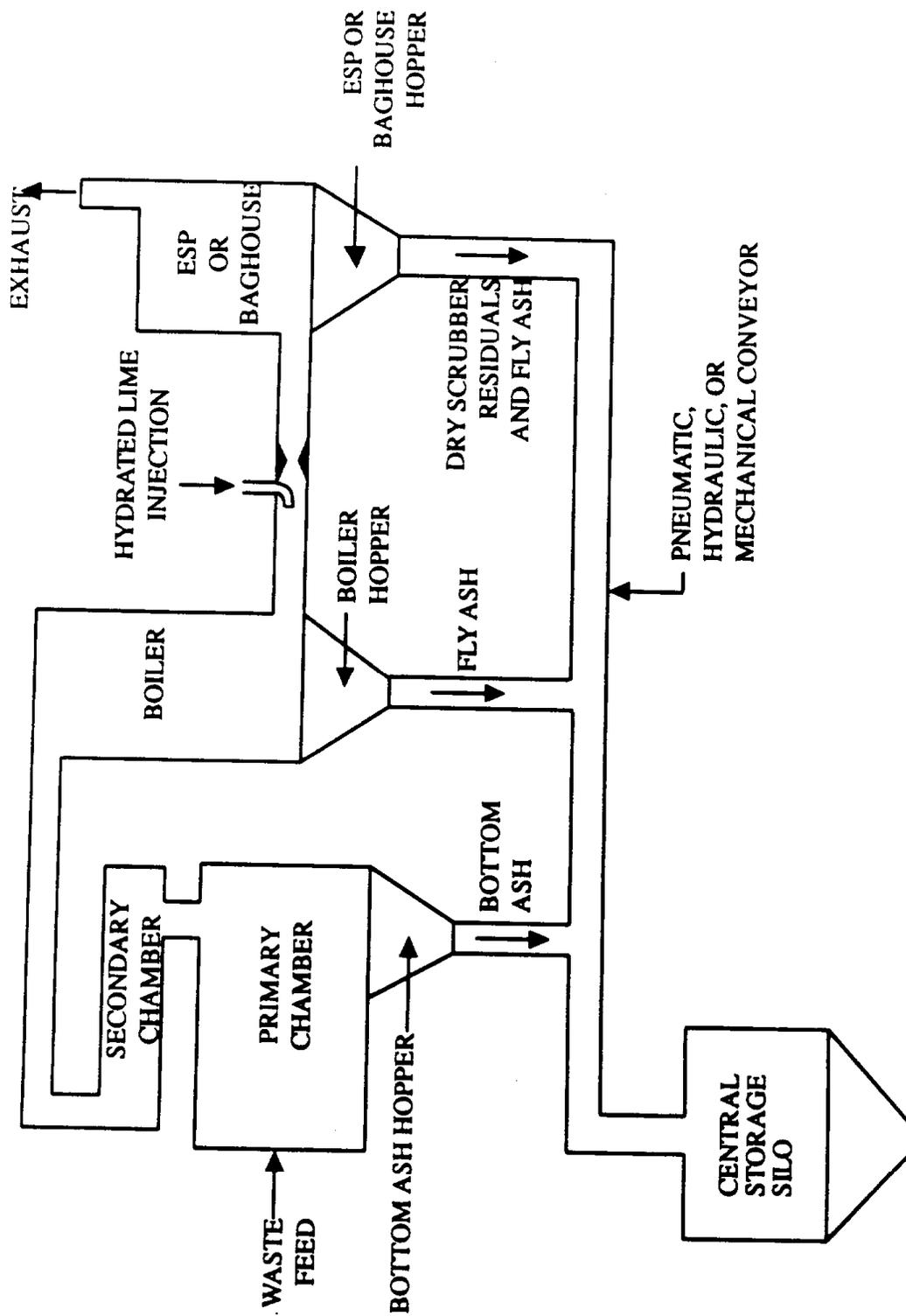


Figure 3-10. Possible configuration of a bottom and fly ash collection system.

3.4 OWNER OR OPERATOR RESPONSIBILITIES

3.4.1 Regulations

This regulation requires that either the owner or operator of a medical waste incinerator maintain a continuous recording system which records the primary and secondary temperatures, carbon monoxide emissions, key air pollution control device operating parameters (as specified by the district air pollution control officer), hourly waste charging rates, and the opacity of stack emissions or another indicator of particulate matter which is approved by the district air pollution control officer. The owner or operator should also keep maintenance records for the incinerator, control and monitoring equipment. Calibration records for the monitoring equipment must also be kept. The above requirements only apply to medical waste incineration facilities which burn over 25 tons of waste per year.

All owners or operators of medical waste incinerators must maintain equipment for determining and recording the weight of waste charged to the incinerator, regardless of the waste feed rate (1).

3.4.2 Implementation

Continuous Emission Monitoring Systems

This portion of the CARB regulations for medical waste incinerators requires the installation of continuous emission monitoring systems (CEMS) to record incinerator chamber temperatures, carbon monoxide emissions, key air pollution control device operating parameters, hourly waste charge rates, and the opacity of stack emissions. Most of these systems will involve the use of an analyzer to detect the pollutant or parameter of interest, a data recorder to convert and store information from the analyzer, and a calibration system.

- Chamber Temperature Continuous Emission Monitoring System

The CEMS temperature measurements for starved air modular, and rotary kilns should occur at the exit of the primary and secondary chamber (see Figure 3-4). Excess air modular incinerators only require one CEMS temperature measurement. This measurement should be at the exit of the combustion chamber (see Figure 3-5).

The thermocouples in both systems can either be embedded completely in the walls of the incinerator or they can protrude from the wall. In either case, the thermocouple should be insulated from the corrosive gases and flame radiation using a ceramic sheath. The sheath should be thin to assure that the CEMS's time response is quick. A system with a slow time response will not be able to detect short upset conditions. If high gas velocities exist around the thermocouple and it is near a flame, convection, and radiation corrections might have to be made. A detailed discussion of these corrections and stem conduction corrections is given by Holman (15).

In addition to the thermocouples, a data acquisition system should be installed to record the thermocouples output. This system might include a digital computer or an analog strip chart recorder. After the system is in place, it should be calibrated using a suction pyrometer or another temperature measurement device of higher accuracy than the CEMS.

- Carbon Monoxide Continuous Emission Monitoring System

Detailed performance specifications for carbon monoxide CEMS are given in the performance specification section of the Code of Federal Regulations (16). A few general topics

from this code will be discussed here, but the complete code should be consulted when evaluating carbon monoxide CEMS's.

The carbon monoxide measurement should be taken in the stack at least two equivalent diameters after the last air pollution control device. The measurement or measurements should also be representative of the carbon monoxide levels in the duct.

In order to test the systems performance and accuracy, calibration drift tests, and relative accuracy tests should be performed. Calibration drift tests give the difference between the CEMS output and an established reference value after period of continuous operation. The relative accuracy test gives the difference between the CEMS output and an established reference method.

- Opacity Continuous Emission Monitoring Systems

The opacity CEMS measures the fraction of incident light that is attenuated by an optical medium (16). Transparent stack emissions have an opacity of zero percent, while opaque stack emissions have an opacity of 100 percent. Detailed performance specifications for opacity CEMS's are given in the performance specifications section of the Code of Federal Regulations (16).

- Key air pollution control device and Exhaust Gas Cooling Device Parameters.

Table 3-10 lists some of the air pollution control device operating parameters which will indicate whether the air pollution control device's are functioning properly.

Part II of this report gives more information on the parameters listed above. It should be consulted before setting up a CEMS for air pollution control device's in a particular system.

3.5 HANDLING VIOLATIONS

3.5.1 Regulations

This CARB regulation for medical waste incinerators states, "any violation, malfunction, or upset condition on the incinerator, the air pollution control equipment, or the continuous data recording system shall be reported to the district within 1 hour of occurrence or by 9 a.m. the next business day if the malfunction occurs outside normal business hours and the district does not maintain a radio room or an answering machine" (1). This regulation only applies to the facilities which burn more than 25 tons of waste per year.

3.5.2 Implementation

This CARB regulations for medical waste incinerators requires that violations, malfunctions, and upset conditions on the incinerator, APCDs, and continuous data recording system be promptly reported to the district. Some of the conditions constituting a violation, malfunction, and upset condition will be discussed in the following sections.

Violations

A violation is any condition which may occur on the incinerator, APCDs, and continuous data recording system which is in direct conflict with the regulations described in sections 3.1 through 3.6. For instance, if the temperature recorded by the continuous recording system at the exit of the secondary chamber drops below 1600°F (1800°F - 200°F), the district must be notified.

TABLE 3-10. KEY OPERATING PARAMETERS FOR AIR POLLUTION CONTROL EQUIPMENT AND HEAT RECOVERY DEVICES (2).

Spray Coolers and Dryers

- * Outlet gas temperature.
- * Amount of alkaline reagent added to water to form solution or slurry.

Heat Recovery Units (Boilers)

Fire Tube Designs

- * Heat exchanger water level.
- * Water inlet temperature.
- * Chemical supply rates for control of PH, O₂, scaling, and foaming.

Water Tube Designs

- * Gas outlet temperature.
- * Water inlet temperature.
- * Steam outlet temperature.
- * Air flow rate to soot blowers.
- * Chemical supply rates for control of PH, O₂, scaling, and foaming.
- * Water level in steam separator.

Fabric Filters (Baghouses)

- * Pressure drop across unit.
- * Inlet gas temperature.
- * Outlet gas opacity.
- * Pulse duration and pressure for pulse-jet cleaning systems.
- * Frequency, peak acceleration, amplitude, and duration of vibration for mechanical shakers.
- * Reverse air flow duration and rate for reverse air cleaners.

Electrostatic Precipitators

- * Corona voltage, current, and spark rate.
- * Voltage across collecting electrodes.
- * Rapper intensity and frequency.
- * Outlet gas opacity.

Scrubbers

Venturi Scrubber

- * Solution flow rate to injector.
- * Amount of alkaline reagent added to water to form solution.
- * Pressure drop across venturi.
- * Water flow rate to quench if present.

Acid Gas Absorber

- * Solution flow rate to absorber.
- * PH of solution.

Dry Sorbent Injection

- * Amount of sorbent injected into duct or reactor.

Malfunction

Any breakdown in the incineration, and air pollution control device equipment would be classified as a malfunction. A malfunction does not necessarily constitute a violation but may lead to one. For instance, if the flow of water to a waste heat boiler is disrupted, the flue gas temperature may exceed 300°F which would be a violation of the regulations. Another example of a malfunction would be if a dry injection nozzle became blocked. A malfunction of the continuous data recording system would be considered a violation since the regulations require a continuous system.

Upset Condition

An upset condition would be classified as any large deviation of the incinerator, air pollution control devices, and continuous data recording system from its normal operating pattern. For instance, if the opacity value deviated from its normal pattern for an extended period of time, this should be reported as an upset condition to the district. This upset condition might indicate that a leak had occurred in the baghouse, thus decreasing the dioxin removal efficiency. Upset opacity and carbon monoxide conditions might be hard to identify since no specific limits have been set in the regulations.

3.6 OPERATOR TRAINING

This CARB regulation for medical waste incinerators states, "no person shall operate a medical waste incinerator unless each individual who operates or maintains the incinerator obtains either a certificate of training in medical waste incineration issued by the American Society of Mechanical Engineers within nine months of the commencement of the training program, or equivalent training as determined by the Air Pollution Control Officer. Copies of the training certificates for the operators and maintenance engineers shall be submitted to the districts and the original certificates shall be available for inspection at the facility with the permit to operate" (1). This regulation applies to all medical waste incinerators, including those which burn less than 25 tons of waste per year.

4.0 COMPLIANCE

The owner or operator of a medical waste incinerator burning over 25 tons of waste per year must:

1. Submit to the district air pollution control officer an application for an authority to construct the equipment necessary to meet the requirements in sections 3.1.1 and 3.2.1. This application must be submitted no later than 90 days after district adoption of regulations enacting the dioxin control measure.
2. Comply with district regulations enacting the dioxin control measure no later than 15 months after district adoption of these regulations.

The owner or operator of a medical waste incinerator burning 25 tons or less waste per year must:

1. Notify the district of his or her intent to keep the incinerator operating. This notification must be within 90 days after district adoption of regulations enacting the dioxin control measure.
2. Comply with district regulations enacting the dioxin control measure no later than 15 months after district adoption of these regulations.

The owner or operator of a medical waste incinerator who intends to permanently shut down operation of the incinerator must notify the district of the shutdown date within 90 days after district adoption of regulations enacting the dioxin control measure. This date shall be no later than 6 months after district adoption of regulations enacting the dioxin control measure (1).

5.0 NOMENCLATURE

acfs	Actual Cubic Feet Per Second
AF	Amount Found
APCD	Air Pollution Control Device
ASTM	American Society for Testing and Materials
AWR	Ratio of Ash to Waste
Btu	British Thermal Unit
C	Carbon
CARB	California Air Resources Board
CEMS	Continuous Emission Monitoring System
Cl	Chlorine
CO ₂	Carbon Dioxide
Ct	Concentration
DHS	California Department of Health Services
dscm	Dry Standard Cubic Meter
EA	Excess Air Ratio
EA _{af}	Excess Air Ratio for Auxiliary Fuel
EA _{wf}	Excess Air Ratio for Waste Feed
ESP	Electrostatic Precipitator
ft ³	Cubic Feet
H	Hydrogen
H ₂ O	Water
HCl	Hydrochloric Acid
kg	Kilogram
lb-waste/hr	Pound Waste Per Hour
lb-waste/min	Pound Waste Per Minute
lbs-excess-air	Pounds Excess Air
lbs-required-air	Pounds Required Air
m _{fuel}	Mass Flow Rate of Burner Fuel
Ms	Mass Emission Rate
m _{stack}	Mass Flow Rate of Stack Gases
m _{waste}	Mass Flow Rate of Waste
N	Nitrogen
ng/kg-waste	Nanogram Per Kilogram of Waste
ng	Nanogram
O ₂	Oxygen
°F	Degrees Fahrenheit
P	Average Waste Feed Rate For A Test Run
PCDD	Polychloro-dibenzo-p-dioxins
PCDF	Polychloro-dibenzo-furans
QA	Quality Assurance
Q _c	Combustion Gas Volumetric Flow Rate
QC	Quality Control
Q _{std}	Standard Dry Gas Volumetric Flow Rate
R	Total TCDD Toxic Equivalent Mass Flow Rate For A Test Run
S	Sulfur
scfm	Standard Cubic Feet Per Minute
sec	Seconds
T _c	Maximum Combustion Chamber Temperature
TCDD	2,3,7,8-Tetrachlorodibenzo-(p)-dioxin

TCDF	2,3,7,8-Tetrachlorodibenzofuran
TE	TCDD Toxic Equivalent Mass Emission Rate
TFAR _{af}	Theoretical Fuel Air Ratio For Auxiliary Fuel
TFAR _{wf}	Theoretical Fuel Air Ratio For Waste Feed
t _{res}	Residence Time
V	Residence Volume
V _{mstd}	Standard Dry Gas Volume
LRMS	Low Resolution Mass Spectrometry
HRMS	High Resolution Mass Spectrometry
DEF _{unct}	Uncontrolled Dioxin Emission Factor
DEF _{ct}	Controlled Dioxin Emission Factor
DEF	Dioxin Emission Factor
TEF	Toxic Equivalency Factor
LC	Cost For The Laboratory Analysis of Two Dioxin Samples
STC	Cost To Conduct A Source Test Run per Hour
T	Time Of Source Test Run
A	Target Detection Limit of a Dioxin Method For TCDD
S	Standard Emission (10 ng/kg-waste)
W	Waste Feed Rate
EF	Fraction of Total Source Emissions Collected in Sampling Train
IF	Fraction of Total Toxic Equivalent Emissions Attributed to TCDD
A _s	Cross Sectional Area of Stack
K _p	Pitot Tube Constant
C _p	Pitot Tube Coefficient
T _s	Absolute Stack Temperature at Traverse Point
P _s	Absolute Stack Pressure
Δp	Dynamic Pressure at Traverse Point
M _s	Molecular Weight of Stack Gas, Wet
m _{airaf}	Total Mass Flow Rate of Air To Auxiliary Burners
m _{airwf}	Total Mass Flow Rate of Air To Waste Feed
m _{qwater}	Total Mass Flow Rate of Water to Quench System

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Part II
EMISSIONS CONTROL SYSTEMS

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1.0 INTRODUCTION

1.1 BACKGROUND

The California Air Resources Board (CARB) has implemented regulations to control the emissions levels of polychloro-dibenzo-p-dioxins (PCDD) and polychloro-dibenzo-furans (PCDF) from medical waste incineration facilities. These pollutants result from the incomplete oxidation of organic materials and are suspected carcinogens.

Volume II Part I of this report discusses the regulations, implementation concerns, and retrofit options. The retrofit options include combustion and air pollution control device (APCD) based strategies. Combustion based strategies involve reducing particle entrainment and assuring the complete destruction of all organics. To reduce PCDD/PCDF emissions significantly using combustion strategies, the incinerator must be modified. Some of the modifications include increasing the residence volume to increase the gas residence time, and adding burners to increase the temperature in the combustion chambers. Other combustion modifications are given in Volume II Part I for each of the three primary medical waste incinerator types, including starved air modular incinerators, excess air modular incinerators, and rotary kilns.

APCD based strategies for the control of PCDD/PCDF involve cooling the incinerator exhaust gases and then capturing the resulting condensate. Spray coolers and heat recovery boilers are the primary cooling devices, while fabric filters (baghouses), electrostatic precipitators (ESPs), and wet scrubbers are the primary particulate collection devices. Acid gases, such as hydrochloric acid (HCl), and precursors to acid gas formation, such as sulfur dioxide (SO₂), can also be controlled by adding sodium or calcium compounds to the cooling water. Dry scrubbers are also effective devices for reducing the emissions of acid gases and their precursors.

1.2 OBJECTIVE

APCD strategies for the control of PCDD/PCDF emissions from medical waste incineration facilities are of primary concern. However, since acid gases will probably be regulated in the future, acid gas control techniques and devices will also be emphasized. This report will discuss several important flue gas cooling, acid gas control, and particulate collection devices. These devices include spray coolers, heat recovery devices, fabric filters, electrostatic precipitators, wet scrubbers, and dry scrubbers. The theory of operation, types of equipment, system capabilities and limitations will be discussed for each device. Economics, retrofit concerns (equipment interactions, scaling considerations, control systems), and information on the ability of currently available systems to control PCDD/PCDF and acid gases will also be discussed.

2.0 FLUE GAS CLEANING TECHNIQUES

2.1 EMISSION CONTROL STEPS

PCDD/PCDF and most toxic metals have been shown to exit the combustion process as vapors which will condense as the flue gases cool. Condensation has been shown to occur primarily on the surfaces of the smallest (or fine) particulate. It is thought that condensation occurs primarily on the fine particulate because the fine particulate presents the greatest available, and best distributed, surface area.

Cooling of the flue gases followed by collection of the fine particles are therefore the two key steps required for removal of PCDD/PCDF compounds. Sodium or calcium compounds can be added to the cooling water for simultaneous removal of the acid gases. Figure 2-1 schematically shows the cooling, acid gas removal, and particulate collection steps. Subsequent paragraphs will discuss these steps separately, followed by sections describing several emission control systems incorporating all three steps.

2.1.1 Cooling

Many medical waste facilities may elect to use water spray cooling of the incinerator flue gases rather than installing a heat recovery boiler. The spray cooler is lower in initial cost and avoids the fouling and corrosion problems associated with a heat recovery boiler. The value of the recovered heat may not be sufficient to offset the boiler installation and operation costs for the small sizes typical of most medical waste incinerators.

The amount of water sprayed into the hot gases is controlled to produce a desired gas stream temperature. 300 °F has been shown to be a good gas temperature for some municipal solid waste installations (1). There are two primary concerns which must be considered when determining the target gas temperature:

1. The temperature must be low enough to condense vapors of the toxic substances of interest. 300 °F has been shown to be low enough for removal of dioxins and most heavy metals.
2. When fabric filters are used to capture the solid particle, too low a temperature can cause sticky or wet ash to clog the filter. In addition, low temperatures result in the condensation of corrosive acids in the equipment.

2.1.2 Control of Gaseous Material

When acid gas control is required, HCl adsorbents including dry lime, lime hydrate slurry or sodium hydroxide solution can be used. The optimum choice is both a materials cost and handling equipment requirements decision. The small quantity of absorbent used has been shown to be a relatively small cost factor. The point is that the small size of medical waste incinerators may result in a different optimum choice than the lime slakes/slurry injection systems favored for the much larger MSW and coal-fired boiler systems.

Water and/or water slurry could be introduced by state-of-the-art single or dual fluid atomizers or by the rotary atomizers used in larger spray dryers. Although most rotary atomizers are used for much larger flow rates than required for medical waste incinerators, the basic design of the rotary atomizer is such that use at reduced flow rates does not, in general, reduce the quality of atomization.

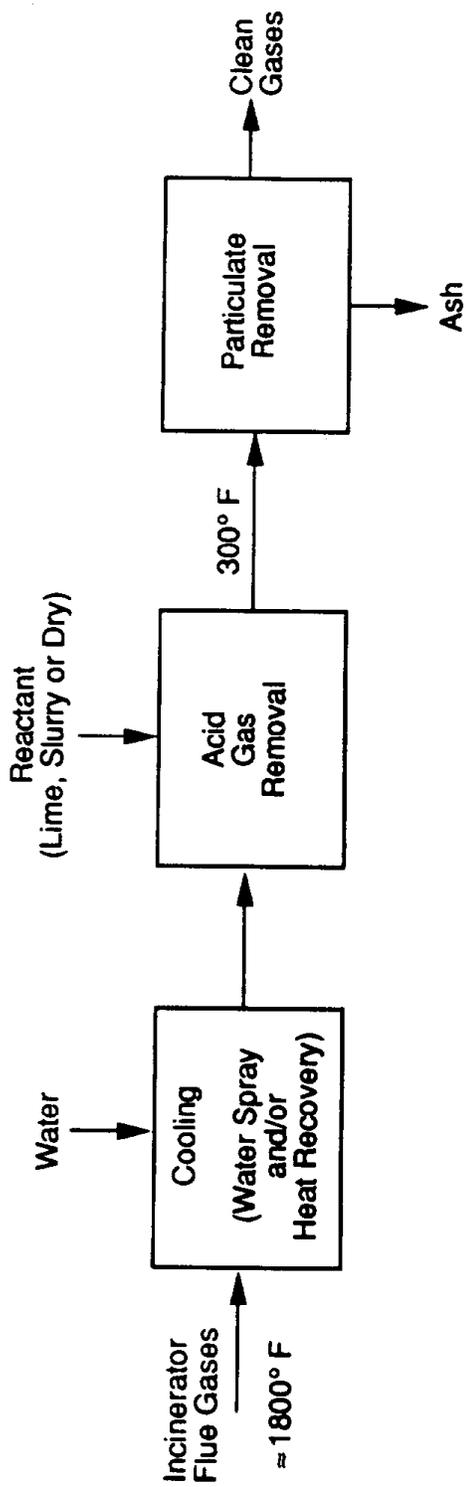


Figure 2-1. The three key steps for control of PCDD/PCDF and acid gases from medical waste incinerators.

2.1.3 Control of Particulate

Fabric filters are generally considered to be most effective equipment for the control of small particles. Wet scrubbers require increased system pressure drop to increase collection efficiency for sub-micron size particles. A multi-field electrostatic precipitator with very large plate area is required to provide fine particulate collection performance comparable to that of a fabric filter, hence an electrostatic precipitator of comparable performance is usually more expensive. Figure 2-2 illustrates the improving trend in the control of particulate emissions by both electrostatic precipitators and fabric filters since 1970 (1).

Several mechanisms are responsible for particulate collection in a fabric filter (2). Theoretical equations exist for the capture efficiency of each mechanism based on single particles approaching single fibers. For an operating fabric filter, however, the fabric is covered with a dust cake and the dust cake is of continually varying thickness. Once the dust cake has reformed after each cleaning, sieving is the dominant capture mechanism. As particles approach the porous mass of dust that constitutes the cake they will either strike one or more surface particles or enter a pore. If the particle is larger than the pore it attempts to enter, it will be sieved out. If the particle is smaller than the pore it enters, it will continue traveling through the pore until it touches the pore wall and adheres, or until the pore narrows to dimensions smaller than the particle, or until the particle passes through the dust pore and then through a fabric pore and exits on the clean side of the filter. Ordinarily only one out of a thousand particles, or one out of ten thousand, finds its way through the filter.

In an electrostatic precipitator the particulate collection process includes three primary steps (3):

1. Electrostatic charging of the particulate, this is normally accomplished by exposing the flue gases to a high voltage, corona discharge.
2. Next the charged particulate are collected by passing them through an intense, direct current electric field where the charged particles are attracted to a collection plate having the opposite electrostatic potential to that applied to the particles in the corona discharge. Flow of the flue gases is not affected by the electrostatic field however any turbulence in the gas flow can affect the movement of the charged particles in the electric field.
3. The final step is the retention and controlled removal of the collected particulate from the collecting plates.

Wet scrubbers collect particulate in a different three step process (4):

1. Water droplets are formed by introducing water into a high velocity gas stream. Shear forces between the gas and water break the water into droplets, the higher the relative velocity between the gas and water the smaller the size of the droplet generated.
2. Particulate matter in the entering gas stream is collected by the water droplets primarily by impaction, that is the particles which are traveling at the high speed of the gas stream run into the slower moving water droplets. Efficiency of collection is increased by increasing the relative velocity between gas and droplets and by increasing the cross sectional area of the droplets. Since the gas is usually accelerated by passing it through a venturi and the droplets formed by injecting water at the throat of the venturi, the efficiency of the collection process is related to the pressure drop across the

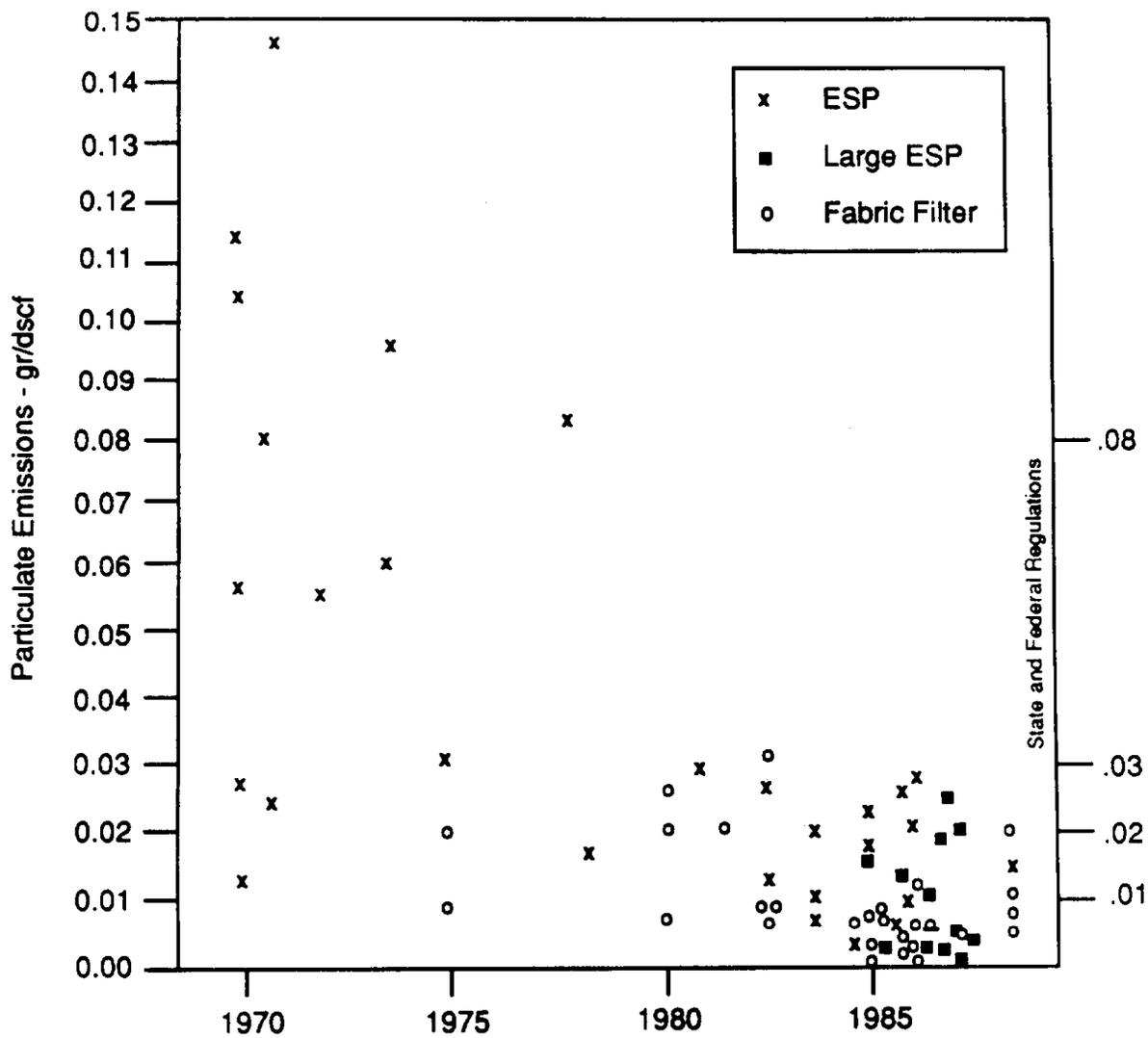


Figure 2-2. Particulate emissions from MSW incineration 1970-1988 (1).

venturi. Most of the pressure drop used to accelerate the flow is not recovered hence high collection efficiency normally means high energy input to the collection process.

3. Finally the water droplets, with the collected particulate entrained, must be removed from the gas stream. This can be accomplished by a cyclone collector or by a scrubber tower. The scrubber tower may consist of a volume filled with large surface area media onto which the droplets impinge and cascade down through. An alternative is to pass the gas/droplet stream through a series of "bubble trays" where the droplets are collected into a flowing water stream.

Wet scrubbers are basically simple, low cost devices but normally require relatively large amounts of energy for the necessary collection of fine particulate. Various techniques are used to reduce the energy expended for a particular collection efficiency. The techniques used, usually resulting a proprietary design, include electrostatic charging of the particulate and multiple collision flow paths for the gas flow.

2.2 EMISSION CONTROL SYSTEMS

Previous paragraphs have identified the necessary basic steps for control of the emissions of concern from hospital waste incinerators. Various types of equipment are available for carrying out these basic steps. To add further confusion, these various types of equipment, which will be discussed in greater detail in subsequent paragraphs, can be arranged in various combinations. Thus a wide variety of emission control system designs are possible.

No single system has been adopted as the best design for all incinerators, hence the purpose of this section is to discuss basic configuration arrangements that might be considered in the selection process leading to optimum design for a particular installation.

2.2.1 Dry Injection, Spray Cool, Baghouse System

Figure 2-3 schematically shows an emission control system incorporating two primary pieces of equipment, a spray cooler and a baghouse. Necessary secondary equipment is required to inject dry, hydrated lime into either the spray cooler as shown or into a separate mixing vessel. A temperature controller would sense the cooler outlet temperature and automatically modulate the water flow to maintain a set value of the baghouse inlet temperature.

A system like that shown in Figure 2-3 has been in successful operation for over two years at the Fairfax County Hospital near Washington, DC.

2.2.2 Slurry Injection, Baghouse

Figure 2-4 presents a variation on the previous system. In this system hydrated lime is slurried with the cooling water prior to injection instead of being injected dry.

This system is similar to the spray dryer systems used for many municipal waste incinerators except for the smaller hospital waste incinerator it appears to be better to use purchased hydrated lime rather than to include the complexity of slaking lime on site. In addition Figure 2-4 suggests the use of compressed air to atomize the slurry rather than the rotary atomizers used for most MSW installations. Air atomized nozzles are more available in the small sizes required. Since the incinerator exit temperature will be much higher if heat recovery is not included, the slurry solids concentration will be lower, hence easier to handle in the slurry pumps and atomizers.

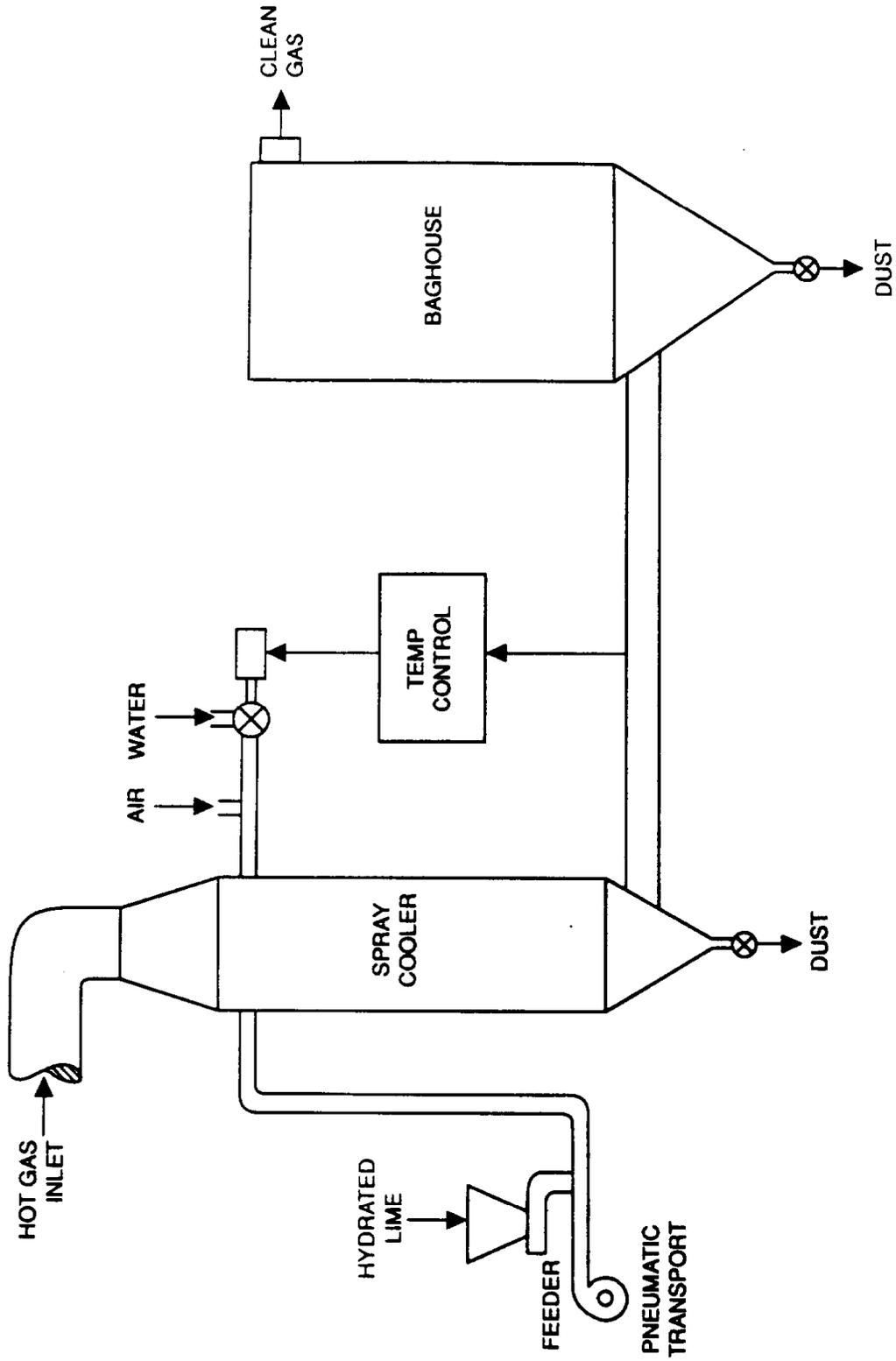
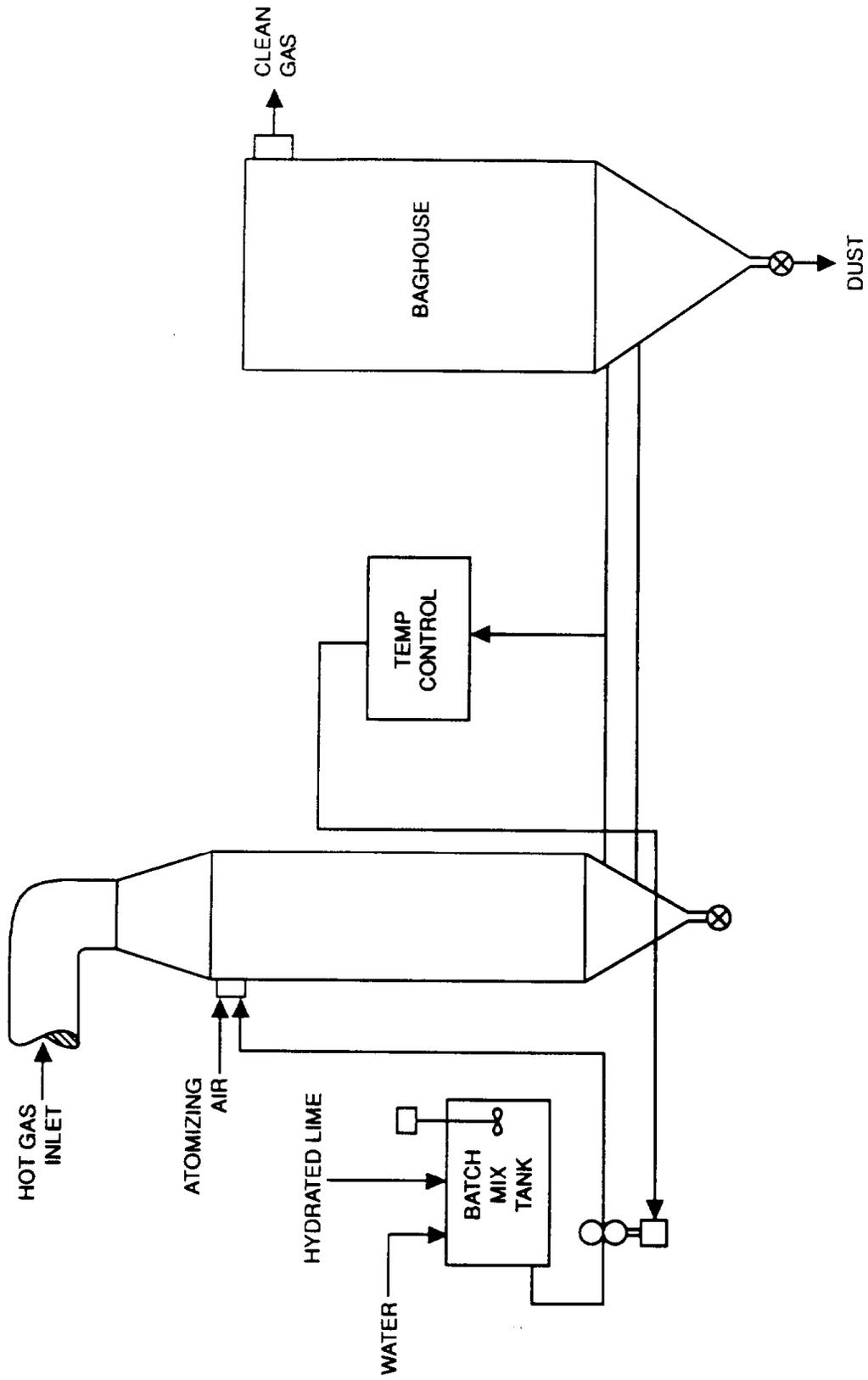


Figure 2-3. Emission control system using dry injection, spray cooling, and fabric filtration.



2-7

Figure 2-4. Emission control system using slurry injection and fabric filtration.

No known installations on hospital waste incinerators or systems like that shown in Figure 2-4 are known however one manufacturer of spray coolers has limited experience with such a system on a cement application.

2.2.3 Wet Scrubber, Re-Heat, Baghouse

Figure 2-5 is a schematic of a system in which a wet scrubber tower is used for both cooling and acid gas removal followed by a baghouse for particulate collection. Since scrubbers cool to saturation temperature (212°F) and would be expected to emit some entrained water it would be necessary to reheat the scrubber exit gases prior to baghouse entry. Reheat might be accomplished using a heat exchanger and the hot incinerator exit gases however the corrosion potential of that approach is the reason that the use of a clean fuel reheat burner is suggested in Figure 2-5. Economics and details of both approaches should be considered prior to a final selection.

No emission control systems similar to Figure 2-5 are known however the system consists of well known and readily available components. Economics and operational considerations would be the key considerations in comparing this approach with others.

2.2.4 Systems using Electrostatic Precipitators (ESP)

In general any of the prior systems could use an ESP rather than a baghouse for the particle collection step. Fine particulate removal performance, purchase cost, and operational requirements (including safety) are important considerations in such a selection.

One interesting possibility is the use of a wet scrubber tower such as discussed in Section 2.2.3 but follow it with a wet ESP. This would avoid the necessity for reheat of the scrubber exit gases such as would be required if a baghouse is used.

The collection plates of a wet ESP are continuously flushed with water to remove the collected dust. Although not as commonly used as dry collection plates, wet ESPs are available from several manufacturers.

2.2.5 Wet Scrubber Systems

Most wet scrubber systems are designed to both collect particulate and to remove acid gases. Section 7 will discuss such systems hence they will not be considered here except to indicate that they should be part of the comparison leading to the optimum selection for a particular application.

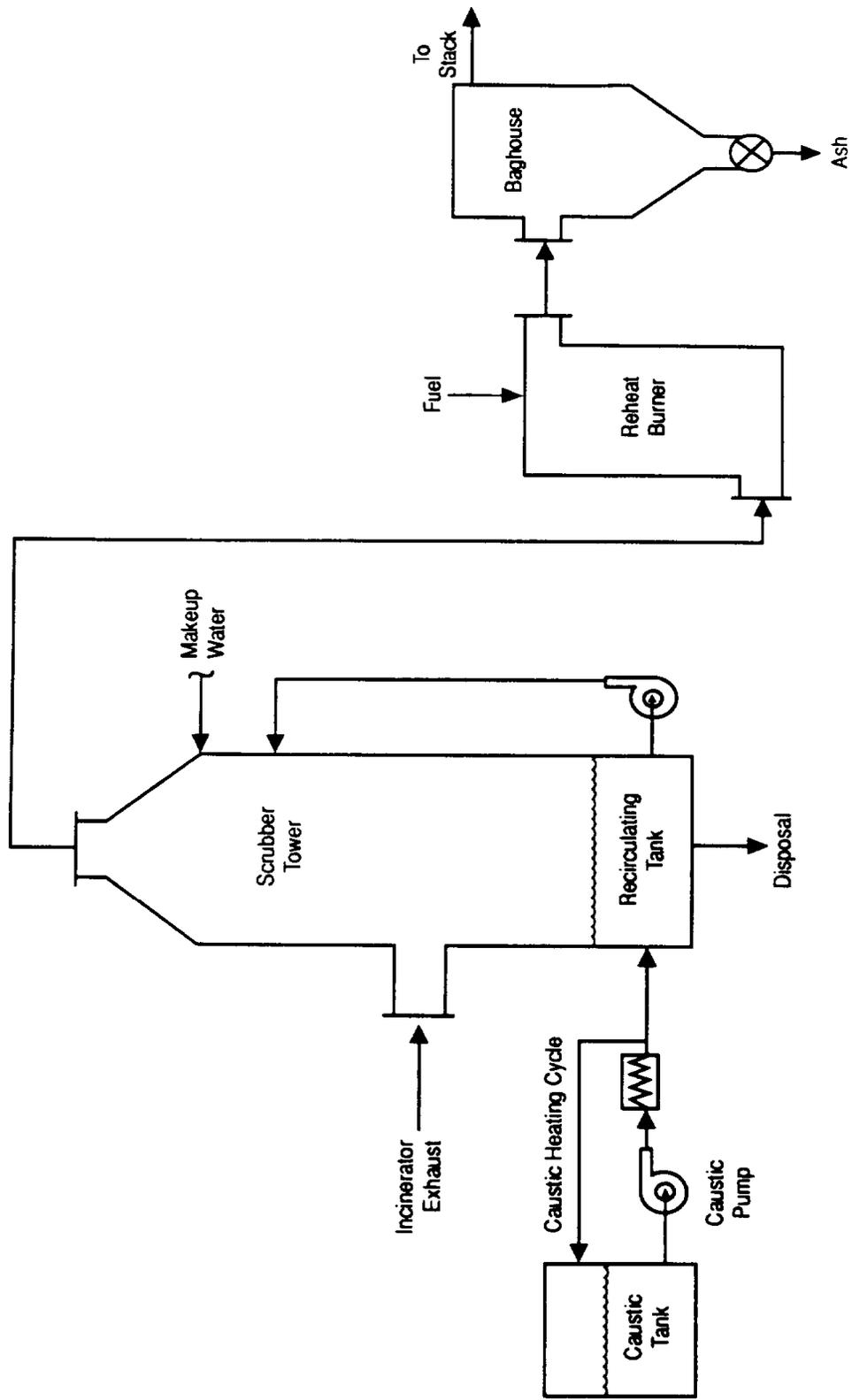


Figure 2-5. Emission control system using wet scrubber, re-heat, and baghouse.

3.0 SPRAY COOLING

3.1 THEORY OF OPERATION

Gas conditioning, cooling, and quenching are different names for the method of injecting water, a water slurry, or a water solution into a hot gas stream in order to cool it from a high temperature (typically 500 to 1800°F) to a lower temperature. Cooling is introduced in order to facilitate the removal of particulate matter from the gas stream in down stream equipment. A second and usually more important consideration is the condensation of certain gaseous constituents contained in the gas stream (such as PCDD/PCDF and certain heavy metals) in order that they can also be removed by the downstream particulate removal equipment. Water slurries or solutions are used to provide a third removal capability, that of providing a chemical reaction between the slurry or solution and any acid gas constituents in the gas stream (such as HCl or SO₂). The chemical reactions result in solid compounds which can then be removed by the downstream particulate removal equipment.

A primary design requirement for the cooling equipment is the provision of spray nozzles that are reliable, cost effective and provide a uniform droplet size distribution. If a mixture of large and small droplets are generated, the small droplets will evaporate first, reducing the gas temperature and thus reducing the evaporation rate of the larger droplets. The proper nozzle must be selected for each application, taking into account the maximum required water flow rate, required spray coverage, available residence time for evaporation, and the corrosive nature of the gas stream.

3.2 TYPES OF EQUIPMENT

Three types of water atomization equipment are generally available:

1. Pressure or hydraulic nozzles
2. Rotary nozzles
3. Two-fluid nozzles

3.2.1 Pressure Nozzles

In a pressure nozzle such as a bathroom shower or lawn sprinkler, the water flow is accelerated to a high velocity by passing it through small holes. The high exiting water velocity causes the formation of water droplets by **shear forces between the exiting water and the ambient air**.

Pressure nozzles are usually not selected for spray cooling since excessive pressure drop, pluggage and hole wear are all problems that would result if injection holes small enough to give the desired droplet size were used. An additional problem is that the droplet size generated by a fixed area pressure nozzle would increase rapidly if the water flow rate decreased. Stated another way, suitable size water droplets are generated by pressure nozzles only over a narrow range of water flow rates. Because of this, pressure nozzles are unsatisfactory for spray cooling systems.

3.2.2 Rotary Nozzles

In a rotary nozzle, the water passes through relatively large holes in the periphery of a rapidly rotating wheel. The high water injection velocity necessary to form fine droplets is provided by the wheel rotation rather than by pressure drop across the injection hole hence the

injection hole can be much larger than in the case of the pressure nozzle. A rotary nozzle can provide the desired small droplets over a much wider water flow rate range than the pressure nozzle is capable of. In addition, the rotary nozzle does not require high water pressures and does not have excessive nozzle wear caused by abrasive substances in the water.

Although technically acceptable, a rotary nozzle may not be the best choice for most hospital incinerator applications because of the small size constraint. Rotary nozzles tend to be expensive due to the use of high speed rotating equipment and therefore are currently available in sizes that usually are larger than that required for many hospital incinerators.

3.2.3 Two-Fluid Nozzles

The two-fluid nozzle is generally considered to be the best choice for a spray cooler of the size required for most hospital incinerators.

Two-fluid nozzles are usually capable of injecting either pure water or a slurry containing up to about 10 percent by weight of solids (5). In a two-fluid nozzle, high pressure air is mixed with the water or slurry. The mixture is then passed through a nozzle designed to accelerate the mixture to a velocity high enough such that the water is sheared into fine droplets. The water droplets are entrained in the high velocity exiting air.

Two-fluid nozzles function primarily because of the high volume per unit weight, and hence low inertia, of the air compared to the water. In addition, the nozzles are sometimes designed to include acoustic resonances of the air, providing even greater shear forces for droplet formation.

The success or failure of a low maintenance air-atomized nozzle is based on its effective and reliable production of a spray plume containing a range of droplets of small and predictable size. It is of utmost importance that the range of droplet sizes does not change dramatically during the cooling process in order to avoid either water carryover into the particle collector or wetting of the cooling tower walls.

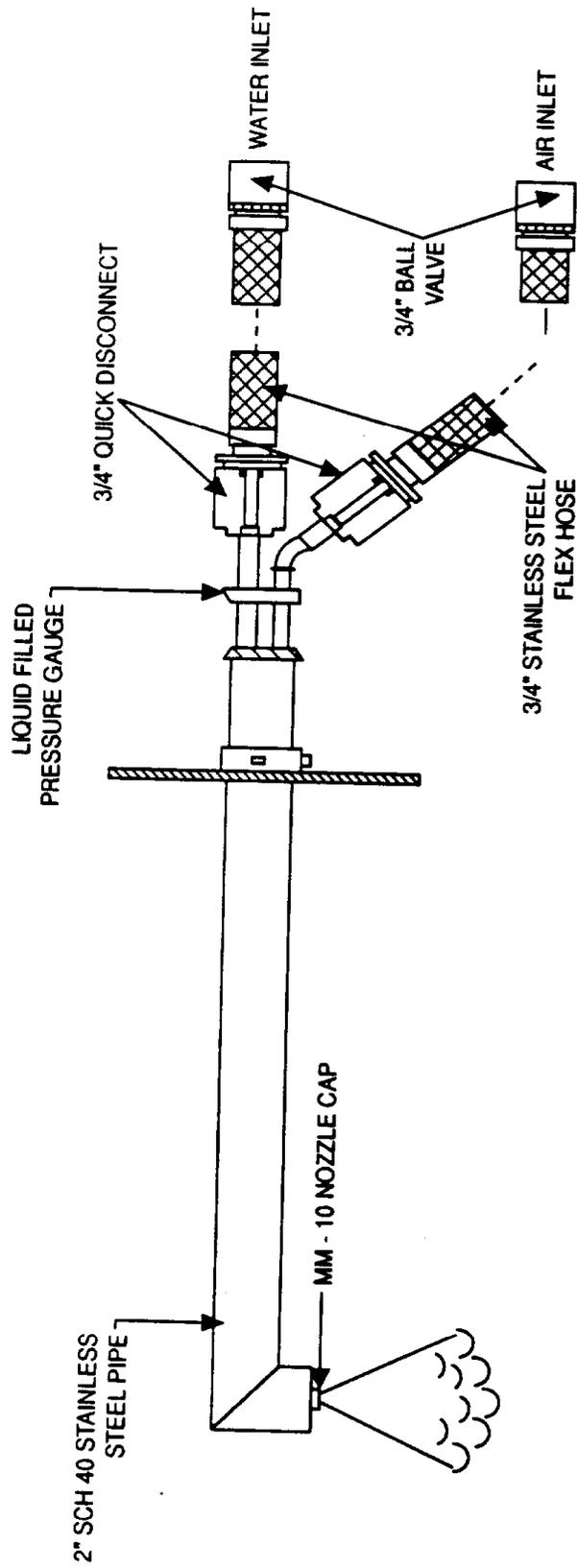
Figure 3-1 depicts a two-fluid nozzle supplied by one manufacturer of spray coolers. It is a size typically required for hospital waste incinerators. A control valve package is available to automatically regulate the flow of both water and air to the nozzle in order to maintain a set value of the gas outlet temperature.

3.2.4 Cooling Vessel

The cooling vessel provides a volume in which the water droplets injected by the nozzles can evaporate. Hot gases from the incinerator enter one end of the vessel. This end would also contain the spray nozzles. The cross sectional area of the vessel (usually round in shape) is sized to decelerate the incinerator gases from a typical duct velocity of 3000 ft/min to 1000-1200 ft/min. Adequate length of the vessel must be provided for droplet evaporation plus some safety margin.

Cooling vessels can be either vertically or horizontally configured. Vertical vessels usually have a top entry for the hot gas and a bottom hopper and gas exit. Horizontal vessels would not have a hopper. Their configuration must allow for any dust drop to be carried directly into the hopper of the particle collector.

Sizing of the necessary cooling vessel involves somewhat complex interactions between the droplet sizes, the gas temperature, gas velocity, and time. Fortunately, the manufacturers of spray cooling equipment have available computer based calculation procedures such that the cooling vessel can be sized once the input parameters such as inlet and outlet temperatures, and gas flow



AIR COOLED, LENGTH ADJUSTABLE
 MicroMist SPRAY LANCE
 SIZE MM-10

Figure 3-1. Typical two-fluid spray cooling nozzle.

rates are determined. An example of such a calculation is included in Appendix A.

3.3 SYSTEM CAPABILITIES AND LIMITATIONS

The primary requirement of the spray cooler is to cool the incinerator exit gases to a set temperature, tentatively selected as 300°F. This will require adequately uniform distribution of the water droplets into the gas stream such that the exiting gas stream is uniformly cooled.

In addition to uniform distribution of the droplets, uniform cooling requires that uniformly sized water droplets be generated. If an excessively broad distribution of droplet sizes were to exist, the smaller droplets would evaporate first, thus cooling the gas, and reducing the available temperature differential for evaporation of larger droplets. Compared to smaller droplets, larger droplets require a longer amount of time to evaporate at the same temperature differential.

If an excessively broad size distribution of droplets in the spray were to exist, two detrimental results may occur. First the evaporating droplets may reach, and wet, the vessel wall, further reducing the potential for evaporation and cooling of the gas stream. Second, and more importantly, the larger droplets may exit the spray cooler and have adverse effects on the downstream particulate collection process.

If an excessive temperature distribution were to exist at the spray cooler outlet, two additional adverse affects could occur. Areas of higher temperature could result in reduced removal of any exiting PCDD/PCDF, while areas of lower temperature could result in increased ash stickiness and thus cause ash removal difficulties.

It is anticipated that these adverse affects would not occur in a properly designed and properly maintained spray cooler. However, these difficulties may arise if the equipment is not properly designed or maintained. An example of improper maintenance could be operation with worn spray nozzles.

4.0 BOILERS

4.1 THEORY OF OPERATION

Boilers or heat recovery devices are used to generate steam for applications such as power generation, heating, cooling and steam sterilization, and to cool incinerator exhaust gases so that PCDD/PCDF and metal vapors will condense. These devices usually generate steam in a three step process, including preheat, evaporation, and superheating (6). In the preheat step, water is heated from the system inlet temperature to its boiling temperature as shown Figure 4-1. In the evaporation step, heat is added to the preheated water, generating steam. The resulting steam is then collected and heated in the superheat step.

The incinerator exhaust gases are used to preheat, boil, and superheat the incoming water. In a typical boiler design, heat is transferred from the exhaust gases to the water stream through the walls of a series of metal pipes. If water is flowing through the pipes, the design is called a water tube design. If the exhaust gases are flowing through the pipes, the design is known as a fire tube design. In both designs, heat is transferred from the exhaust gases to the water stream by a combination of convective and conductive processes. Convection is the transfer of heat assisted by the flow of a fluid or gas while conduction is the transfer of heat through either a still gas or liquid, or a material.

Figure 4-2 illustrates both the convective and conductive processes at an isolated location on a pipe wall in the superheater section of a typical boiler. This figure also contains a graph, which shows the temperature distributions in each medium (exhaust gases, slag, metal, scale, and steam). Slag is a light colored substance consisting of molten fly ash (7). When the boiler is not operating, slag cools to form a solid adherent on the pipe's surface. Slag usually only forms on pipes used for superheating, since pipes used for preheating and boiling are at lower temperatures (see Figure 4-1). Soot and fly ash deposits form on pipes used for preheating and boiling. Scale forms on the water side of the pipe (see Figure 4-2) and is composed of mineral and metal oxide deposits (8). As scale builds up, the temperature of the tube increases (see the temperature distribution in Figure 4-2), leading to a higher potential for tube corrosion and failure.

The heat flux from the exhaust gas side of the tube to the steam side of the tube is controlled by the convective resistances of exhaust gases, and water, and the conductive resistances of pipe wall, scale, and slag. Since these resistances are in series, they can be added and then divided into the temperature difference between the exhaust gases and steam to determine the heat transfer rate, q , as illustrated in Equation 4-1:

$$q = \frac{T_{eg} - T_{H_2O}}{R_{eg} + R_{slag} + R_{pipe} + R_{scale} + R_{H_2O}} \quad 4-1$$

where T_{eg} and T_{H_2O} are the maximum exhaust gas and water temperatures, and R_{eg} , R_{slag} , R_{pipe} , R_{scale} , and R_{H_2O} are the exhaust gases, slag, pipe, scale, and water resistances. As the heat transfer rate increases (total resistance decreases), less total surface area is needed to accomplish a given job, facilitating a smaller boiler size. As the boiler ages, R_{slag} and R_{scale} will increase, because of the build up of slag and scale, reducing the heat transfer rate. Thus, a given design must either account for slag and scale build up on the pipe surfaces or it must provide cleaning mechanisms such as soot blowers, chemical treatment, and rappers to remove scale and slag deposits.

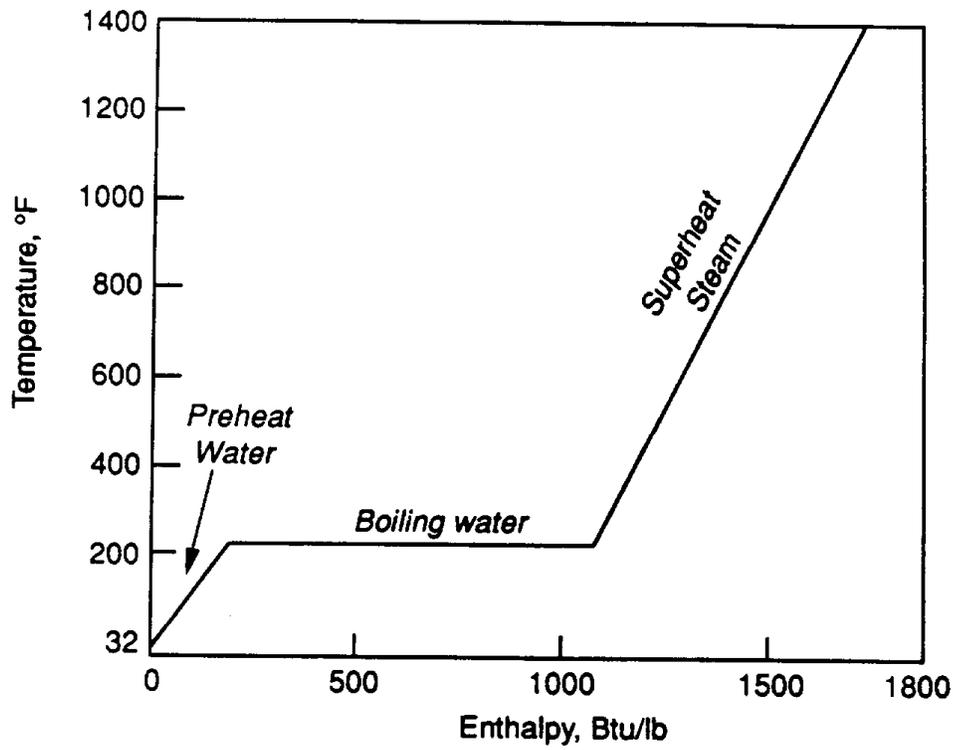


Figure 4-1. Water heating curve (6).

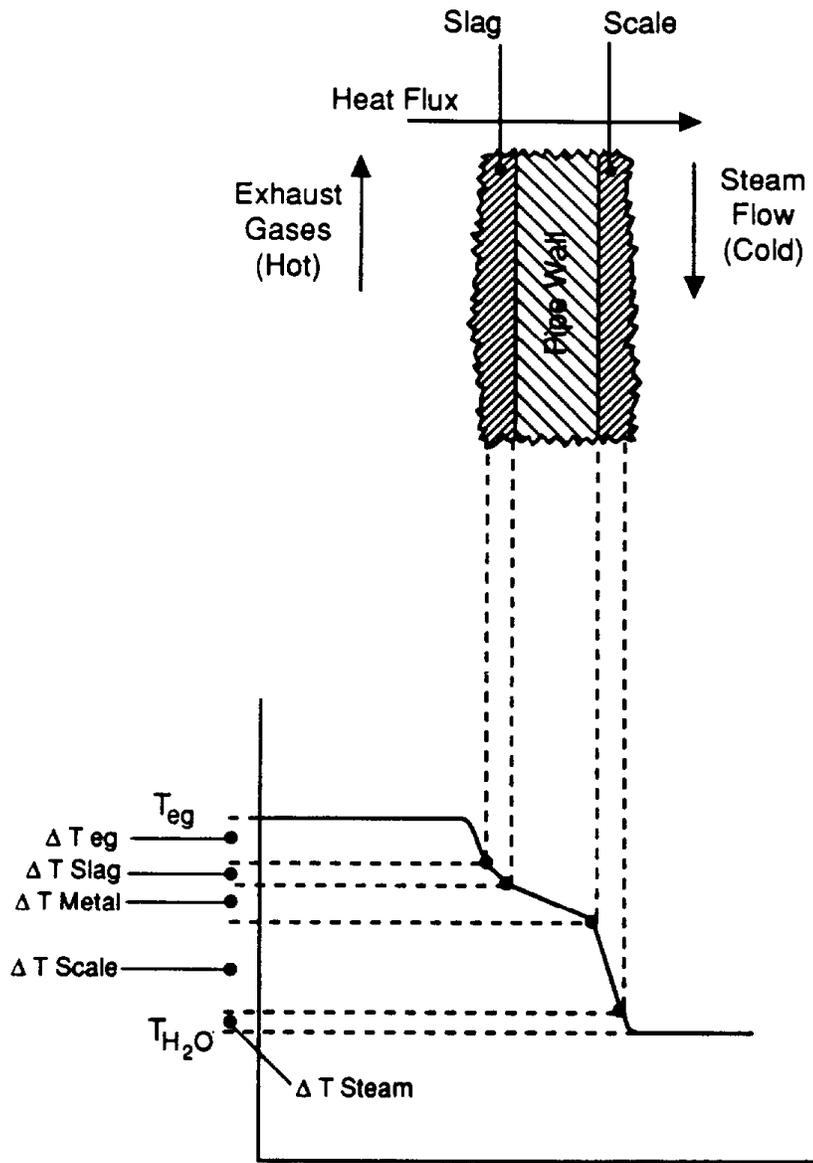


Figure 4-2. Convective and conductive resistance and associated temperature drops.

To maximize heat transfer rates (minimize heat exchanger area and size), various pipe configurations are used as illustrated in Figures 4-3(a-c) (9). Figure 4-3(a) illustrates a parallel flow configuration where the exhaust gases and water flow in the same direction. In the counter flow configuration in Figure 4-3(b), the fluids flow in opposite directions. The most popular configuration is the crossflow geometry (see Figure 4-3(c)), where exhaust flows perpendicular to the water stream.

The in-line and staggered configurations shown in Figure 4-4(a,b), are the most popular crossflow geometries (9). The staggered crossflow arrangement produces higher heat transfer rates while the in-line crossflow arrangement yields a lower pressure drop across the boiler.

Another important criterium in boiler design is the pressure drop. A large pressure drop across the boiler can yield excessive pressures in the incinerator, which can cause potentially harmful gases to be expelled from the system. In a given in-line or staggered crossflow design under turbulent flow conditions, the heat transfer rate is proportional to $m^{0.8}$ (m is the mass flow rate), and the pressure drop is proportional to $m^{1.8}$ (9). Thus, the degree which the heat transfer rate can be increased by increasing the mass flow rate is strongly limited by the pressure drop. A fan can be added to the system to reduce the effects of pressure drop across the boiler. However, such a fan will increase system operating costs.

4.2 TYPES OF EQUIPMENT

The two general equipment classifications are the fire tube and water tube boilers. In fire tube boilers, exhaust gases flow in the pipes while in water tube boilers, water flows in the pipes.

4.2.1 Fire Tube Boilers

In a fire tube boiler, exhaust from the incinerator enters a series of pipes (see Figure 4-5). Heat is then transferred through the pipe walls into a pool of boiling water. Each tube can pass through the water several times. As the number of passes increases, the system efficiency, mechanical complexity, fan power, and shell diameter increase. Because of these factors, the number of tube passes is usually restricted to four (6). After the last pass, the exhaust gases exit the fire tube boiler as shown in Figure 4-5.

One of the key advantages of fire tube boilers is their ability to handle dirty gas streams. Also, since a large portion of the water is present at saturation conditions, incinerator load variations are easily handled. Startup and shutdown modes are slow, however, due to the large thermal inertia of the device. Fire tube incinerators also lack the ability to superheat steam, thus only preheat and boiling operations are available (6).

4.2.2 Water Tube Boilers

Water tube boilers have a much wider range of operating conditions than fire tube boilers and can produce superheated steam. Furthermore, water tube boilers have higher efficiencies than fire tube boilers under similar conditions, due to the greater diversity in water tube boiler designs (6).

Water tube boilers generally consist of an economizer to preheat the water, an evaporator to boil the water, and a superheater to superheat the steam as shown in Figure 4-6 (10). The economizer, evaporator, and boiler sections are usually isolated by a steam separator or steel drum. The steel drum separates the liquid and gas streams. This prevents contaminants from entering the superheater circuit. A deaerating system is also present before the economizer to reduce the

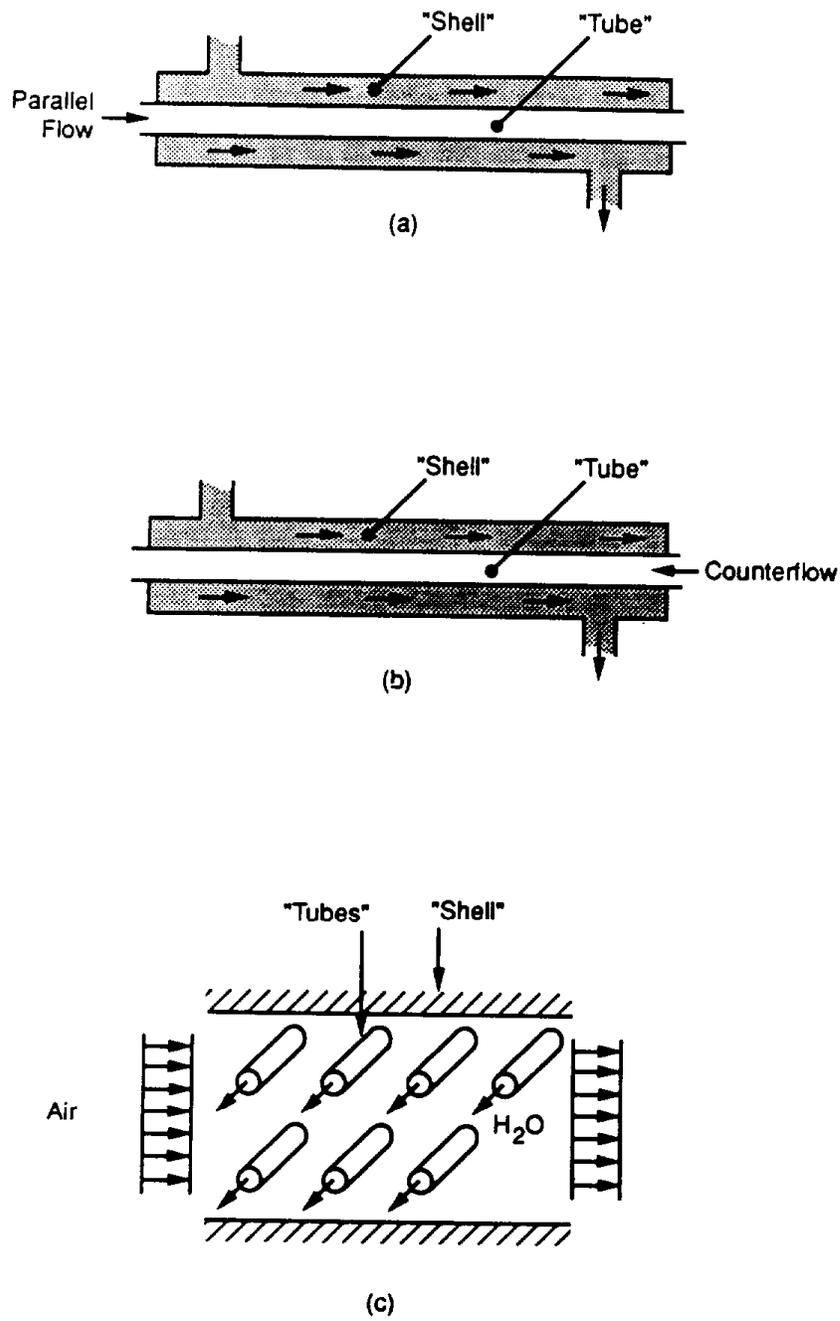


Figure 4-3. Flow configurations a) parallel flow b) center flow c) cross flow (9).

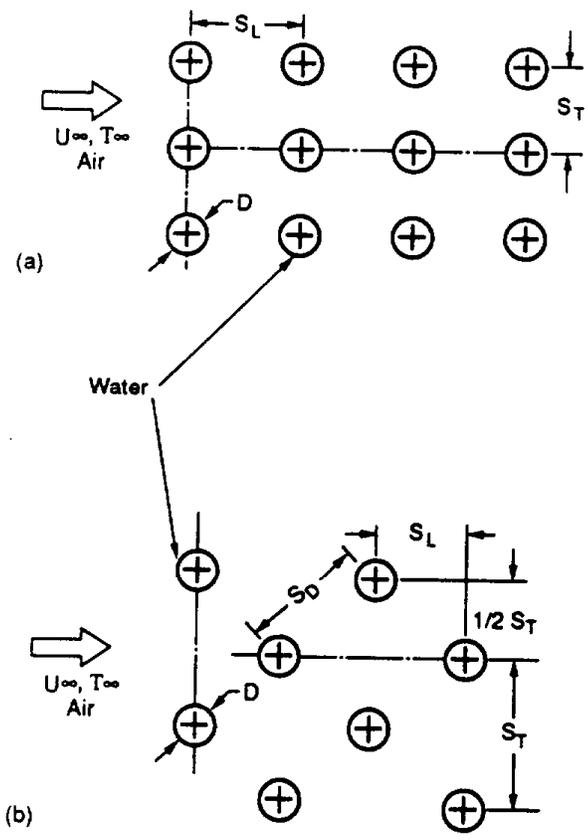


Figure 4-4. Commonly used crossflow configurations
 (a) in-line (b) staggered (+ indicates water
 flowing out of page) (9).

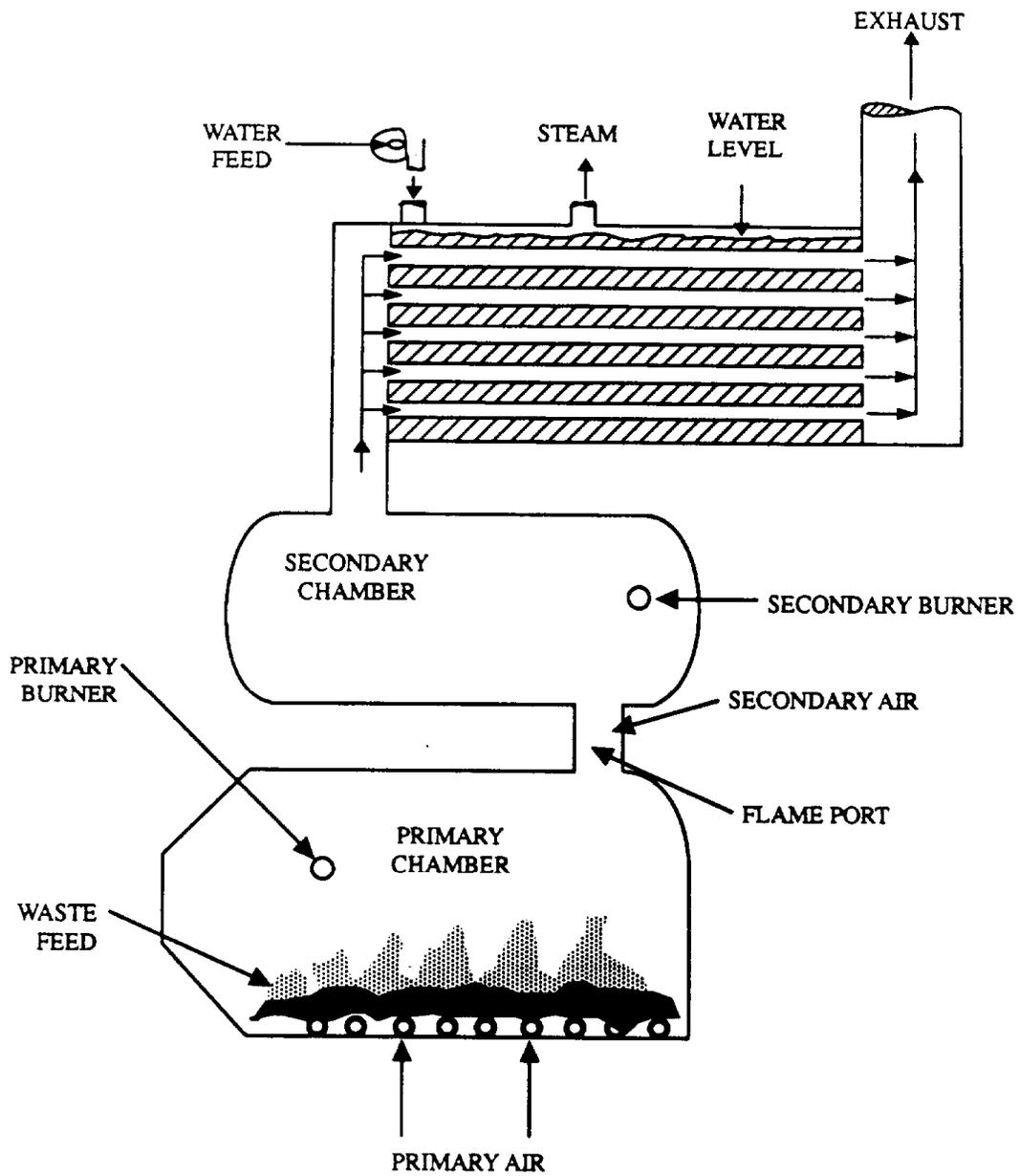


Figure 4-5. Fire tube heat exchanger.

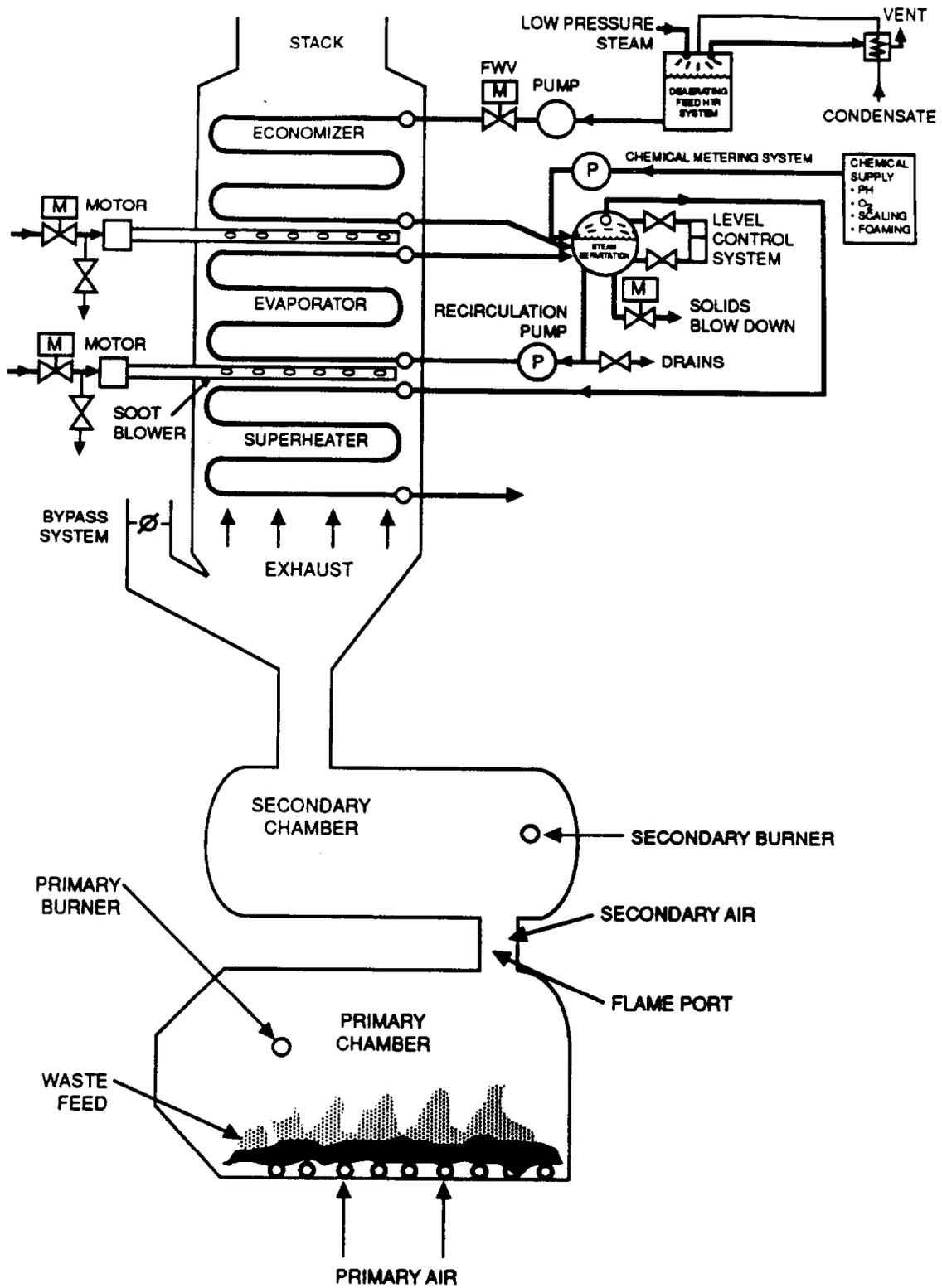


Figure 4-6. Typical heat exchanger design incorporating steam separation (10).

concentrations of oxygen present in feed water, which reduces scale formation on the economizer tubing. Blowers are present to remove soot and fly ash deposits from the exterior of the economizer, evaporator, and superheater tubing (10).

A deviation from the traditional water tube design discussed above is the once-through heat recovery system, pictured in Figure 4-7 (10). This design eliminates the steam separator and recirculation feed pumps present in the traditional water tube boiler design (see Figure 4-6). Thus, the once-through design is simpler, more compact and reliable, and responds quickly to waste feed variations.

If high strength, corrosion resistant materials such as 800 alloy (30% nickel, 20% chrome) are used in the pipe and fin construction (see the Solar's Once-Through, Stainless Steel Heat Recovery Steam Generator (10)), once-through systems can operate dry (no water in pipes). Dry operation capabilities eliminate the need for bypassing the exhaust gases when steam is not needed. Dry operation will also clean slag from the superheater sections, and soot and fly ash deposits from the boiler and preheater sections, eliminating the need for soot blowers.

One of the primary faults of all once-through systems is that a demineralizer must be added to the water feed (see figure 4-7) to remove contaminants normally captured in the steam separator. If not removed, these contaminants can cause problems in the superheater circuit and to devices using the generated steam (6).

Some water tube designs also incorporate water walls (walls containing water tubes) into the incinerator design as shown in Figure 4-8. The tubes in the water walls are heated primarily by radiation as opposed to the economizer, evaporator, and superheater tubes, which are heated by convection. Water walls increase the efficiency of the heat recovery system, but will also reduce the combustion chamber's overall temperature and the temperature of the gases near the walls. This could allow PCDD/PCDF species to escape the combustor. Thus, a boiler without water walls is probably a better choice than a boiler with water walls, at least when medical waste is burned.

4.3 SYSTEM CAPABILITIES AND LIMITATIONS

4.3.1 Corrosion

Corrosion is one of the most serious problems plaguing both fire tube and water tube boilers. In fire tube systems, corrosion occurs on the water side of the tube because of oxidation reactions. These reactions cause scale to form on the outside of the tube, which results in increased resistance to heat transfer and higher tube temperatures. Higher tube temperatures will promote corrosion on the inner side of the tube due to the presence of chlorine, sulfur, and heavy metals in the exhaust stream (11). Both corrosion on the inside and outside surfaces of the tube can cause tube failures, resulting in long shut down periods.

Due to the presence of steam in the superheater and boiler pipe sections in water tube systems, these systems are more susceptible to corrosion problems than fire tube systems. The superheater pipes, for instance, can reach temperatures as high as 2000 °F, which makes them highly prone to chlorine, sulfur, and heavy metal corrosion (11). Studies have shown that the addition of PVC (a chlorine containing plastic) to the waste feed strongly increases the corrosion rate (12). Since medical waste incineration facilities generally burn higher percentages of plastics, chlorine assisted corrosion could be a severe problem in these facilities. The superheater tubes also have erosion and deposit problems due to the high exhaust stream velocities and the high concentrations of fly ash and soot present in the exhaust stream (10). Fire tube designs have less

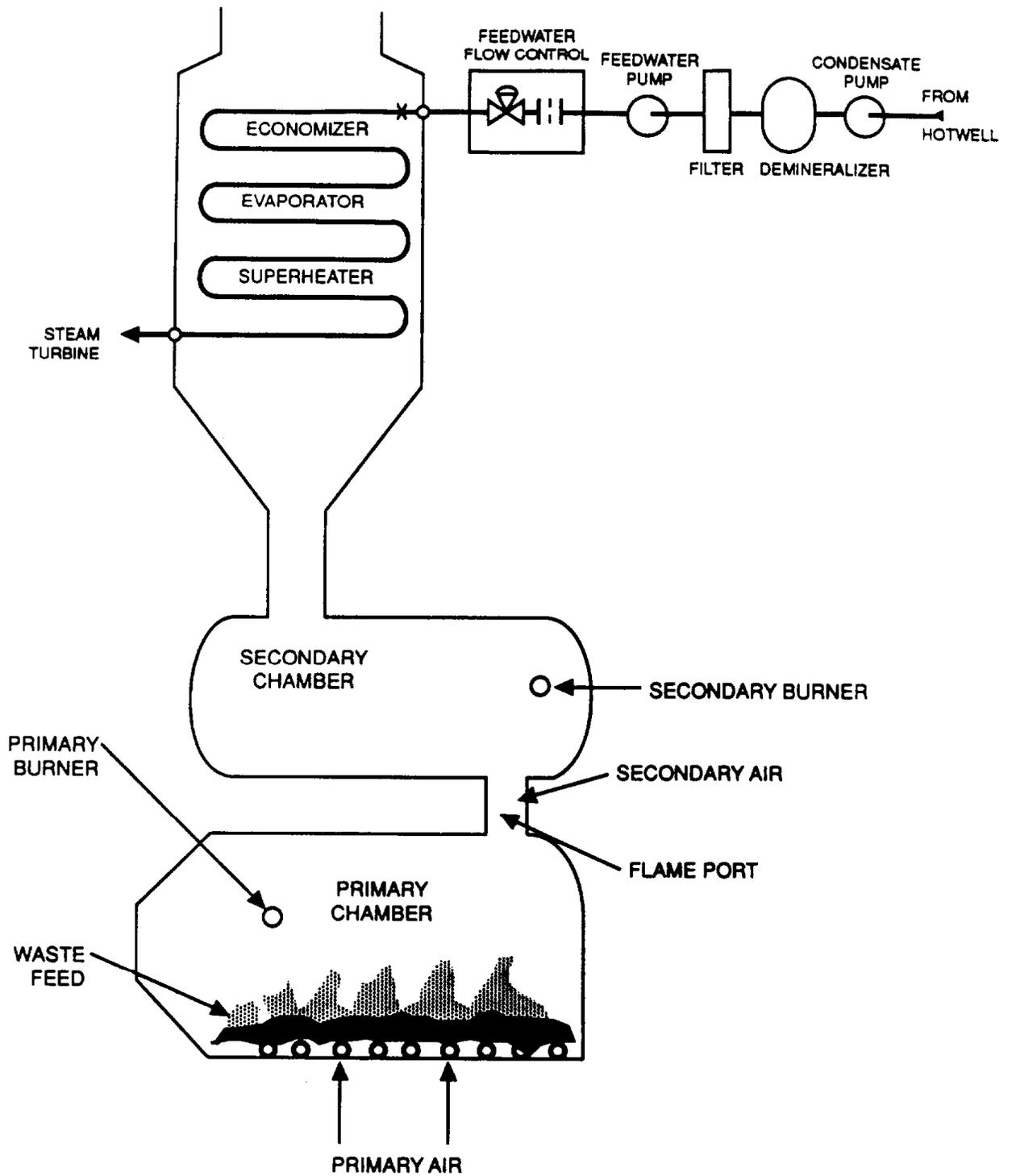


Figure 4-7. Once-through heat exchanger design (10).

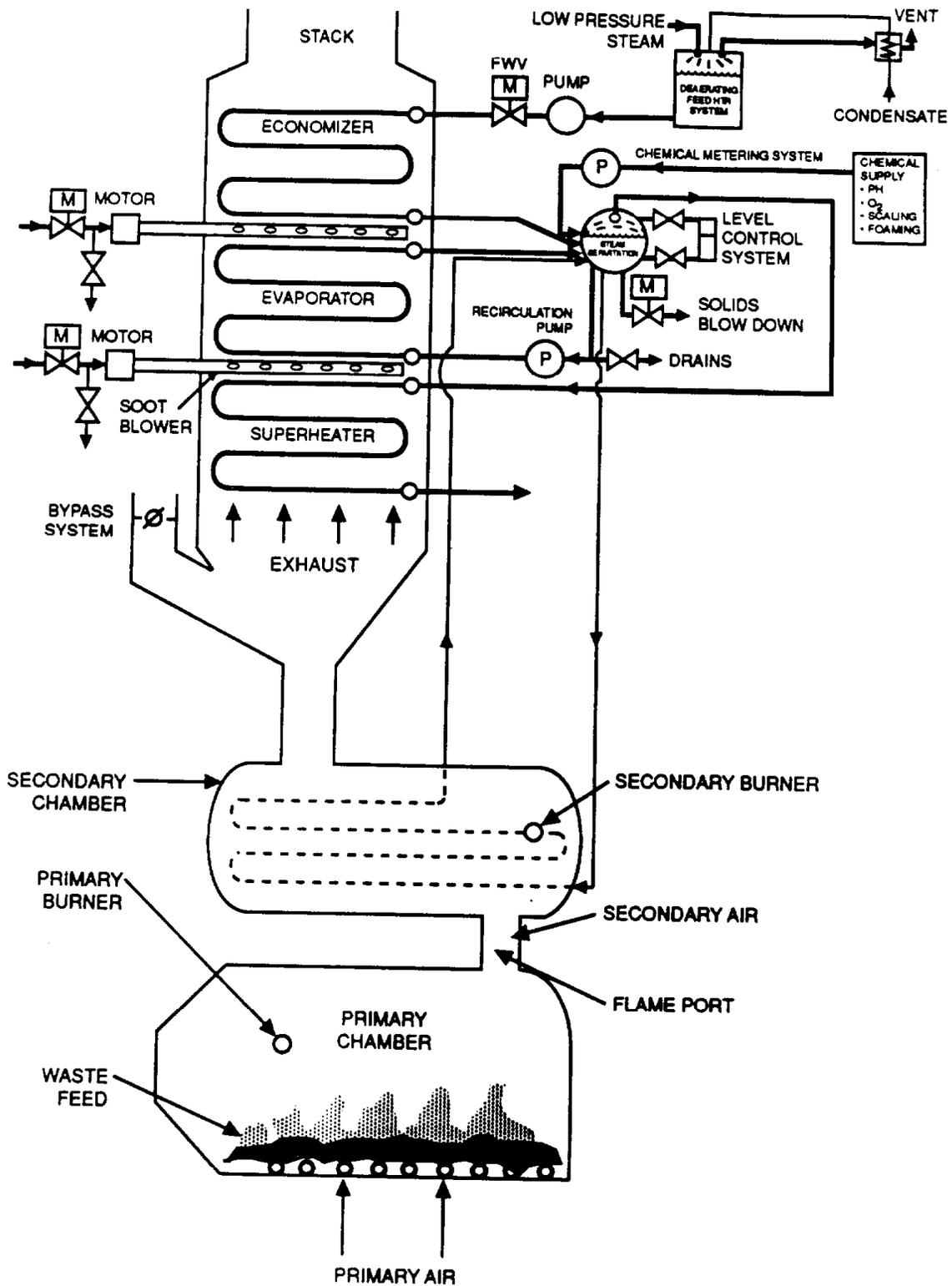


Figure 4-8. Water tube heat exchanger with tubes incorporated into secondary chamber walls (10).

erosion problems since the combustion gases travel parallel to the tubes.

Evaporator tubes are also susceptible to chlorine, sulfur, and heavy metal corrosion, but at lower rates due to the lower gas temperatures (superheaters extract much of the heat from the gas stream and most water is in liquid form). Local reducing and oxidizing atmospheres, and soot and fly ash deposits will also cause corrosion problems on the evaporator tubes (10). These problems can be controlled by assuring complete combustion of the exhaust gases and low particulate carry over.

The primary corrosion mechanism of the economizer tubes is by the oxidation of the inner tube surface. All oxygen must be removed by the deaerator to prevent this type of corrosion. Finally, if the inlet water temperature drops below the acid gas dew point, acids can condense on the outside of the economizer tubing, causing severe corrosion. For effective economizer corrosion protection, the inlet water temperature should be above 250 °F, no dissolved oxygen should be present, and the water's pH should be between 10 and 11 (10).

4.3.2 Water systems vs. Fire tube systems

Water tube systems and fire tube systems each have their own distinctive advantages and disadvantages as listed below (6).

1. Water tube systems can produce superheated steam while fire tube systems can't. Superheat capabilities could be a factor if power generation is desired. Since most medical waste facilities have only limited steam generation capabilities, power generation is usually not possible.
2. Fire tube systems can handle dirtier gas streams than water tube systems as discussed in section 4.3.1. If superheat capabilities are not needed, however, water tube systems and fire tube systems will have closer corrosion resistance potentials.
3. Water tube boilers usually have higher efficiencies than fire tube boilers under similar conditions, due to the greater diversity in water tube boiler designs.
4. Startup and shutdown modes are quicker in water tube systems, while fire tube systems handle operating load variations easily due to the large amount of water present at saturation conditions.
5. Fire tube systems generally require less headroom than water tube systems.

4.3.3 Boilers vs. Spray Coolers

Generally, fire tube and water tube boilers will only be economical if steam production is important and the incinerator has the capacity to produce the desired quantities of steam cheaply. If steam production is not economical, an alternate cooling device such as a spray cooler (see section 3.0) can be used to condense the PCDD/PCDF and heavy metals present in the exhaust stream. Spray coolers have higher reliabilities and response times, fewer corrosion problems, simpler maintenance requirements, and lower equipment costs than boilers.

5.0 FABRIC FILTERS

5.1 INTRODUCTION

Fabric filters remove dust from a gas stream by passing the gas stream through a porous fabric. Collected dust particles form a porous cake on the surface of the fabric. It is normally this cake that actually does the filtration.

The manner in which the dust is removed from the fabric is a crucial factor in the performance of the fabric filter system. If the dust cake is not adequately removed, the pressure drop across the system will increase dramatically. If too much of the cake is removed, excessive dust leakage will occur while fresh cake develops. Selection of design parameters is crucial for optimum performance of a fabric filter system.

Fabric filter systems are frequently referred to as baghouses since the fabric is usually configured in cylindrical "bags". The two most common baghouse designs are the reverse air and the pulse jet types. These names describe the cleaning system used by each design.

Baghouses are generally considered to be a superior choice, relative to electrostatic precipitators (ESP), for fine particulate control. A multi-field precipitator with a very large plate area is required to provide comparable fine particulate collection performance, therefore an ESP of comparable performance is usually more expensive. Figure 5-1 illustrates the greatly improving trend in the control of particulate emissions by both ESP's and fabric filters since 1970 (1). Figure 5-2 indicates that for typical two-field ESP's, the removal efficiency for fine, submicron, particles is considerably less than that achieved in a fabric filter (13).

As experience with the use of baghouses increases, their reliability has increased due to improvements in the design of bag fabrics and cleaning techniques. These measures have extended bag life to an average of five years or more in some cases. Well designed and operated baghouses have been shown to be capable of reducing overall particulate emissions to less than 0.010 and in a number of cases as low as 0.001 to 0.005 gr/dscf. Based on the potential for greater removal efficiencies overall and in the submicron particle size range, a number of states, including California, Connecticut and Michigan, as well as Canada, prefer the use of scrubber/baghouses for solid waste resource recovery plants.

Reverse air baghouses operate by directing the dirty flue gas into the inside of the bags, therefore collection of dust is on the inside surface of the bags. The bags are cleaned periodically by reversing the flow of air, causing the previously collected dust cake to fall off the bags into a hopper below. Since this cleaning procedure is accomplished at relatively low gas velocity, the fabric is not exposed to violent movement, therefore the reverse air cleaning technique normally results in maximum bag life. In a variation of reverse air baghouse design, the bags are shaken during the reverse air cleaning interval.

Pulse jet baghouses are designed with internal frame structures, called cages, to allow collection of the dust on the outside of the bags. The dust cake is periodically removed by a pulsed jet of compressed air into the bag causing a sudden bag expansion. Dust is removed primarily by inertial forces when the bag reaches its maximum expansion. This bag cleaning technique is quite effective, however, the vigorousness of the technique tends to limit bag life and also tends to increase dust migration through the fabric, thus decreasing dust collection efficiency.

The selection of the fiber material and fabric construction is important to baghouse performance. The fiber material from which the fabric is made must have adequate strength characteristics at the maximum gas temperature expected and must have adequate chemical compatibility with both the gas and the collected dust. Felted fabric construction generally gives

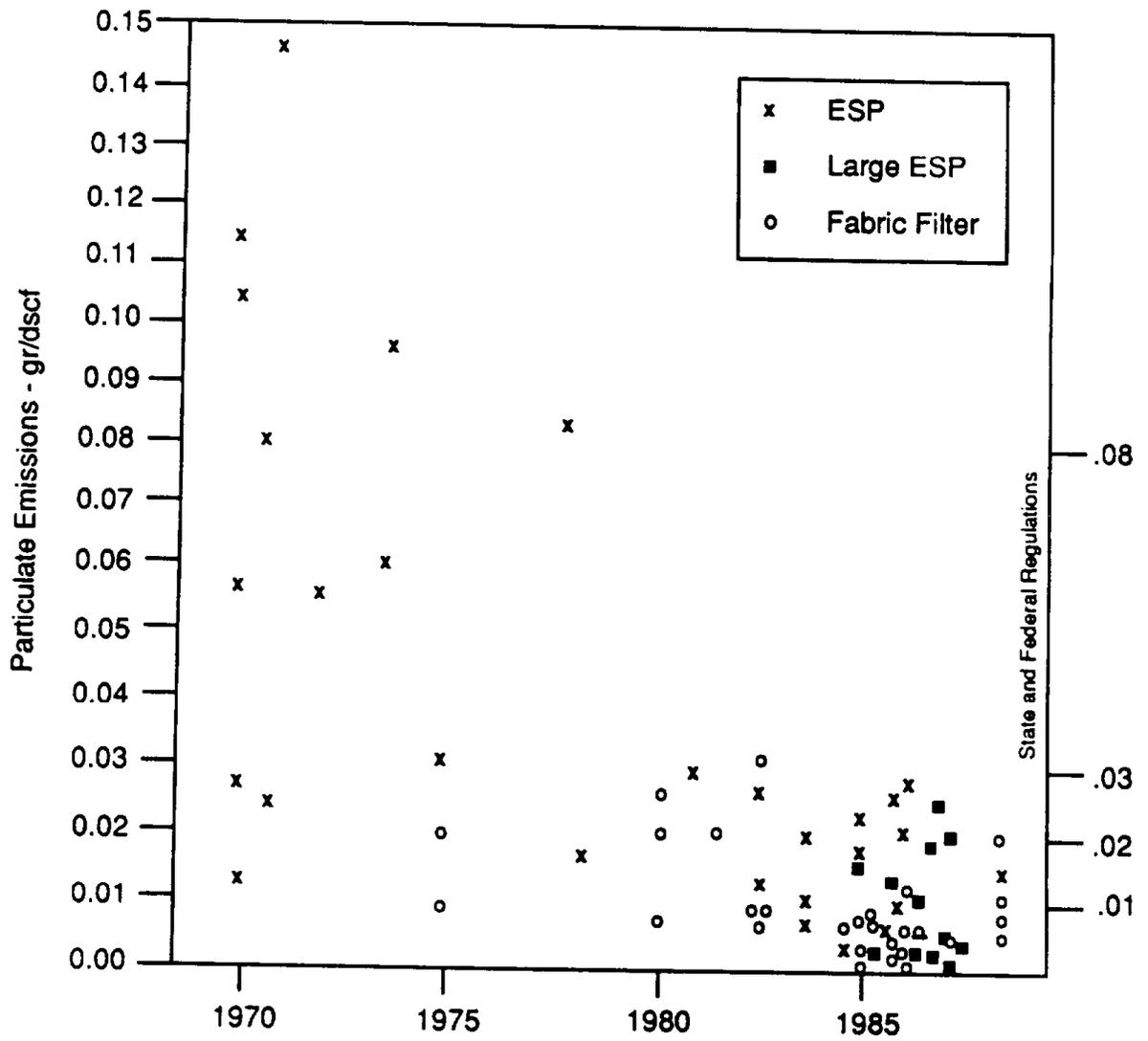


Figure 5-1. Particulate emissions from MSW incineration 1970-1988 (1).

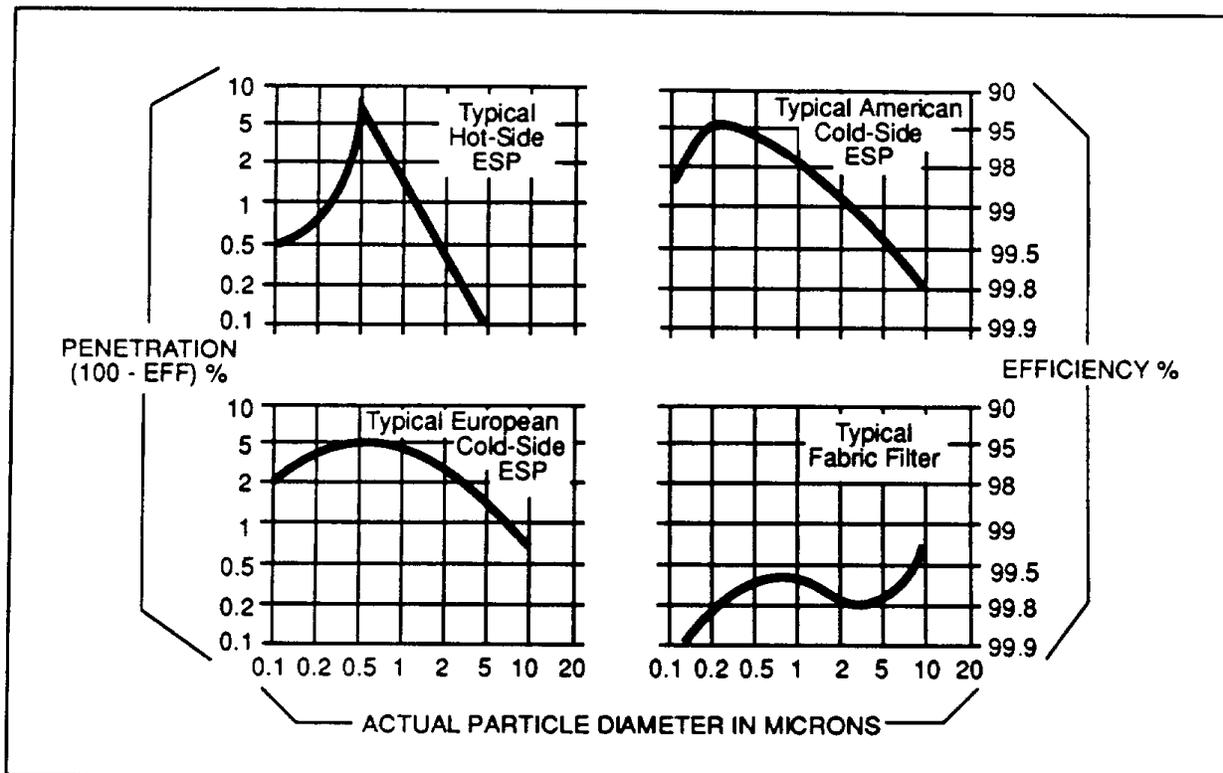


Figure 5-2. Typical fractional efficiencies for existing collectors (13).

better removal of fine dust particles as compared to woven fabrics, however not all fiber materials can be felted into a fabric of adequate strength hence most filtration fabrics are constructed, at least in part, of fibers that are first twisted into yarns then woven into a fabric.

The following sections are composed largely from a document titled Fabric Filter-Baghouses I by Mckenna and Turner (2).

5.2 THEORY OF OPERATION

Several particle collection mechanisms are normally responsible for filter efficiency. Theoretical equations exist for the capture efficiency of each mechanism based on single particles approaching single fibers. For an operating fabric filter, however, the fabric is covered with a dust cake and the dust cake is of continually varying thickness. Once the dust cake has reformed after each cleaning, sieving is probably the dominant mechanism. As particles approach the porous mass of dust that constitutes the cake, they will either strike one or more surface particles or enter a pore. If the particle is larger than the pore it attempts to enter, it will be sieved out. If the particle is smaller than the pore it enters, it will continue traveling through the pore until it either touches the pore wall and adheres (rather than bounding or rolling along the wall), or until the pore narrows to dimensions smaller than the particle, causing the particle to be sieved out, or until the particle passes through the dust pore and a fabric pore and exits on the clean air side of the air filter. Ordinarily only one out of a thousand particles finds its way through the filter (2).

One might expect that larger particles would be sieved out with greater efficiency than smaller particles. That is, the size distribution of particles leaving the filter would have a smaller median diameter than the particles entering the filter. Experimentation has shown, however, that the size distribution across the filter surface changes only slightly. The reason for the lack of change in size distribution stems from the manner in which most particles find their way through the filter. Most particles that transit the filter do so by a leakage process.

Consider a freshly cleaned bag. As filtration resumes, the cleaned areas of the fabric present pores of various sizes to the oncoming dust cloud. Individual particles strike the edges of the pores and attach and begin to form chains or dendrites across the pores. Soon the smaller pores are ridged over by the chains and eventually become completely covered by porous cake. As time passes, more and more pores become covered with cake and the gas velocity through the remaining, uncovered pores, becomes higher. Instead of a few feet per minute face velocity, it is now up to several thousand feet per minute pore velocity. Eventually the velocity through the few remaining uncovered pores becomes so high, and the pores so large, that the pores cannot be bridged. For the remainder of the filtration cycle these relatively free pores will be leakage points in the filter, and most of the particles passing through the filter will pass through these leakage points.

Billings and Wilder (14) report work by Tomaides suggesting that particles in a filter can bridge over a pore gap about ten particle diameters wide. Presumably the adhesive forces holding the chain together are exceeded by the aerodynamic forces trying to rupture the chain if its length exceeds ten particle diameters.

5.2.1 Gas-to-Cloth Ratio

Gas-to-cloth ratio, G/C, is a measure of the amount of gas driven through each square foot of fabric in the baghouse, and is given in terms of the number of cubic feet of gas per minute passing through one square foot of cloth $[(ft^3/min)/ft^2]$ or fpm (2):

$$G/C = \frac{\text{ft}^3 \text{ per minute of gas}}{\text{ft}^2 \text{ of fabric}} \quad 5-1$$

G/C can be considered as a superficial gas velocity. This is not the actual velocity through the openings in the fabric, but rather the apparent velocity of the gas approaching the cloth, although it is often referred to as "the gas velocity," (2) and reported as ft/min or m/min.

As the gas-to-cloth ratio increases, the pressure drop, ΔP , also increases. Pressure drop is normally measured and reported as inches of water (in. H₂O, also written as inches water gauge, in W.G.), the convention in the U.S.

5.2.2 Pressure Drop

During the mid-1800's, Darcy formulated the following law for fluid flow through a porous bed (2):

$$\Delta P = \frac{L\mu_f V}{K} \quad 5-2$$

where ΔP = pressure difference across the bed;
 L = bed thickness;
 μ_f = fluid viscosity;
 V = superficial fluid velocity;
 K = bed permeability.

This equation assumes that the fluid is essentially incompressible, steady, fluid viscosity is Newtonian, and the velocity is low enough so that only viscous effects occur. Over the last hundred years, investigators have been trying to find ways to predict K and to refine the Darcy equation.

The basic Darcy equation can be used to predict the pressure drop for an operating fabric filter with dust cake accumulating on the fabric as follows (2):

$$\Delta P = S_E V + K_2 C_i V^2 \Delta t \quad 5-3$$

where:

ΔP = Pressure Drop, In-H₂O
 S_E = Effective Residual Drag, In-H₂O/ft per min
 V = Superficial Fluid Velocity, ft/min
 K_2 = Specific Cake Coefficient, [in H₂O/ft/min]/(lb/ft²)
 C_i = Inlet Dust Concentration, lb/ft³
 Δt = Filtration Time, min

The pressure loss through a fabric filter is composed of two parts; the first, $S_E V$, represents the frictional pressure drop expended in pumping gas through the cleaned equilibrium fabric of the fabric filter. The second part of the equation, $K_2 C_i V^2 t$, represents the pressure loss when pumping gas through the filter cake that builds up on the surface of the fabric. The superficial gas velocity appears in both terms, but because it is squared for the cake portion of the equation, it is especially important for describing the pressure loss when pumping gas through the filter cake.

Another important part of the equation is K_2 , the specific cake coefficient. This term depends on the characteristics of the dust, gas velocity, type of fabric, particle size, and electric field strength in the vicinity of the fabric, and is a measure of how rapidly pressure drop will build up in a system (2).

A fabric filter in stable, cyclic operation will normally reach a point of constant drag characteristics. That is, the resistance to the gas flow of the freshly cleaned fabric is the same at the beginning of successive filtration cycles. In practice, the value may change as the fabric ages. The amount of residual drag is a measured value, and there is no analytical equation for predicting residual drag.

5.2.3 Efficiency

Efficiency is a measure of how well the filter separates the dust from the gas. For an operating baghouse, overall efficiency is calculated from (2):

$$\text{Efficiency} = \frac{C_i - C_o}{C_i} \quad 5-4$$

C_o = outlet concentration

C_i = inlet concentration

Penetration, which is equal to one minus the efficiency, is also used as a measure of performance of a filter.

Efficiency and penetration may be measured or calculated for specific particle sizes or size ranges. Inertial impactors are used to measure efficiency by measuring particle concentration over several size ranges on the inlet and outlet streams of a baghouse. Overall efficiency can be determined by simultaneously measuring the total concentration of particulate at the inlet and outlet of the baghouse. There is no satisfactory set of published equations that allow a designer to calculate efficiency for a prospective baghouse. If the fabric is selected properly and the baghouse is maintained and operated correctly a particulate collection efficiency of over 99% can be expected over a wide range of particle sizes.

5.2.4 Filtration Fabrics

Fiber Types

This section discusses fibers and fabric properties that will help the user select and specify fabrics for particular fabric filter applications. Fabrics made of natural fibers such as cotton or wool are still employed for many filter applications. The development of man-made or synthetic fibers, however, has greatly extended the possible range of applications for fabric filters. Continuing developments in fiber and fabric technology may be anticipated.

Synthetic fibers are widely used for filtration due to their low cost, better temperature and chemical resistance characteristics, and small fiber diameter. Synthetics used include acetates, acrylics, polyamides, polyesters, polyethylenes and polyvinyl chlorides. Specialty fibers for high temperature, such as Teflon, Ryton, P84 and carbon fibers, have been developed (2). However the most used synthetic fiber for high temperature applications is glass.

The properties of glass fiber such as good acid resistance, good heat resistance, and high tensile strength, solve many of the problems inherent in baghouses.

Fiberglass has these characteristics:

- Noncombustible because it is completely inorganic.
- Zero moisture absorption. Therefore it is not subject to hydrolysis.
- Dimensional stability (low coefficient of linear expansion).
- Very high tensile strength but poor resistance to flex and abrasion. There are some chemical surface treatments (e.g., silicone, graphite, Teflon B) that improve the flex/abrasion characteristics of glass.
- Poor resistance to acid anhydrides and metallic oxides (e.g., fluorides and sulfur oxides). For this reason, glass baghouses should not be operated at or below the dewpoint.

Table 5-1 lists the major fiber alternatives for gas filtration and gives some of the important properties of these fibers.

The first, and probably the key inlet condition that must be identified prior to selecting filtration medium is the temperature the fabric will experience. Figure 5-3 compares the recommended operating temperatures for the most often used filtration fabrics. Note that as the temperature increases, fabric choices become limited. In 1987, the maximum temperature for which economical filter media are commercially available is about 500°F (260°C), although this may change with the advent of ceramic and metallic filters. When confronted with higher temperatures, the usual approach has been to cool the gas down, at least to the vicinity of 500°F (260°C). Once a preliminary selection of filtering fabric has been made, the filter supplier can usually provide additional information that should be considered when finalizing the fabric choice.

Important Fiber Characteristics

When selecting a fiber for gas filtration, consideration must be paid to the following interacting factors:

1. **Temperature:** The fiber must have a maximum continuous service temperature higher than the normal temperature of the application. If the temperature surges above the normal range occur, the ability of the fiber to withstand the expected conditions of the surge temperature and its duration must be considered.
2. **Corrosiveness:** The ability of the fiber to resist physical degradation from the expected application levels of acids, alkalies, solvents or oxidizing agents must be considered.
3. **Hydrolysis:** Effects of the expected level of humidity must be taken into account.
4. **Dimensional Stability:** If the fiber is expected to shrink or stretch under the application environment, the effects of such a change must be tolerable.

TABLE 5-1. FABRIC SELECTION CHART (2)

FABRIC	MAX TEMP	ACID RESISTANCE	FLUORIDE RESISTANCE	ALKALI RESISTANCE	FLEX ABRASION RESISTANCE
COTTON	180°F	POOR	POOR	GOOD	VERY GOOD
POLY-PROPYLENE	200°F	EXCELLENT	POOR	EXCELLENT	VERY GOOD
POLYESTER	275°F	GOOD	POOR TO FAIR	GOOD	VERY GOOD
NOMEX	400°F	POOR TO FAIR	GOOD	EXCELLENT	EXCELLENT
TEFLON	450°F	EXCELLENT	POOR TO FAIR	EXCELLENT	FAIR
FIBERGLASS	500°F	FAIR TO GOOD	POOR	FAIR TO GOOD	FAIR

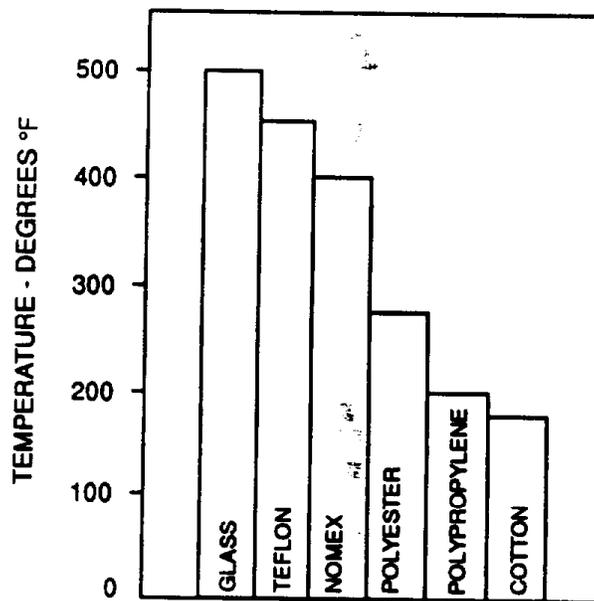


Figure 5-3. Recommended maximum operating temperatures for fabrics (2).

5. Cost: As with any engineering product, the least costly selection that will meet overall requirements is usually the best selection.

Media Selection

Baghouse operating costs are reduced if the baghouse has a high gas-to-cloth ratio, a low pressure drop and a long life. In each case, the key to operation at minimum cost is the medium selected for bag construction. This selection is crucial but not easy because many, often conflicting, requirements must be met.

The primary media selection criteria are the compatibility of the selected fiber with the gaseous environment, and the physical configuration of the fiber and resulting fabric as it affects filtration performance. Usually the selection criteria interact so much, or are not well enough understood, that the best selection is not apparent without long-term testing. Sometimes it is possible to equip complete baghouse compartments with various media and observe the results for future selections. In 1985, ETS, Inc., introduced an individual bag flow monitor that is useful in making side-by-side comparison of alternative media.

Satisfactory performance of a fabric filter on a specific application requires not only the selection of a fiber material compatible with the gas/particle environment, but also a fabric design appropriate to dust collector geometry and collector cleaning requirements. Fiber yarn and fabric parameters all influence the filtration process.

Both fabric strength and flexibility are important parameters in the ability of the fabric to resist wear due to abrasion. The term "abrasion" is defined as an eroding away of fabric fibers or fiber surface material, as a result of moving contact between the fiber and dust particles or between adjacent fibers. The flexibility of a filtration fabric is important for at least two reasons: cleanability and durability. Removal of the dust deposit may be improved by flexing of the fabric substrate, but such flexure may degrade the fabric. Thus, fabric flexibility may be both necessary and harmful.

Permeability of the fabric must be considered when selecting a filter medium. It must be understood however that the permeability of filtration fabrics is so reduced by residual dust deposit that the permeability of clean fabric appears to have little relationship to permeability during use. The objective in fabric design is to maintain a highly permeable combination of residual dust and fabric while allowing a minimal amount of dust to pass through. To meet this objective, the pore size through a fabric must be closely controlled. They must not exceed a certain bridging diameter, but if they are too small they will either become plugged or pass to little gas. In an ideal filtration fabric, all the fabric pores should be the same size, that size depending on properties of the dust and gas, fabric characteristics, etc. Yarn texturizing treatments to the post-weave surface contribute greatly to the permeability of a clean fabric, and perhaps also to the permeability of residual dust deposit.

The last, but certainly not least, criterion of media selection is the ability of the fabric to release collected dust during the cleaning cycle. This ability depends largely on the mode and intensity of cleaning, but also on the adhesive character of the fabric. The way in which fabric construction relates to deposit release has not been completely determined, but it is known that a smooth fabric surface releases dust more readily than a fuzzy surface. Dust may agglomerate on loose fibers and move away from the surface during cleaning, only to return once filtration resumes. This action, whose outcome is sometimes referred to as "dingleberries," can result in poor cleaning. Some fabric surface treatments are specifically intended to enhance cake release. Dust release also depends on the electrical resistances of selected fibers. Electrical resistance is known to depend on humidity, which itself has a marked effect on filtration fabric performance. An

extensive table of electrical properties for a variety of fabrics is given by Frederick (16).

In about 90 percent of the baghouses presently operating on coal-fired boilers, the bags are fabricated from glass fibers. Glass fibers are tiny filaments as small as 0.00015 in. (4 μm) in diameter that are extremely flexible and thus may be woven into a fabric. Before 1930, discontinuous "glass wool" fibers were the only form produced commercially. The new technology was first used to develop continuous fibers for high temperature insulation of fine electrical wires, designated "E" glass because of its unique electrical insulation properties. Today "E" glass is used in nearly all glass fiber applications, ranging from printed circuit boards to boat hulls and filtration fabrics. Other formulations were also developed, by altering percentages of the glass composition to obtain special performance characteristics. "C" glass is particularly resistant to chemical attack while "S" glass possesses outstanding strength characteristics. Thus far, production constraints and economics have limited glass filtration fabrics to "E" glass.

Woven Fabric

Almost without exception, filtration fabrics are either completely or at least partially made by weaving. Even felted or so-called "non-woven" fabrics include a base (scrim) of woven fabric. Baghouses where the gas flow is from the inside of bags to the outside, such as reverse-air and shaker-cleaned baghouses, use woven fabrics almost exclusively. These baghouses generally operate at lower gas flow rates where the flow restriction of the fabric is not so significant. Woven fabrics usually have greater flow restriction but greater strength (for a given fabric weight) than comparable non-woven fabrics and thus are usually chosen for reverse-air and shaker applications.

Pulse-jet-cleaned baghouse designs offer increased cleaning energy and operate at higher gas flow rates. The tendency of woven fabrics to "bleed," resulting in low filtration efficiency when clean, usually restricts the use of woven fabrics for pulse-cleaned applications. Woven fabrics made with texturized yarn, or woven fabrics with membrane films applied to the upstream surface, offset the tendency to bleed when cleaned, and these types of fabrics are used in pulse-cleaned applications.

Woven fabrics are formed by interlacing yarns at right angles on the loom, after which the raw (greige) fabric may be further treated. While there are many patterns of interlacing, the fabrics most commonly used in gaseous filtration are twill, sateen or plain weaves. These three weave patterns are depicted in Figure 5-4. Both the twill and the sateen weaves have fabric sides where warp or fill yarns predominate, and those sides are referred to as warp-face or filling-face.

In its basic construction, sateen weave is similar to twill but generally uses a pattern of fill yarns going under one, then over four to twelve warp yarns. Sateen differs in appearance from twill because the diagonal of sateen weave is not visible; it is purposely interrupted in order to contribute to the flat, smooth, lustrous surface desired. There is no visible design on the face of the fabric because the yarns that are to be thrown to the surface are greater in number and finer in count than the yarns that form the reverse of the fabric.

Plain weave is sometimes referred to as tabby, home-spun or taffeta weave. It is the simplest type of construction and consequently the least expressive. Each fill yarn goes alternately under the over the warp yarns across the width of the fabric. On its return, the yarn alternates the pattern of interlacing. If the yarns are close together, plain weave has a high thread count. Figure 5-4 shows typical fabric weaves.

Non-Woven Fabrics

Non-woven fabrics generally are defined as sheet or web structures made by bonding and/or interlocking fibers yarns or filaments by mechanical, thermal, chemical or solvent means.

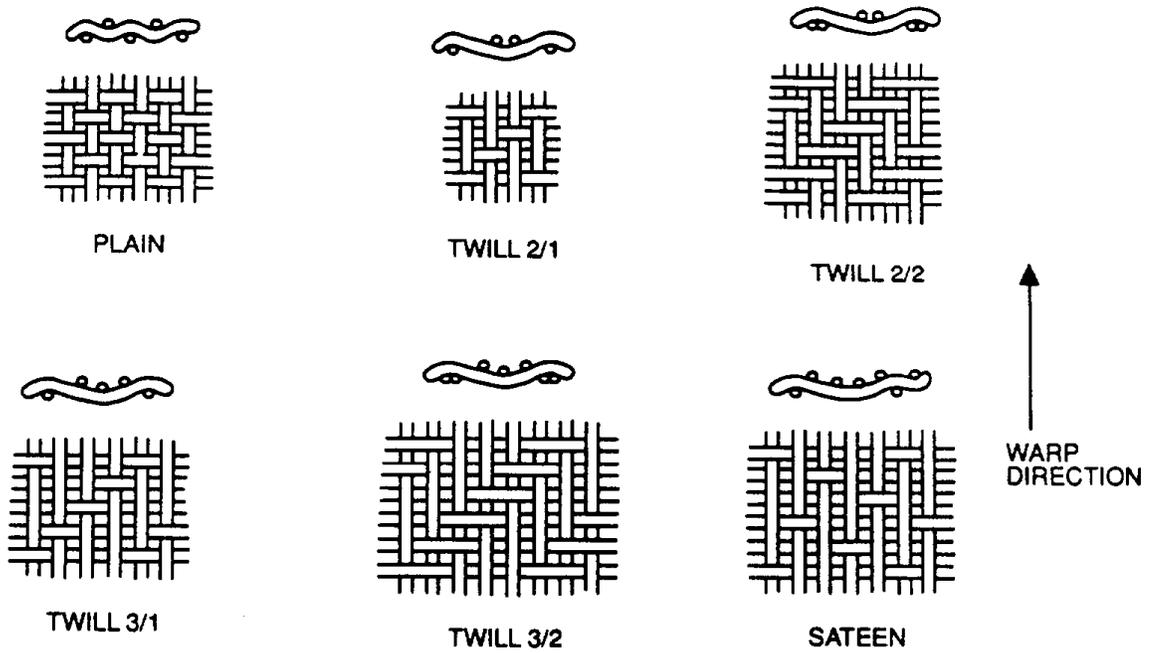


Figure 5-4. Typical filter cloth weaves (2).

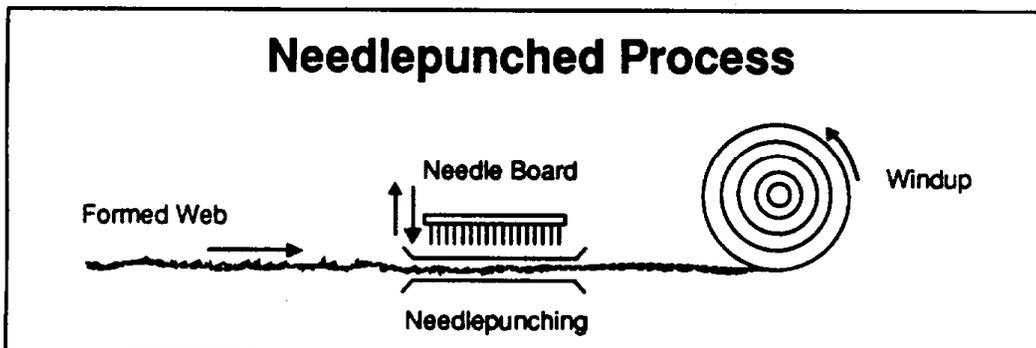


Figure 5-5. Needlepunched process (17).

The International Non-woven and Disposable Association, INDA, a trade association of the non-woven fabrics industry, has given this definition: "A non-woven is any fabric made directly from a web of fiber without the yarn preparation required for weaving or knitting. Natural or synthetic fibers can range in length from 0.5-15 cm from crimped staple products, up to continuous filaments for spunbonded products. The fibers may be oriented in one direction or may be deposited randomly. This web is given structural integrity by either mechanical fiber intertangling, thermal or chemically induced fusing of the tiers, or application of any of several adhesives or resins" (17).

Perhaps the most significant feature underlying all nonwoven fabric production, and the one that contributes most to its economic appeal, is the speed at which fabric is produced. Many non-woven production units in place today can produce fabric at speeds of 400 ft/min (200 cm/s) or more. Some advanced units operate at speeds over 1,000 ft/min (500 cm/s). These rates may be compared to knitting machine speeds of about 5.0 ft/min (2.5 cm/s), and the even slower rates of weaving machines.

A needlepunched fabric is produced by introducing a fibrous web already formed by carding or air-laying, into a machine equipped with groups of specially designed, barbed needles (see Figure 5-5). While the web is trapped between a bed plate and a stripper plate, the needles punch through it and reorient the fibers so that mechanical bonding is achieved among the individual fibers. The needlepunching process is generally used to produce fabrics that have high density yet retain some bulk. Fabric weights usually range from 1.7-10 oz/yd² (58-340 g/m²), thicknesses from 15-160 mils (0.38-4.1 mm).

Needlepunching is often used to combine two or more layers of fiber into a felt-like fabric. Usually one layer for strength is a woven fabric, called a scrim, while the other(s) may consist of fibers of almost any description or combination. Thus, considerable control over separate properties of the finished material is possible. For example, the scrim may contribute to desired dimensional stability while the top, or batting layer, contributes appropriate properties for filtration. Needle punching is accomplished by punching needles with forward barbs from the batting side into or through the scrim, and the batting fibers thus laced into the scrim remain behind when the needles are withdrawn. Variations in the needling process include needle angle, number of repetitions, two-sided needling, etc. When a shrinkable scrim is used, the needled material may later be felted in various ways to produce a still more dense and uniform material.

To improve the filtration characteristics of the fabric surface, it may be napped. This is done by teasels (woody, thistle-like parts of weed plants), whose barbs pluck fibers from the surface of the felt. When enough nap has been raised in this manner, it may be singed or otherwise trimmed to the desired thickness.

Needlepunched fabrics, sometimes called needle felts, are employed in many filtration applications. Modification of the basic structure produced by the needling process determines filtration performance. When the punch density is increased during needling, one of the results is an increase in fabric density. Eventually an optimum punch level is attained above which density falls off. The maximum density possible from needle punching alone would be insufficient to produce an efficient filtration medium. Additional processes are required to give the necessary densification and closing-up of the structure. Heat treatments are normally employed at temperatures suited to the thermal characteristics of the particular fiber in use. Suitable processes include the squeezing of fabric between rollers, or roller and stationary bed. Up to a point, an increase in fabric density increases filtration efficiency.

Fabrics are also required to provide good discharge of the dust cake. Good discharge is usually achieved by means of surface modification in the form of singeing to remove individual fibers protruding from the surface. Good cake release surfaces can also be formed by heating the fabric surface to such an extent that fiber melting and fusion occurs although this will also increase the flow resistance of the fabric.

Relaxation of tensions built into the fabric structure by the needling operation can be brought about by passage through an oven. Such treatment is insurance against dimensional changes occurring when the fabric first encounters operating conditions.

Treatments and Finishes

The term "finishing" includes those processes that improve appearance or serviceability of the fabric after it leaves the weaving machine. Greige (unfinished) fabrics intended for use as filtration fabrics are treated and/or finished after weaving to improve their filtration characteristics and cleaning (release) characteristics. Fabric life and strength may also be affected. Treatments are defined as post-weaving processes that affect the entire fabric, while finishes are post-weaving processes that affect only the surface of the fabric.

One fabric treatment of significance in filtration fabrics is heat setting. In the process of heat setting, the fabric is exposed to temperatures exceeding those experienced in service. This treatment is done on a machine known as a pin tenter. The fabric is held under tension in both warp and fill directions and passed through a heated oven.

Special finishes have been developed for the glass fabrics used in high temperature filtration (18). For glass filter bags, organic materials such as the starch binder that the yarn producer applies and the warp sizing (starch and mineral oil) applied to facilitate weaving, must be removed before applying a finish to the fabric. This is necessary because these organic lubricants would not be stable at the process temperature, and also because they would interfere with the application of the desired finish. It is desirable that the applied finish have as close contact as possible with the bare glass filaments, penetrating the yarn bundle and encapsulating individual filaments.

Organic sizings are removed thermally by a process called coronizing, which also sets the crimp in the glass yarns. Crimp is the bend in a yarn caused by interlacing during weaving. The yarn is heated to the softening point and the crimp is set as the yarn cools. It is believed that setting the crimp in the yarn maximizes the flex life of the fabric.

The finish used for glass fabrics must be thermally stable at process temperature (500-550°F or 260-290°C) and chemically resistant to the gas environments found in fiberglass filter bag applications. The basic purpose of the finish is to protect the glass fibers from abrading themselves, but it can also enhance dust release characteristics.

In addition to providing lubricity to extend bag life, glass fabric finishes also help to promote dust release from the fabric and offer varying degrees of protection from chemical attack. The success of the glass fabric as a viable filter medium depends to a large degree on the quality of the finish. Finish development has occurred in roughly three stages, with finishes comprising primarily three groups:

- I. Silicones
- II. Silicones and graphite with small amounts of fluorocarbons
- III. Fluorocarbon compounds

All three groups are still in use, although Group I, the silicone finish, has largely faded from the scene. Group II finishes are divided into Tri-Component and Acid Resistant groups (19).

Tri-Component:

- Graphite (natural or synthetic)
- Teflon
- Agents to assist application

Acid-Resistant:

- Graphite (natural or synthetic)
- Polymers
- Binders
- Silicone
- Teflon
- Agents to assist application

Teflon is used in both Group II and III finishes. Group III finishes consist of Teflon, binders, and agents to assist application.

Most of the experience to date with Group II finishes has been at 10 percent loading. For example, 10 percent of the finished fabric weight is Teflon B. Amounts of finish vary greatly, but in general, the Teflon finish is 7-10 percent weight added per weight of cloth; the acid resistant finish is 4-6 percent; and the tri-component finish is 1-2 percent (19). Some experience indicates that Group II finishes are more resistant to chemical attack, while other experience favors the use of Group III finishes. There has been progress in using Group II finishes to protect Nomex fabrics from acid exposure in coal-fired boiler applications.

A special surface treatment gaining increased use in gaseous filtration is the application of a Gore-Tex membrane to the fabric surface (20). The Gore-Tex membrane is expanded polytetrafluoroethylene (PTFE) deposited as a thin, fibrillated film. Gore-Tex membranes have been applied to many available backing materials including woven polyester, Nomex, glass and Teflon. Usually the backing fabric is quite porous. Gore-Tex filter bags are constructed for pulse-jet, reverse-air, and shaker collectors. Gore-Tex membrane filter cartridges are also available.

Measured properties of fabric finished with a Gore-Tex membrane show the tensile and burst strengths characteristic of the woven fabric but the resulting permeability is lower. Lower permeability might suggest higher than desirable pressure drops, but that is usually not the case because the membrane improves cleanability and reduces residual dust build-up in the fabric.

5.3 TYPES OF EQUIPMENT

The primary way to categorize a fabric filter is by the method used to clean it. In general, accumulated dust is separated from the fabric by some combination of the following effects:

1. Deflection of the fabric/dust cake, tending to fracture the cake and separate it from the fabric.
2. Acceleration of the fabric/dust cake, yielding separation forces.
3. Gas flow in the reverse direction, yielding aerodynamic forces that separate the dust from the fabric and subsequently move the dust toward the collecting hopper.

Four cleaning methods have evolved, each of which generates some combination of these fabric/dust cake separation effects. The majority of baghouses currently in use employ one or

more of these cleaning methods. The four cleaning methods are summarized below and then discussed in greater detail in subsequent paragraphs.

1. **Shaker-Cleaned Baghouses.** In shake cleaning, the tops of the bags are shaken, resulting in deflections and acceleration forces throughout the bag. Gas flow with zero or negative velocity is normally combined with the shaking.
2. **Reverse-Air-Cleaned Baghouses.** In reverse-air cleaning, a combination of bag deflection (inward collapse) and reverse flow is used to remove dust from the fabric. This process results in very low stresses on the fabric, hence is often preferred for easily damaged fabrics such as fiberglass.
3. **Pulse-Jet-Cleaned Baghouses.** Pulse-cleaned baghouses use outside-in flow, where the fabric collapses against a wire cage during filtration. During cleaning, a pulse of high pressure air is directed into the bag (the reverse flow direction), inflating the bag and causing fabric/cake deflection and high inertial forces that separate the dust from the bag. Although reverse-air flow is involved, it is thought to have a minor effect on cleaning.
4. **Sonic Cleaning.** Sonic cleaning, if used, usually augments another cleaning method. Sonic energy is normally introduced into the baghouse by air-powered horns. Although the process is not well understood, the sonic air shock waves apparently generate acceleration forces that tend to separate the dust from the fabric.

The significant parameters of shaker, reverse-air and pulse-jet cleaning are given in Table 5-2, 5-3 and 5-4.

5.3.1 Shaker

Shaker type baghouses are generally considered to be the oldest known form of fabric filter but still have a significant place in present day technology. It is known that in the smelter industry during the early 1900s, filter bags were cleaned by hand shaking. Shake cleaning has subsequently progressed through stages, from manually operated racks to present day devices that are automated for either motor or air operation. Many mechanisms have been developed to impart motion to the filter bags to clean them. The motion has been either vertical, horizontal or some combination of the two, although shakers have been developed that twist or otherwise move the bags. In essence, all of the mechanisms impart energy to the filter fabric in such a way that a change of direction allows inertial forces to remove the collected filter cake from the bags.

The one constant that must be provided in all shaker-type baghouses, regardless of the type of action imparted to the fabric, is that flow in the positive direction must be absent during cleaning. Forward differential pressure across the bags of less than 0.05 in. (12 Pa), has been observed to significantly retard bag cleaning.

Conversely, a slight reverse flow through the bags during shaking can be beneficial. Shaking is usually accomplished by the use of a motor driven assembly. This bag cleaning technique is currently employed over the full range of baghouse capacities, from very small off-the-shelf units to extremely large structural design units.

The bag is generally open at the bottom and closed at the top, fixed in the tube sheet at the bottom and attached to the shaking mechanism at the top. With this configuration, dust is collected on the inside of bag. The bag normally contains no rings or cages. The flow of dirty gas to the

TABLE 5-2. SHAKE CLEANING - PARAMETERS (21)

Frequency	Usually several cycles/second; adjustable
Motion Type	Simple harmonic or sinusoidal
Peak Acceleration	1 - 10g
Amplitude	Fraction of an inch to few inches
Mode	Off-stream
Duration	10 -100 cycles 30 sec to few minutes
Common Bag Diameters	5, 8, 12 in.

TABLE 5-3. REVERSE-AIR CLEANING - PARAMETERS (21)

Frequency	Cleaned one compartment at a time, sequencing one compartment after another, can be continuous or initiated by a maximum-pressure-drop switch
Motion	Gentle collapse of bag (concave inward) upon deflation; slowly repressurize a compartment after completion of a back flush
Mode	Off-stream
Duration	1 - 2 min, including valve opening and closing and dust settling periods; reverse-air flow itself normally 10 - 30 sec.
Common Bag Diameter	8, 12 in.; length 22, 30 ft.
Bag Tension	50 - 75 lbs. typical, optimum varies; adjusted after on-stream

TABLE 5-4. PULSE-JET CLEANING - PARAMETERS (21)

Frequency	Usually, a row of bags at a time, sequenced one row after another; can sequence such that no adjacent rows clean one after another; initiation of cleaning can be triggered by maximum-pressure-drop switch or may be continuous
Motion	Shock wave passes down bag; bag distends from cage momentarily
Mode	On-stream; in difficult-to-clean applications such as coal-fired boilers, off-stream compartment cleaning being studied
Duration	Compressed-air (100 psi) pulse duration 0.1 sec; bag row effectively off-line
Common Bag Diameter	5 - 6 in.

bags is stopped during the cleaning process.

In the U.S., shakers normally employ woven cloth at gas-to-cloth ratios below 4:1. Attempts thus far to use shaker cleaning in combination with domestic felts have led either to ineffective cleaning, and thus high pressure drop, or to the filter medium being shaken apart.

5.3.2 Reverse-Air

Reverse-air cleaning is the gentlest cleaning method. Dust is removed from the bags by back-flushing with low-pressure (a few inches water gauge) reversed flow. In high temperature applications, the just-cleaned hot gas is employed for back-flush, rather than ambient-temperature air. Woven filter media are generally employed with reverse-air cleaning. Flow is provided by a separate cleaning fan that is normally much smaller than the main system fan, since only a fraction of the total system is cleaned at any one time. In the case of a negative pressure system, one often can clean without a reverse flow fan. The flow rate of cleaning gas is normally about equal to that of the dirty gas.

Reverse flow systems most often comprise a number of isolatable compartments, or modules. The gas-to-cloth ratios usually employed are less than 4:1. Dust is normally collected on the inside of the bag, the bag being open at the bottom and closed at the top. The bag contains rings to keep it from collapsing completely during flow reversal. Complete collapse would, of course, prohibit cleaning because the dust particles could not fall down within the bag to the hopper. Cleaning is accomplished both with and without flexing (partial collapsing) of the bag. Reverse flow without flexing can be employed when the dust is very easily dislodged from the bag surface. Figure 5-6 shows a typical reverse-air cleaning cycle. In the onstream gas filtering mode, the compartment and outlet dampers are open and dirty gas enters the bag at the bottom. Dust collects on the inside of the bag and the cleaned gas exits the outlet damper. During the bag cleaning cycle, the flow is reversed by closing the outlet plenum and opening a third damper that allows cleaned gas to enter the compartment on the clean side of the bags, thus back-flushing the bags and exiting the compartment through the inlet damper. This now-dirty gas progresses to the balance of the on-stream compartments. It should be noted that this process increases the system gas-to-cloth ratio by adding to the total gas volume the volume of gas employed in the back-flushing process.

One baghouse manufacturer has studied the reverse-air cleaning process both analytically and experimentally and concluded that the improved cleaning frequently observed when a thick dust cake is allowed to build up can be attributed to the piston-like action of a falling plug of dust cake (22). The manufacturer theorizes that the cascading dust cake both scours the cake ahead of it and causes significant evacuation, hence additional reverse flow behind it. The concept is shown pictorially in Figure 5-7.

Reverse-air flow can serve to flush out loosened particles from fabric interstices and carry the dislodged agglomerates toward the collecting hopper. Based upon gravimetric measurements and filter resistance characteristics, there is, however, little evidence to suggest any significant removal of dust particles by aerodynamic action alone. The above findings are in agreement with those of Larson (23) who states that air velocities on the order of 200 ft/min (102 cm/s) are required to remove a single 20 μm particle from a fiber; and with Zimon (24), who indicates that air velocities sweeping tangentially over a layer of dust must be in the range of 400 ft/min (203 cm/s) before any appreciable dust removal is accomplished.

Because significant dust removal is attained in reverse flow systems, one must conclude that separating forces other than aerodynamic drag are involved. According to the drag theory, the adhesive forces between adjacent particles are actually increased as dirty gas moves radially through the dust cake. During reverse-air flow, any dust dislodgement is more likely to follow a

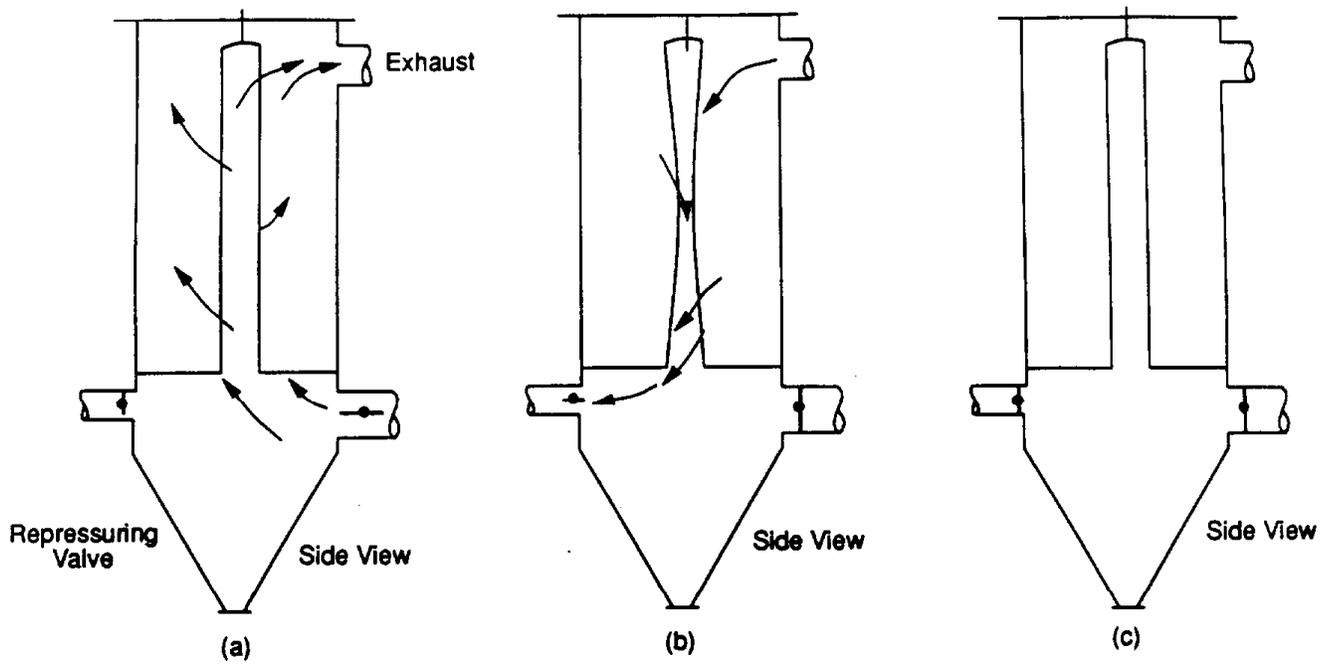


Figure 5-6. Reverse air cleaning; (A) filtering, (B) collapsing, (C) cleaning (21).

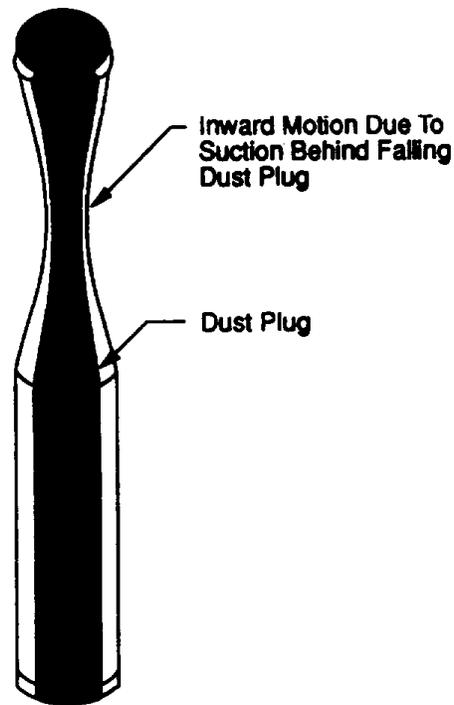


Figure 5-7. Idealization of the falling dust cake upon cleaning (22).

spallation process with the adhesive bond failure probably occurring close to the dirty face of the filter. Aerodynamic drag can be expected to flush out loosened particles.

Another adjunct to dust separation is the flexure produced in the fabric when the flow is reversed. In most systems, sufficient bending of the fabric surface occurs to cause a significant spallation at the dust/fabric interface. This effect is most pronounced for reverse-air cleaned systems because with the low gas-to-cloth ratios normally used, a large fraction of the collected dust appears as a superficial layer on the surface of the fabric.

If dust releases readily from the fabric, a reversal of flow alone may suffice for adequate cleaning. Because of its structural depth, and hence greater dust retentivity, a felted fabric is not usually cleaned by reverse flow. When reverse flow is used as the sole method of cleaning, the rate of flexure is probably the controlling factor with respect to fabric (or fiber) failure. Thus, a gradual inflation or deflation process is unlikely to cause any serious fabric damage. Increased bag tension and reduced reverse flow rates also minimize the degree of flexure as well as preventing a complete flattening of the bag. If the bag is flattened, there is no opportunity for loosened dust to fall to the hopper nor is there a pathway for the reverse flow air. The insertion of retraining rings or a supporting cage eliminates complete bag collapse but introduces a potential problem of fabric chafing. Sewing the rings to the bag minimizes the problem of chafing or attrition.

5.3.3 Pulse-Jet

Pulse-jet cleaning employs high pressure (60-120 psi or 410-830 kPa) compressed air, with or without a venturi, to back-flush the bags vigorously. This cleaning method creates a shock wave that travels down the bag, knocking dust away from the fabric. Normally this method is employed in conjunction with felted filter media and the gas-to-cloth ratio is generally higher than in shake and reverse-air cleaning methods. The duration of cleaning is shorter than for the other two methods; generally, the pulse lasts only a fraction of a second. The baghouse is often not subdivided when pulse-jet cleaning is employed.

The usual pulse-jet configuration has the bag closed at the bottom and open at the top, as shown in Figure 5-8. A metal cage is used inside the bag to keep it from collapsing. In the normal mode of operation, dirty gas enters the hopper and proceeds to the bags. Dust collects on the outside of the bags and cleaned gas exits through the top of the bags and baghouse. Usually, a row of bags is cleaned simultaneously by introducing compressed air briefly at the top of each bag. The shock wave created drives the dust off the outside of the bag and down into the hopper. Continuous discharge of dust from the hopper is often employed. Cleaning parameters are given in Table 5-4. It is noteworthy that this system has no internal moving parts and allows for removal of the bags from the clean side of the house, since the bags are usually connected only at the top.

The pulsed jets of compressed air commonly used to clean non-woven fabrics are relatively inefficient at removing deposited dust. Measurements on a pilot-scale pulse-jet fabric filter using fly ash test dust indicate that typically less than 1 percent of the dust on a bag is removed to the hopper by a cleaning pulse (26).

The following factors are important to the design and/or operation of a pulse-cleaned baghouse (27):

1. The location of the pulse-jet nozzle may aid or detract from the uniformity of bag cleaning.

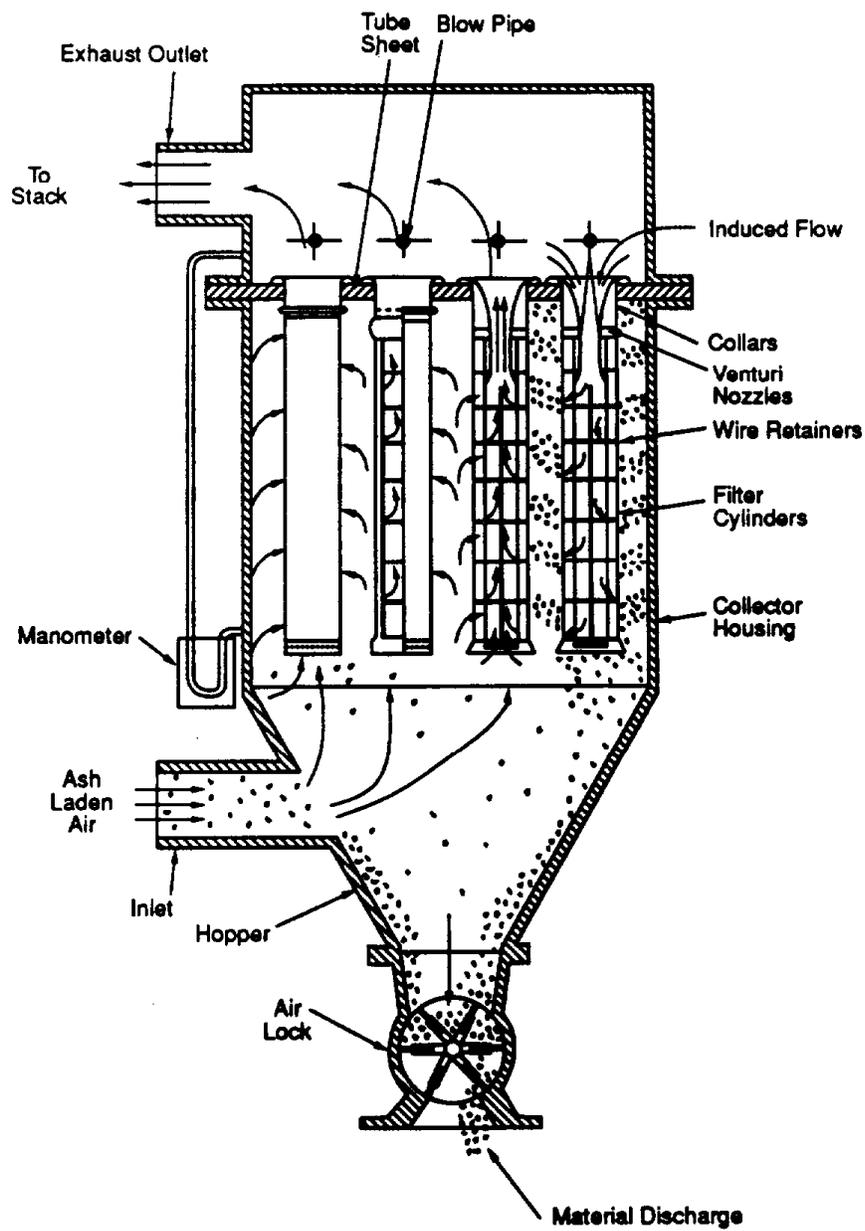


Figure 5-8. Pulse-Air-Jet Type Bag Filter (25).

2. Bag material should be flexible, light weight and inelastic to obtain maximum acceleration for dust removal during the pulse. The fabric should have sufficient weight (i.e., number of fibers per unit area) to present many targets for dust collection. The pore structure should be as uniform as possible.
3. A large housing and hopper volume on the dirty side of the filter bag will minimize the pressure build-up in this region during the pulse, and thus enlarge the magnitude of the pulse differential.
4. The pulse delivered to the bag should begin as abruptly as possible, with sufficient inflating flow to subject the entire bag length to a sudden pressure differential.
5. The back flow of air through the filter that accompanies the pulse assists cleaning in several ways. It flushes from the pore structure agglomerates loosened by the acceleration. It can itself loosen agglomerates if the shock alone were insufficient, although this appears to be a very inefficient use of compressed air. It also accelerates agglomerates that have already left the felt surface, helping to convey them to the hopper.
6. Pulse intensity should be as low as can be tolerated to save on compressed air (and reduce power needs) but sufficiently high to maintain equilibrium in the cleaning process.
7. Pulse duration should ordinarily be as short as possible.

5.3.4 Sonic Horns

Sonic horns are increasingly used to augment shaker-cleaned and reverse-air-cleaned baghouses. The horns are usually powered by compressed air, and acoustic vibration is introduced by a vibrating metal plate that periodically interrupts the air flow. A cast metal horn bell is normally used for acoustic coupling. Typically, one to four horns are installed in the ceiling of a baghouse compartment which contains several hundred bags (28).

Sonic frequencies of 150-550 Hz have been tested; Cushing, Pontius and Carr got the best results with horns that concentrated most of their energy at the lower frequencies. Relative sound pressure levels of 120-140 db inside the baghouse are used.

Probably the most significant effect of sonic cleaning is on the weight of residual dust load on the bags. Menard and Richards (29) found that, before the sonic horns were operated, bag weights ranged from 34-55 lb with an average weight of approximately 46 lb. After extended use of the sonic horns, bag weight ranged from 12.5-25 lb with an average weight of approximately 18 lb. A new bag weighs approximately 9 lb. The sonic air horns had thus reduced the amount of residual cake on the filtering elements by an average of 76 percent.

Cushing, Pontius and Carr (28) concluded that: "Sonic horns are an effective method for enhancing fabric filter performance. Their generally low cost and simple construction make them attractive additions to the available methods for cleaning fabric filter bags at coal-fired utility baghouses. Tests of six commercial sonic horns at the EPRI Fabric Filter Pilot Plant have demonstrated that, under appropriate conditions, reverse-air cleaning with sonic assist can be effective in reducing operating pressure losses. The test results have shown that overall sound pressure levels and the output frequency spectrum are important factors in determining whether a particular sonic horn application will enhance baghouse performance. One penalty encountered

with sonic assist may be higher particulate penetration due to less residual dust cake on the bag surface. It is possible, however, that less frequent applications of horns will result in small pressure losses without a significant increase in emissions."

5.4 SYSTEM CAPABILITIES AND LIMITATIONS

The primary capability of fabric filtration, or baghouses, of importance to emission control systems for hospital waste incinerators is the ability to efficiently collect fine particulate. Although baghouses have demonstrated superior collection efficiency for fine particulate, there are several factors that limit the collection efficiency, and other factors that can limit the life of the fabric. These factors are the subject of this section.

As previously discussed, felted fabrics or woven fabrics made of texturized yarns have higher inherent efficiency than woven fabrics made of smooth yarns. The ability, or lack of ability, of the fabric to provide a substrate on which the collected dust will build a continuous dust cake actually establishes the filtration efficiency, hence any openings in the fabric weave that do not bridge over with dust or any holes resulting from manufacturing (such as sewing holes) and handling of the fabric prior to use can reduce the expected high level of fine particle collection.

Similarly any leakage paths from the collector inlet to the outlet, except through the fabric will obviously reduce the overall collection efficiency. Holes in the tube sheet attachment of the baghouse walls or holes in the attachment of the bags to the tubesheet can provide such leakage paths. Fluorescent powders can be injected into the inlet of a new baghouse to inspect for such leaks. Leaks are detected by inspection for the powder on the clean side of the bag using ultraviolet light.

Baghouses used in hospital waste incinerators will be subjected to corrosion since operation is intentionally carried out near the dew point of the flue gas. Adequate insulation of the baghouse walls, in order to maintain their temperature above the dew point, is necessary to prevent continuous condensation on the walls which would result in an excessive corrosion rate. Insulation should be specified to maintain the baghouse outlet at or above 250°F while the inlet flow is at the nominal flow rate and 300°F. Minimum temperature of the baghouse walls exposed to the flue gases should not be less than 230°F during steady state operation.

Condensation in the baghouse cannot normally be avoided during start-up and shut down. Standard operating procedures must be implemented to minimize the amount of condensation and to minimize the adverse effects of the condensation that does occur. Basically heat up should be as rapid as possible such that any condensation formed will be evaporated as quickly as possible. Prior to shut-down all combustion gases must be purged from the baghouse using fresh air to minimize, or eliminate, condensation of acidic components of the flue gases as the baghouse cools down.

The baghouse must be protected from a special type of corrosion known as stress cracking. This special type of corrosion results in cracks and/or failures along the metal grain boundaries when the metal is highly stressed and when chloride ions are present. Austenitic stainless steels, including all 300 and 400 series stainless steels, are particularly vulnerable to stress cracking. If condensation occurs, chloride ions most probably will be present as a result of HCl from the flue gases or alkaline salts from the acid gas removal process dissolving into the condensate. Either low stressed carbon steel or nickel based alloys have been found to resist the stress cracking corrosion process.

Many design and/or operational factors can result in reduced life of the fabric bags. Pulse jet baghouses should have a bag life of at least two years, while reverse air baghouses frequently provide a bag life of over 5 years. Factors that can reduce bag life include:

1. Temperature surges above the fabric rating, even if short in duration.
2. Poor bag fit
3. Inadequate fabric finish, or local failures of the finish
4. Excessive cleaning frequency or magnitude.

6.0 ELECTROSTATIC PRECIPITATORS (ESP)

6.1 THEORY OF OPERATION

An electrical precipitator may be defined as an apparatus which utilizes electric forces to separate suspended particles from gases. In practice, electrical precipitators are of many types and configurations, but all are derived from the same underlying principles. Separation of suspended particles from a gas by the electrical precipitation process requires three fundamental steps:

1. Electrical charging of suspended particles,
2. Collection of the charged particles in an electric field, and
3. Removal of the precipitated material from the collecting electrodes.

This section is composed largely from a document titled Industrial Electrostatic Precipitation by Harry White (3).

6.1.1 Particle Charging

Particle charging may occur naturally during the formation or life of a particle, for example, by flame ionization, friction, or even exposure to the cosmic radiation which constantly permeates the earth's atmosphere. In fact uncharged or neutral particles are very rare. However, these natural charges on particles are too small for effective precipitation.

Of the several possible artificial methods for charging particles, the high-voltage direct-current corona is by far the most effective and is universally used in electrical precipitation. The corona is usually established between a fine wire, or active electrode, maintained at high voltage and a smooth cylindrical or plate electrode at ground potential. Under these conditions, the corona is manifested by a highly active visible glow in the strong electric-field region near the wire's surface. Large numbers of both positive and negative ions are formed in this active glow zone. The positive ions are attracted to the wire, and the negative ions are attracted to the ground pipe or plate. Although both positive and negative ions are formed in equal numbers in the corona-glow region near the wire, over 99 percent of the gas space between the wire and ground electrode contains only negative ions.

Particles in passing through the corona field are subjected to intense bombardment by the negative ions and become highly charged in 0.01 seconds or less.

6.1.2 Particle Collection

Particle collection is effected by subjecting the charged particles to a high voltage direct-current field maintained between suitable electrodes. The separation force acting on a particle is given by Coulomb's law which states that the force is proportional to the product of the particle charge and the intensity of the collecting field. Other minor electric forces, for example electrostatic image and dipole forces, are sometimes invoked in discussing the electrical precipitation process, but these forces are small compared with the Coulomb force. The magnitude of the Coulomb force may be best illustrated by numerical examples. In a typical precipitator, the Coulomb force may be about 3000 g (g = acceleration of gravity) for a one-micron particle and about 300 g for a 10 μ particle.

The particles are accelerated toward the collecting electrode by the Coulomb force, but the motion is resisted by inertial and viscous forces. For particles in the size range of interest, it is easily demonstrated that the inertial forces are negligible and that the viscous or retarding force of the gas is governed at least approximately by Stokes' law. Consequently a particle in the precipitation field attains velocities determined by the equilibrium between the Coulomb and Stokes

forces. This velocity is conveniently referred to as the *migration velocity* of the particle and it increases with particle diameter, particle charge, and collecting-field intensity. For typical precipitator conditions, the migration velocities of suspended particles usually range from about 0.1 ft/sec for very fine particles of one-half micron diameter, up to three or four feet per second for 20 μ or 30 μ particles.

Particle-collection theory is complex for the most general case but is manageable under certain limiting assumptions. Assuming completely turbulent gas flow, efficiency may be calculated by probability theory. The mathematics of this process leads to an exponential type formula for the probability of capturing a particle. Extended to the case of a large number of particles which do not interact appreciably, the formula expresses the efficiency of the precipitator. An important deduction is that 100 percent collection efficiency is possible only as an asymptotic limit.

6.1.3 Rapping

The third fundamental phase of electrical precipitation is removal of material collected on the ground or passive electrodes to an external receptacle. This is fundamental because the collected particles may be lost by entrainment in the gas stream while still inside the precipitator.

Particle removal is initiated by rapping, striking the collecting plate with a hammer. Acceleration of the metal collecting plate causes the collected duct cake to shear off, thus being free to fall into a collecting hopper below. The dust is then removed from the hopper and transplanted to a central dust storage bin.

In general, rappers may be classified in two categories, 1. the impulse type which produces an impact or hammer blow, and 2. the vibrator type which produces a continuous vibration of some duration. The impact type appears to be most useful for collecting electrode rapping, while the vibration type is useful for corona-electrode cleaning.

6.1.4 Reentrainment

Reentrainment may occur by direct scouring of the collecting electrode surfaces by the gas stream, by redispersion of collected particles during a rapping of the electrodes, and by sweepage of collected dust from hoppers. Vulnerability to reentrainment is in part determined by the fundamental characteristics of the particles themselves. For example, metallurgical fumes, such as lead or zinc oxide, are comprised of very fine irregular-shaped particles one micron or less in size, and form on the collecting surfaces in loosely-packed, low bulk-density layers. These layers are fairly cohesive, and under the influence of the gas stream and rapping, they tend to break up in to fluffy agglomerates which settle slowly in the gas. In contrast, coarse dust particles of say 50 μ or greater generally lack cohesiveness and do not form agglomerates. These particles will tend to fall into the hoppers if they have high density but will float lazily in the gas if they have low density. Finer dust particles of a few microns size usually agglomerate well, yet they have sufficient bulk density to fall rapidly into the hoppers.

Particle reentrainment is also closely related to gas-flow patterns and characteristics. Unbalanced, highly turbulent gas flow, characterized by high gas velocity zones, swirls, jets, and eddies is highly potent in scouring and sweeping collected dust from the collecting plates and from the hoppers, and it results in great losses in collection efficiency. It is not uncommon, for example, to raise precipitator efficiency from 85 percent under pore gas flow conditions to 95 percent to 98 percent by correction of the gas flow.

6.1.5 Voltage and Corona Current

Corona-electrode design is determined chiefly by application conditions such as gas temperature, nature and concentration of the dispersoid, and presence of corrosive gases or particles. Most precipitators use steel or steel alloy corona wires of about 0.1-in. diameter. Square wires of 1/8 in. to 1/4 in. have advantages in a few applications because of their greater cross section. Lead-covered and Hastalloy wires are used for sulfuric acid mist precipitators. Corona currents usually are in the range of 0.01 ma to 1 ma/ft of discharge wire, with voltages of the order of 30 kv to 100 kv for Cottrell, or single-stage, precipitators, and 10 kv to 15 kv for two-stage precipitators.

6.1.6 Electrical Energizing and Control

The equipment for supplying electrical energy or corona power to precipitators is very important. Since a precipitator functions by electric forces acting on the particles, precipitator performance can be no better than the electrical energization.

Contrary to initial expectation, best precipitator performance is obtained not with steady or pure direct current, but rather with intermittent or pulsating waveforms largely because of the higher voltages and currents that can be maintained with intermittent voltages under the sparking conditions which commonly exist in precipitators. For these reasons most precipitators are powered by high-voltage unfiltered rectifier sets, although pulse methods somewhat similar to those used in high-power radar equipment are used with advantage.

6.1.7 Fields and Sections

The corona electrodes in larger precipitators usually are subdivided into multiple groups, or sections, frequently referred to as *high-tension bus sections*. These sections are individually powered by separate rectifier sets to reduce the bad effects of precipitator sparking and equipment outages, and to provide better matching of corona voltages and currents to the electrical characteristics of the gas and dust. Ideally, best precipitator performance would be obtained by individually energizing each corona wire from a separate rectifier set. In practice, the goal is an economic balance among degree of sectionalization, precipitator size, and cost. The effect of high-tension sectionalization on precipitator efficiency is typically very large. For example, a fly-ash precipitator designed for a gas flow of 100,000 cfm with just one section typically might produce a collection efficiency of only 60 percent, but the same precipitator with two corona sections might have an efficiency of 90 percent and with four sections it might be 99 percent efficient. The much greater efficiency of the four-section arrangement basically results from the substantially higher precipitator voltage possible compared with the single large section.

6.1.8 Collection Efficiency

Efficiency is a measure of how well the precipitator separates the dust from the incinerator exhaust gas. For an operating precipitator the model produced for the EPA by Faulkner and Dubard (EPA-600/7-84-069b) of SRI can be used to predict efficiency. The SRI model is based on the following equation derived by White (3) in 1963:

$$E = 1 - \exp[-A_p W_p / Q_G] \quad 6-1$$

where: E = Collection Efficiency
 A_p = ESP plate area
 W_p = Particle drift velocity
 Q_G = Gas flow rate

Thus, collection efficiency increases with increasing plate area and drift velocity, and decreases with increasing gas flow rate. Particle drift velocity is the speed of particles in the direction of the collection plate and is given by the following equation.

$$W_p = \frac{q_p E_p}{6\pi d_p \mu} \quad 6-2$$

where: q_p = Particle charge
 E_p = Electric field Intensity
 d_p = Particle radius
 μ = Gas viscosity

Because electrical conditions change along the length of a precipitator, the SRI model divides the precipitator into small increments, and assumes that electrical properties are constant in each section. The model also makes corrections for gas sneakage and particle rapping reentrainment and can be used for wet ESPs.

Overall precipitator performance depends on the device length, plate area, applied voltage and gas flow rate. Figure 6-1 shows the impact of plate area and particle size on collection efficiency. The efficiency decreases as particle size decreases down to 0.5 microns. As the particle diameter decreases below 0.5 microns the efficiency begins to increase. Efficiency increases for very small particles because of Brownian diffusion increases the mobility of ultrafine particles.

Experience with municipal and hazardous waste incinerators shows that precipitator performance is typically over 99% (EPA/530-SW-87-021b). The specific performance of a precipitator will depend on its design and operation, and the properties of the incinerator exhaust gas.

6.2 TYPES OF EQUIPMENT

Type and size of precipitator are determined by the basic properties of the gas and particles handled, by the gas flow, and by the required collection efficiency. Generally pipe-type precipitators, as shown in Figure 6-2, are used for small gas flows, for collection of mists and fogs, and frequently for applications requiring water-flushed electrodes. Duct-type precipitators (Figure 6-3) are used for larger gas flows.

Collecting-electrode size for pipes usually is from about six inches diameter by six feet long, for small units, up to 12 inches in diameter by 15 feet long for large units. In duct precipitators, the collecting plates vary in size from two or three feet wide by six feet high up to six or eight feet wide by 20 feet to 25 feet high. Fundamental requirements for collecting-plate design include (1) good corona and high sparking-voltage characteristics (2) shielded or shadow zones for particle collection to keep reentrainment losses at a minimum, (3) good rapping characteristics, and (4) high mechanical strength coupled with light weight.

6.2.1 One and Two Stage

The collecting field of the precipitator may be either a continuation of the corona in which case the precipitator is designated as a single-stage type or it may be a purely electrostatic field between smooth, nondischarging electrodes which is the so-called two-stage arrangement, illustrated in Figure 6-4. The general method of using the corona discharge in a single-stage

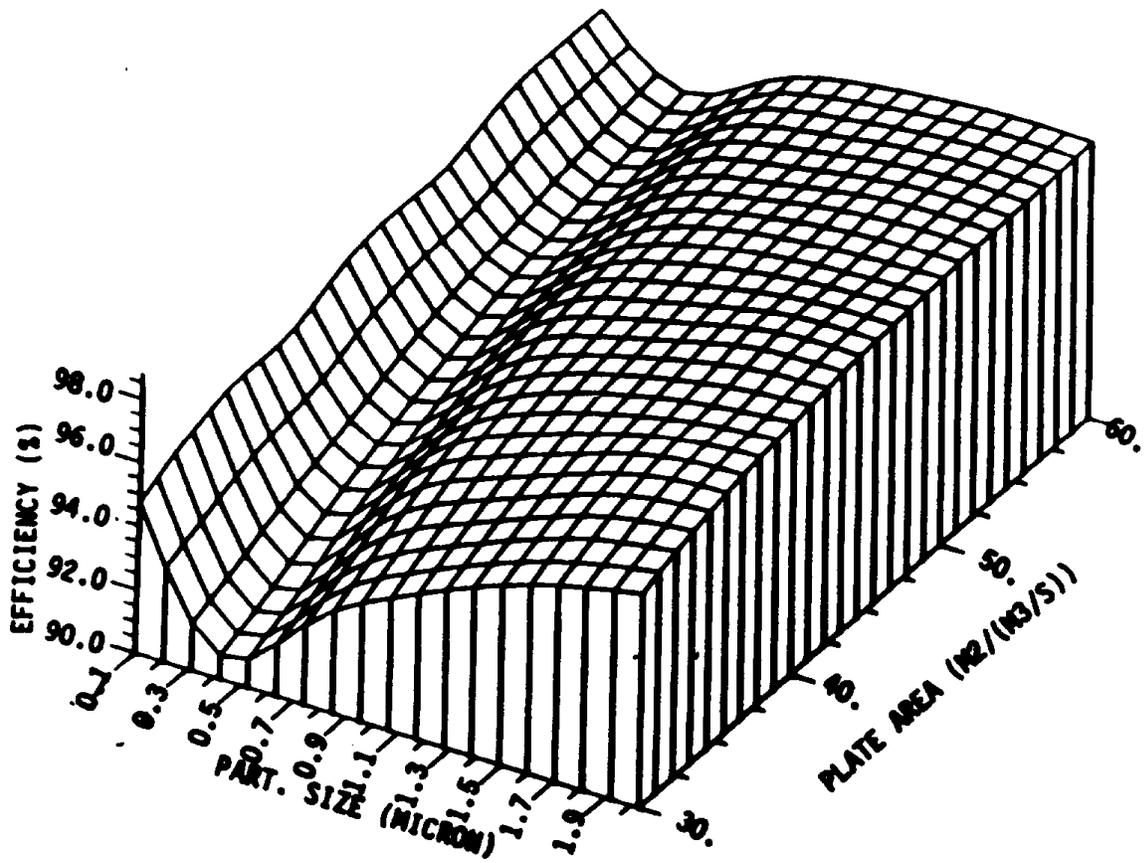


Figure 6-1. The effects of particle size and specific collection area on ESP efficiency.

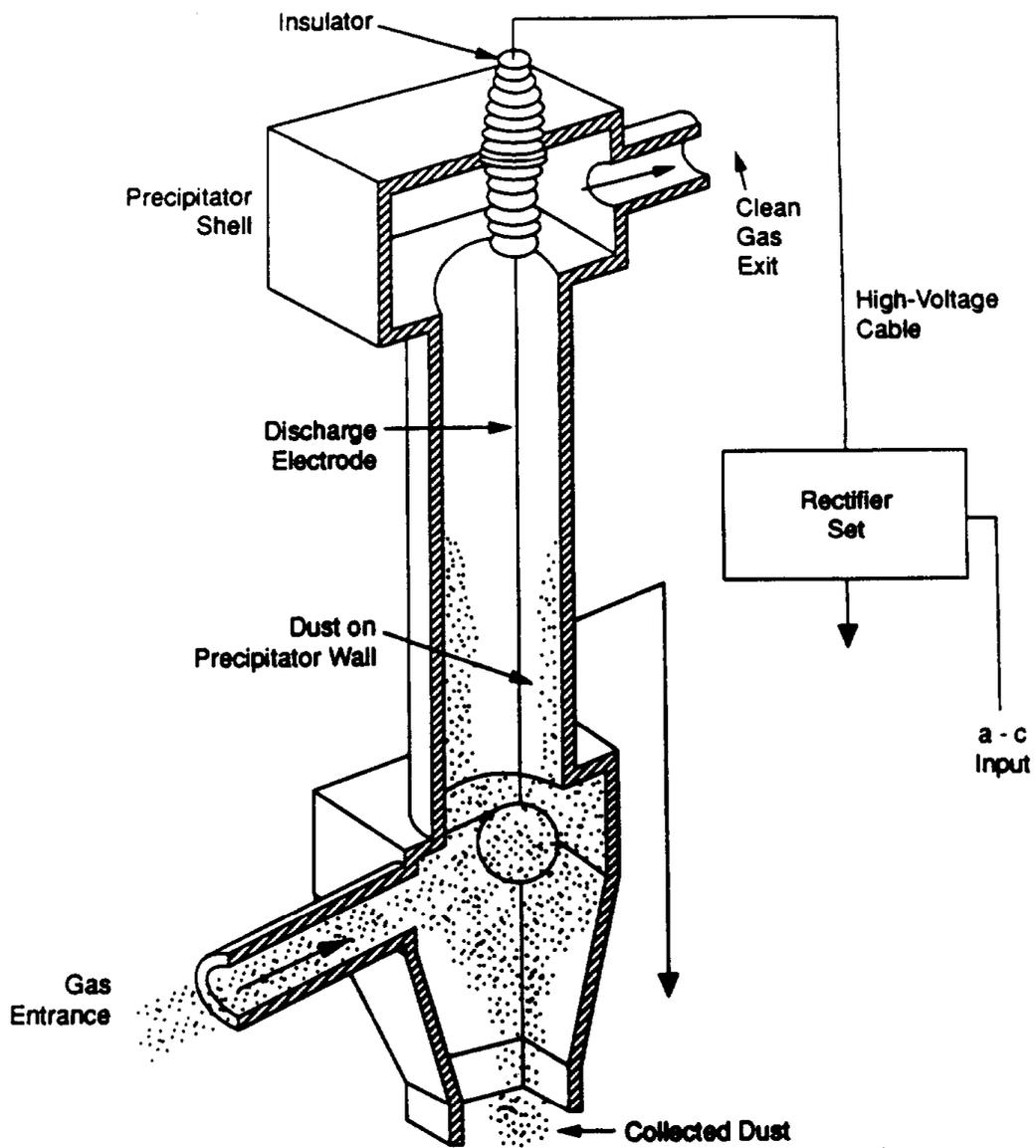


Figure 6-2. General method for producing and utilizing corona in a single-stage precipitator.

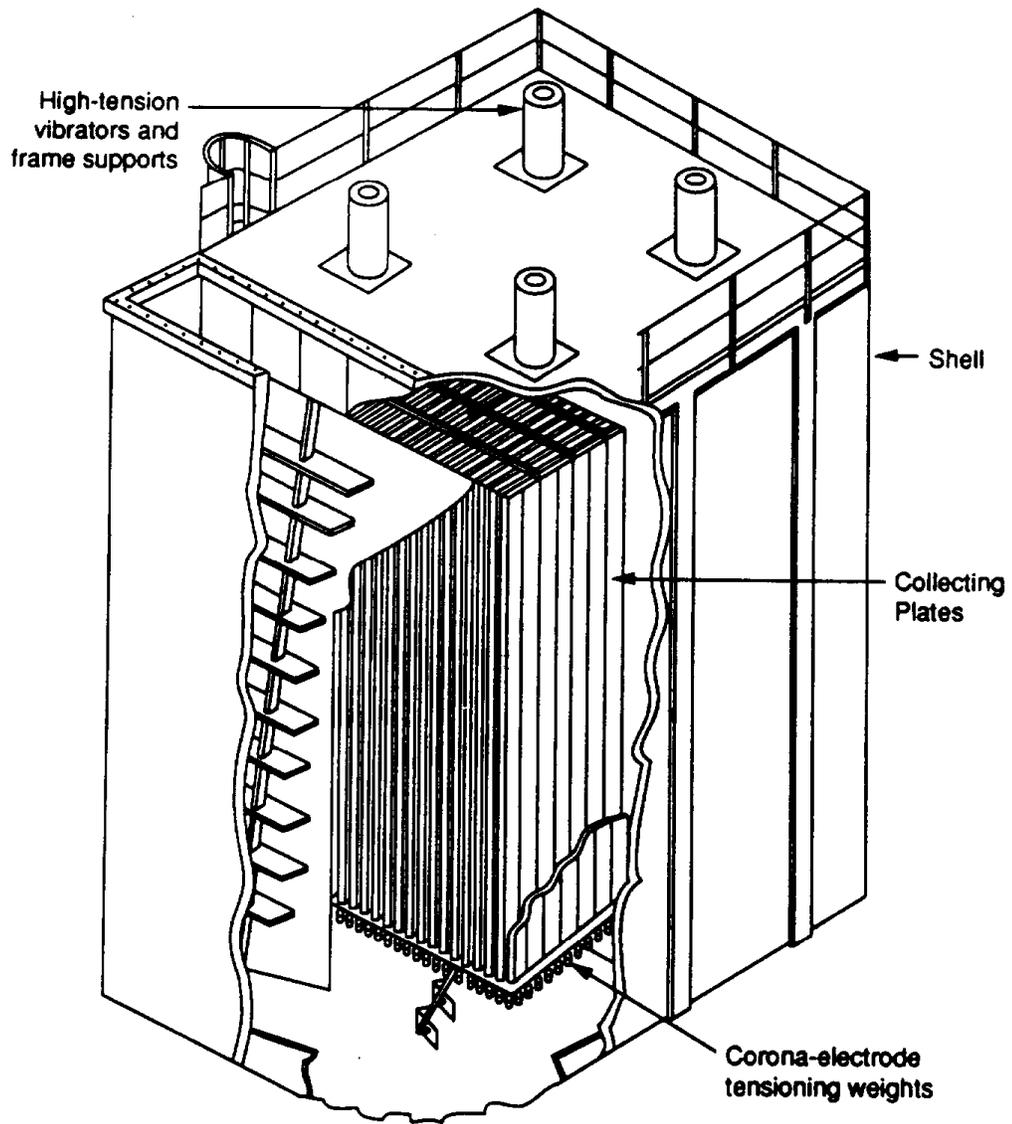


Figure 6-3. Design arrangement for duct type precipitator used for collection of fly ash (31).

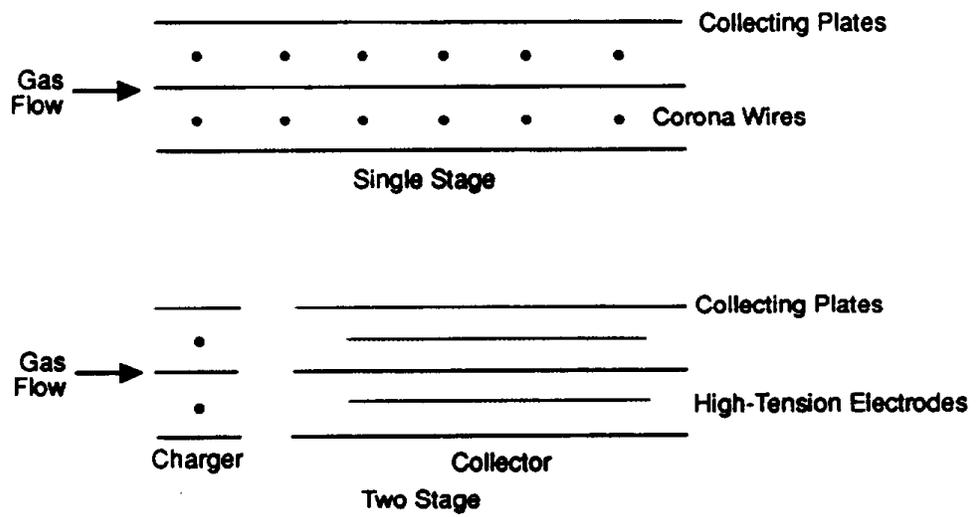


Figure 6-4. Schematic diagrams of single-stage and two-stage precipitation electrode.

precipitator is illustrated in Figures 6-2 and 6-3. Here the corona is emitted from the fine wire which is maintained at negative potential by a high-voltage rectifier set.

Particle collection occurs in the same electric field that established the corona.

6.2.2 Wet Precipitators

Wet precipitators are used to collect dry particulate, mists or particles entrained in the water droplets.

Liquid particles are easy to cope with because they drain from the collecting electrodes and out of the precipitator by gravity. With liquid particles, reentrainment does not occur except at very high gas velocities of 30 ft/sec or more, which is several times the precipitation gas velocities ordinarily used with dry collection, which comprises the large majority of cases. Particles may be quite easily reentrained and this presents one of the major technical problems of precipitation.

In some wet precipitators the collecting plates are continually washed with liquid to flush away the collected dry particulate.

6.2.3 Instrumentation and Automatic Voltage Controls

Instrumentation for precipitators includes electrical readings for rectifier equipment, high-voltage, current, and spark-rate measurements for the corona electrodes of the precipitator, rapper intensity, hopper dust-level indication, and metering of gas-process variables, such as total gas flow and temperature. In some cases, photoelectric devices are installed in the precipitator-outlet flue, or stack, to indicate the optical density or cleanliness of the discharge gas.

Direct-reading spark-rate meters have proved invaluable in establishing and maintaining optimum corona power input levels for precipitators.

Precipitator control is closely associated with instrumentation. Manual control to obtain best performance usually is impossible without adequate instrumentation to monitor the operating variables. Virtually all processes are subject to both slow and rapid changes in conditions. Gas flow often fluctuates widely with process conditions, and in some cases, in an intermittent and random manner.

These characteristic and unavoidable process variations place a heavy burden on manual methods for controlling precipitator operation. As a result, manually controlled precipitators commonly are operated at comfortable compromise levels where stability and continuity of operation can be maintained over long periods without attention, but usually at a substantial loss of precipitator efficiency. These conditions have led to the development of complete automatic control systems for rectifier equipment to provide maximum precipitator performance at all times, independent of operations.

The magnetic impulse rapper has found wide acceptance as a practical means of providing closely controlled continuous rapping to eliminate the highly objectionable rapping puffs characteristic of intermittent rapping systems. This rapper system provides precisely controlled impact blows over a wide intensity range and, at a normal rapping frequency of one two raps per minute per electrode, is essentially continuous. Vibrator-type rappers usually are powered by compressed air or by electricity. Vibration frequencies commonly are in the range of 50 to 100 cycles per second. Vibrators usually are operated intermittently.

6.3

SYSTEM CAPABILITIES AND LIMITATIONS

Although ESPs are widely used for dust collection, some of the limitations of this type of particle collection equipment need to be addressed prior to selection of an ESP for a hospital waste incinerator. These limitations include:

1. **Fine Particle Collection Efficiency** - Can the precipitator provide adequate collection of submicron sized particulate. Many factors including flow distribution, turbulence effects, and reentrainment need to be considered. In general, fabric filtration has been demonstrated to be simpler than an ESP in both design and operation and to provide superior fine particulate collection.
2. **Personnel Hazards** - An ESP involves the proper operational use of lethal high voltage equipment. This can represent unacceptable personnel hazards for the hospital incinerator operation.

7.0 WET SCRUBBERS

7.1 THEORY OF OPERATION

Most wet scrubbers consist of two basic pieces of equipment that are designed to accomplish two different tasks. The two tasks are particulate collection and acid gas removal. In what probably is the most common mechanization of the wet scrubber, the task of particulate collection is performed in a device called a venturi scrubber while the acid gas removal is accomplished in a packed bed scrubber tower. Although these two tasks are interrelated, scrubbers can be designed to do either task separately.

The conventional venturi scrubber consists of a converging section, a throat section, and an expansion section. Typically an alkaline recirculating liquid is injected into the throat section to facilitate the removal of particulates and acid gases. The basic principle of venturi operation is to accelerate the gas and liquid to a high velocity in the throat section, causing atomization of the liquid. Finely divided liquid droplets provide a large surface area for the collection of fine particulates and acid gases in the gas stream. Particulate and acid gas removal efficiency in a venturi is primarily related to the amount of liquid atomization that is achieved which in turn is proportional to the pressure drop across the device.

The venturi scrubber is often followed by a packed bed scrubber to remove additional acid gases from the gas stream. Alkaline chemicals such as NaOH are typically added to the recirculating liquids in the venturi and packed bed to neutralize acid gases that are scrubbed from the combustion gases.

This section was composed largely from a document titled Evaluation of Liquid Waste Incinerator Air Pollution Control System Alternatives by Focus Environmental (32). Additional information including design equations, important parameters, and operating curves for wet scrubbers is given in Volume I Section 5 of this report.

7.2 TYPES OF EQUIPMENT

Venturi scrubbers offer high removal efficiencies of both particulate matter and soluble acid gases at a moderate capital investment. However, operating costs can be high because of high ID fan power requirements. Very high pressure drops between 60 inches to 100 inches of water column are necessary to achieve over 95 percent removal of fine particulates. Few conventional venturi scrubber/packed bed scrubber systems have been installed in the past five years. This technology has been largely replaced by other types of wet scrubbing systems that have equivalent or better particulate and acid gas removal performance characteristics and use significantly less energy. Three examples of such technology are described in the next paragraphs.

More data is available from scrubber installations on hazardous waste incinerators. Therefore, these are discussed. It will be noted that hazardous waste incinerators are similar in size and similar in emission control requirements to hospital waste incinerators.

7.2.1 Calvert Collision Scrubber

The Calvert Collision Scrubber (CCS) is a gas cleaning device designed, fabricated, and marketed by Calvert Environmental of San Diego, California. Fourteen Calvert systems have been installed on hazardous waste incineration applications.

The CCS is an impact scrubber with mechanical features based on the principles of venturi scrubbing. Gases entering the CCS are split into two streams that are directed to separate venturi throats where scrubbing liquid is injected into the gas stream to atomize the liquid into fine

droplets. The CCS improves upon the venturi principles by providing secondary atomization of the fine droplets. The discharge gas/liquid streams from the two venturi scrubbers are directed toward each other, causing them to collide at a high relative velocity. The head-on collision of the two streams causes the droplets to shear into finer drops, thus improving the scrubbing efficiency of the device. A schematic diagram of the CCS is presented in Figure 7-1.

Calvert integrates the CCS with additional gas conditioning and gas cleaning components into what is called a "Flux Force/Condensation Scrubbing System." The gas conditioning and air pollution control components consist of a quench condenser/absorber collision scrubber, entrainment separator, induced draft fan, and stack. Supplemental equipment includes a cooling tower, heat exchanger or heat pump, and alkali solution preparation and injection systems.

Flux force condensation is based on the principle that when a gas stream is saturated with water and then cooled, a portion of the moisture will condense. The condensation effects enhance the scrubbing system's collection of fine particulates, acid gases and metals. When a saturated gas is cooled below its adiabatic saturation temperature, moisture in the gas condenses and the fine particulate matter in the gas stream serves as condensation nuclei. As moisture condenses on the particles they grow in mass and are then more easily collected by conventional impaction techniques. In addition to particle growth, the condensation process imparts diffusional and thermal forces to the particles, which also enhance collection efficiency. It is the combined "flux" forces of diffusion and thermophoresis, coupled with the condensation effects, that give rise to the "flux force/condensation" name.

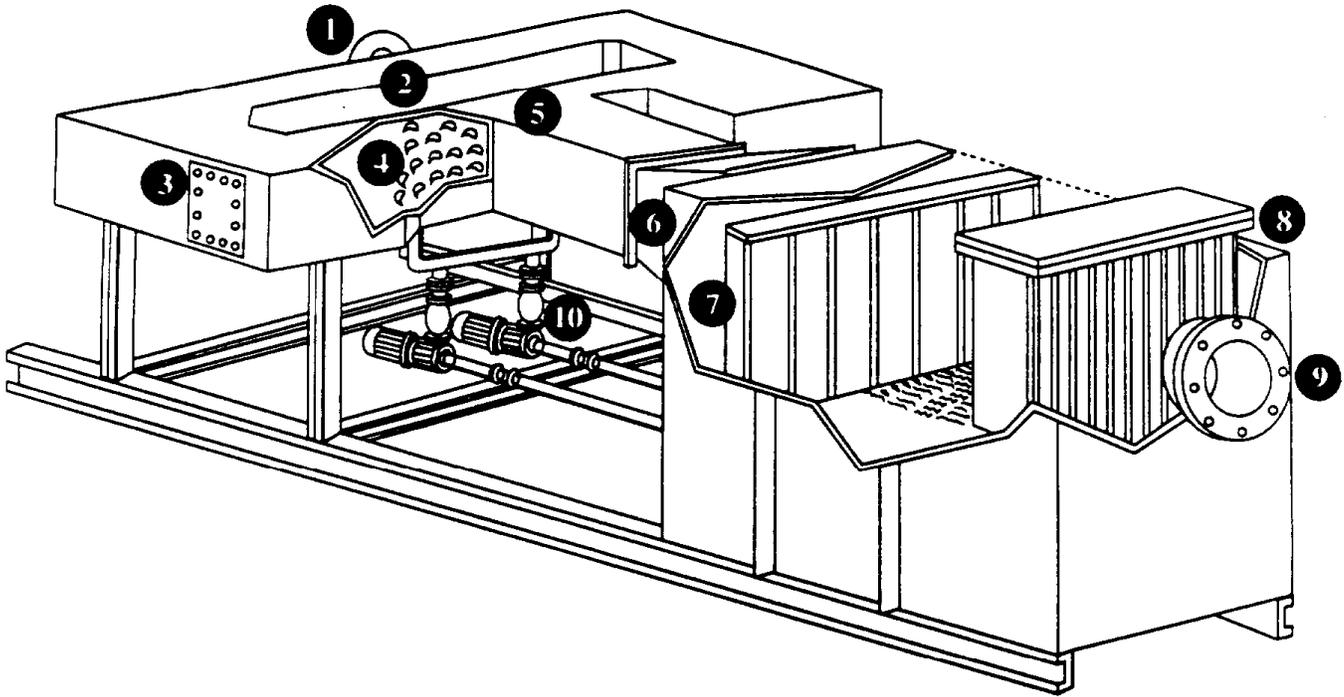
While flux force/condensation techniques can potentially be applied to almost any wet gas cleaning system, Calvert has been a leader in integrating it into the gas cleaning system design. The condensation effects have an additional benefit beyond enhancing scrubber performance in that some degree of steam plume suppression will be achieved by removing a portion of the water vapor from the combustion gas.

In operation, high temperature incinerator combustion gas enters the Calvert system through a quench chamber, where scrubbing solution sprays are used to cool the gas to its adiabatic saturation temperature or lower. Some acid gas and particulate removal occurs in the quench. Excess water is collected in a sump and is neutralized by adding an alkaline solution.

The saturated gas leaves the quench and enters a packed bed condenser/absorber where the gas is subcooled and most of the acid gas is removed. Subcooling of the gas is achieved by irrigating the packing with either fresh, cool water or with recycled scrubbing solution that has been cooled in a cooling tower or heat exchanger. Acid gas removal is accomplished through absorption into the scrubbing solution. The column packing provides a high surface area for gas/liquid contact and high mass transfer needed for acid gas absorption.

After passing through the condenser/absorber, the gases enter the collision scrubber where additional acid gas removal and particulate collection takes place. The collision scrubber can be designed with either a fixed or a variable throat.

The gas/liquid stream exits the collision scrubber and enters an entrainment separator where the water droplets containing the captured particulate matter are removed from the gas by inertial impaction. Typically, a horizontal cross-flow type entrainment separator is used, consisting of a preliminary knock-out section followed by two stages of parallel wave-form baffle blades. The cleaned gases are drawn through the system by an induced draft fan and discharged through a stack. Combustion gas can be recycled from the ID fan outlet to the Collision Scrubber inlet to maintain a minimum required pressure drop under varying gas flow conditions.



- 1 Gas Inlet**
Dust, fume and acid gases enter through the flanged inlet.

2 Throat Inlet
The gas is split into two equal flows.

3 Access Doors
Available for throat inspection.

4 Throats
Liquid is injected into the gas (adjustable throats available).

5 Collision Zone
Collision Zone removes submicron particulate and acid gases from the gas stream.
- 6 Energy Recovery Diffuser**
Energy recovery diffuser expands the gas and liquid stream.

7 Primary Droplet Eliminator
Primary Droplet Eliminator removes most of the water.

8 High Efficiency Waveforms
Fine droplet eliminators polish the gas.

9 Gas Outlet
The clean gas exits through flanged connection.

10 Pump
Pump (with optional stand-by) returns water to the throat via distribution headers.

Figure 7-1. Calvert collision scrubber schematic.

Table 7-1 lists the measured particulate and acid gas removal performance for 12 Calvert installations on hazardous waste incinerators.

7.2.2 Ceilcote Ionizing Wet Scrubber

The Ionizing Wet Scrubber (IWS) is a gas cleaning device designed, fabricated, and marketed by the Ceilcote Company of Berea, Ohio. The IWS technology has been used on 26 hazardous waste incinerator applications.

The IWS is specifically designed to remove submicron particulates from combustion gases by using a technology that requires significantly less energy than a venturi type scrubber. The IWS combines the principles of electrostatic particle charging, image force attraction, inertial impaction, and gas absorption to simultaneously collect submicron solid particles, liquid particles, and acid gases.

The IWS consists of two sections: a high voltage ionization section and a tellerette packed scrubber section. The gas stream passes through the ionization section where the particulate matter is electrostatically charged. The charged particles then enter the packed bed section where particles are removed by attraction to neutral surfaces. A water or caustic recirculating stream continuously washes the packed bed section to remove collected particulates and to absorb acid gases from the gas stream. Because the IWS is a fractional removal device, particulate removal efficiency is increased by employing multiple units. Typically, two or more units are installed in series to achieve high particulate removal efficiencies. A schematic diagram of a two-stage IWS system is presented in Figure 7-2.

In operation, high temperature incinerator combustion gas enters the IWS system through a quench chamber where scrubbing solution sprays are used to cool and saturate the combustion gas. Some acid gas and particulate removal occurs in the quench. Excess water collects in a cup and can be neutralized by adding an alkaline solution.

The cooled, saturated gas exits the quench chamber and enters a packed bed prescrubber where additional acid gases are removed and some particle conditioning is accomplished through wetting and agglomeration. The gases then pass into the ionizing wet scrubber where particulate matter and most of the remaining acid gases are removed. An induced draft fan draws the combustion gas through the scrubbing system and discharges it through a stack.

The major advantage of the IWS is that it operates at a lower overall system pressure drop. It therefore requires less ID fan horsepower and uses less electrical energy than competing technologies. The IWS is a fractional collector and collection efficiency can be increased by adding additional IWS stages.

It will be noted that although the IWS does provide particulate charging by a corona discharge as discussed in Section 6 on electrostatic precipitators, it does not provide the intense electric field for collection. The IWS uses instead the relatively weaker electrostatic image forces for collection. The relatively short collection paths (or large collection plate area) tend to offset this disadvantage making reasonable collection efficiency possible.

Table 7-2 lists the measured particulate and acid gas removal performance for seven installations of the Ceilcote IWS on hazardous waste incinerators.

7.2.3 Hydro-Sonic Systems Scrubbers

Hydro-Sonic scrubbers (HSS) are marketed by the John Zink Company of Tulsa, Oklahoma under a license from Hydro-Sonic Systems. Hydro-Sonic scrubbers have been used

TABLE 7-1. CALVERT PERFORMANCE DATA (32)

Owner/ Location/ Application	Ref. Scale	APC Configuration	Run No.	Particulate (gr/dscf)		HCI (lbs/hr)		Pres. Drop (in. wc)	Stack Temp. (F)	Stack Flow (acfm)
				Quench Inlet	Stack Outlet	Quench Inlet	Stack Outlet			
Uniroyal/ Baton Rouge, LA/ Liquid hazardous waste	(33)	Quench		0.025						
	(34)	Condenser/absorber Collision scrubber Entrainment separator						> 99.99		
Rollins/ Bridgeport, NJ/ Commercial hazardous and PCB wastes	(35)	Quench		.02-.03		4066	16.5	99.59	122	
	(34)	Condenser/absorber Collision scrubber Entrainment separator								40
Rollins/ Deer Park, TX Commercial hazardous and PCB wastes	(34)	Quench		0.015				> 99.90	40	
		Condenser/absorber Collision scrubber Entrainment separator								
Rollins/ Deer Park, TX Commercial hazardous and PCB wastes	(34)	Quench		0.015				> 99.90	45	
		Condenser/absorber Collision scrubber Entrainment separator								
Pfizer/ Groton, CT/ Pharmaceutical production wastes	(34)	Quench		0.04				> 99.90	20	
		Condenser/absorber Collision scrubber Entrainment separator								

TABLE 7-1. CALVERT PERFORMANCE DATA (CONTINUED)

Owner/ Location/ Application	Ref.	Scale	APC Configuration	Run No.	Particulate (gr/dscf)		HCI (lbs/hr)		Prea. Drop (in. wc)	Stack Temp. (F)	Stack Flow (acfm)	Stack Flow (acfm)	
					Quench Inlet	Stack Outlet	Quench Inlet	Stack Outlet					Stack Effic. (%)
American Cyanamid/ Hannibal, MO/ Aqueous herbicide wastes	(34)	Full	Quench Condenser/absorber Collision scrubber Entrainment separator		0.04				35				> 99.90
Eli Lilly/ Huyaguet, PR/ Pharmaceutical production wastes	(34)	Full	Quench Condenser/absorber Collision scrubber Entrainment separator		0.04				35				> 99.90
Westinghouse Haz Tech/ LaSalle, IL/ Site remediation wastes	(34)	Full	Collision scrubber		0.01				35				> 99.90
DuPont/ Sabine River, TX/ Chemical production wastes	(34)	Full	Collision scrubber		0.04				35				> 99.90
CE Raymond/ Tijuana, Mexico/	(34)	Full	Collision scrubber		0.03				45				> 99.90
Chem-Security/ Alberta, Canada/ Commercial hazardous and PCB waste	(34)	Full	Collision scrubber		0.02				45				> 99.90
Am Cy/ Hannibal/MO/ Aqueous herbicide wastes	(34)	Full	Collision scrubber		0.04				35				

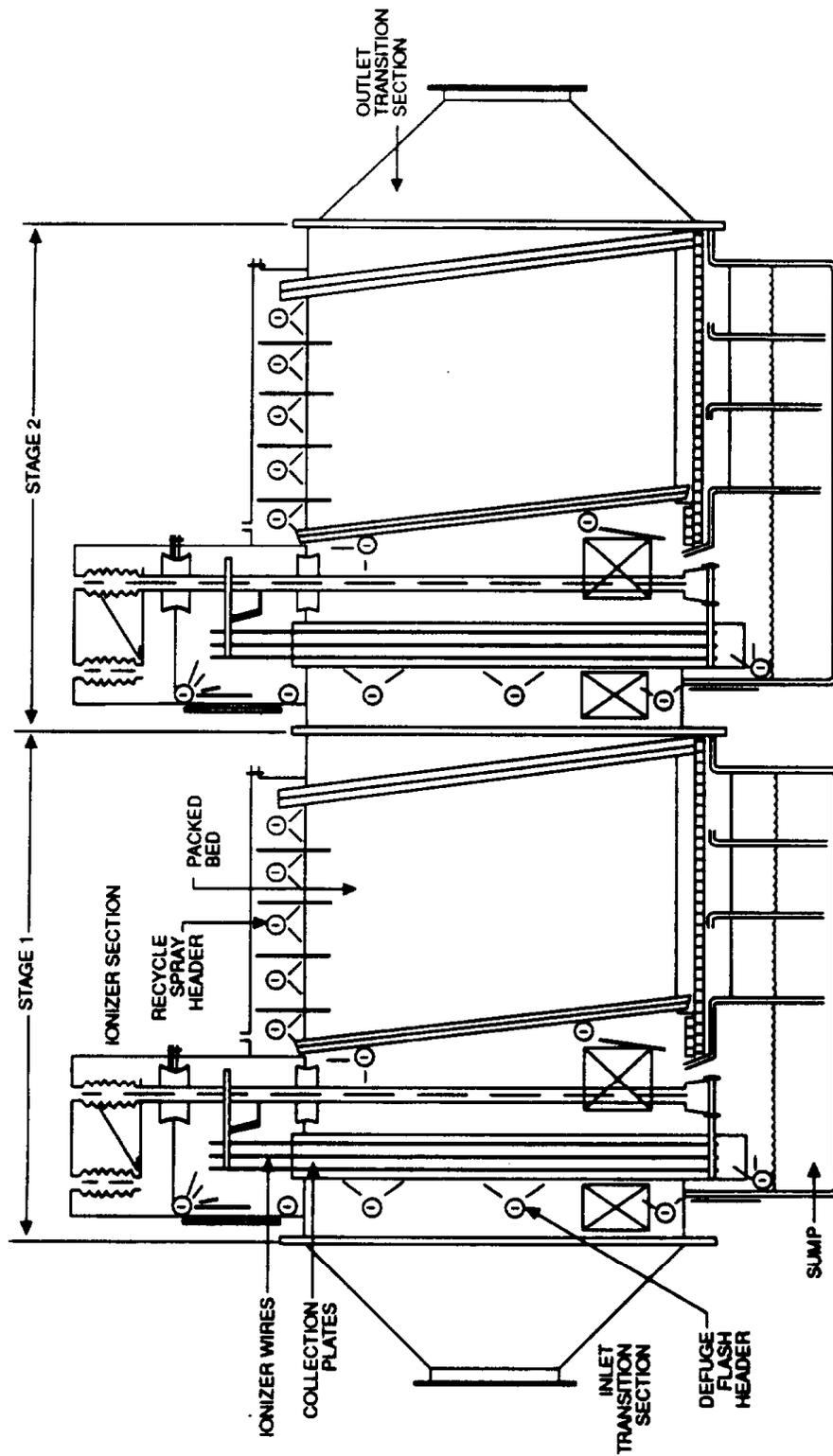


Figure 7-2. Ceilcote ionizing wet scrubber schematic (32).

TABLE 7-2. CEILCOTE PERFORMANCE DATA (32)

Owner/ Location/ Application	Ref. Scale	APC Configuration	Run No.	Particulate (gr/dscf)		HCI (lbs/hr)		Pres. Drop (in. wc)	Stack Temp. (F)	Stack Flow (acfm)	Stack Flow (acfm)	
				Quench Inlet	Stack Outlet	Quench Inlet	Stack Outlet					
Chemical Security/ Alberta, Canada/ Commercial hazardous wastes	(36)	Full Quench Venturi Prescrubber Condenser 2 stage IWS	1			304 <	0.0400	>	99.987	115	9,524	8,093
			2		0.0142	226 <	0.0200	>	99.990	115	9,278	7,820
			3			189 <	0.0200	>	99.989	124	9,584	7,710
			4		0.0067	455 <	0.0100	>	99.998	120	6,412	5,258
			5		0.0178	461 <	0.0100	>	99.998	136	10,850	8,201
			6		0.0044	478	0.0100	>	99.998	118	11,175	9,295
			7		0.0013	406	0.0100	>	99.998	124	10,543	8,602
			8		0.0009					111	3,552	3,037
			9		0.0009					109	3,441	3,001
			10		0.0003					109	3,388	2,950
			11		0.0028					108	5,336	4,641
			12		0.0054					100	5,396	4,813
			13		0.0066					102	5,770	5,124
			14		0.0038					88	6,506	6,101
			15		0.0040					86	6,325	5,959
			16		0.0041					86	6,316	5,950
PPG/ Lake Charles, LA/ Chemical production wastes	(37)	Full Cyclone Quench Venturi scrubber 2 stage IWS	1-1		0.1134							
			1-2		0.2053							
			1-3		0.1483							
			2-1		0.0086							
			2-2		0.0068							
			2-3		0.0173							
			3-1		0.0572							
			3-2		0.0433							
			3-3		0.0813							
APTUS/ Coffeyville, KS/ Commercial PCB wastes	(38)	Full Spray dryer Baghouse Quench 2 stage packed bed 2 stage IWS	1-1	0.0087	0.0054	37.9						
			1-2	0.0477	0.0075	84.3						
			1-3									
			2-1									
			2-2									
2-3												

TABLE 7-2. CEILCOTE PERFORMANCE DATA (CONTINUED)

Owner/ Location/ Application	Ref. Scale	APC Configuration	Run No.	Particulate (gr/dscf)		HCl (lbs/hr)		Pres. Drop (in. wc)	Stack Temp. (F)	Stack Flow (acfm)	Stack Flow (acfm)	
				Quench Inlet	Stack Outlet	Quench Inlet	Stack Outlet					Stack Effic. (%)
Confidential Hazardous waste Incinerator	(36) Pilot	2 stage IWS	1	0.404	0.0450	88.86						
			2	0.235	0.0009	99.62						
			3	0.406	0.0500	87.68						
			4	0.256	0.0137	94.65						
			5	0.486	0.0002	99.96						
			6	0.430	0.0856	80.09						
			7	0.240	0.0080	96.67						
			8	0.120	0.0090	92.50						
			9	0.207	0.0356	82.80						
			10	0.371	0.0020	99.46						
			11	0.228	0.0001	99.96						
			12	0.272	0.0050	98.16						
			13	0.204	0.0264	87.06						
			14	0.340	0.0340	90.00						
			15	0.228	0.0034	98.51						
			16	0.236	0.0002	99.92						
			17	0.267	0.0050	98.13						
			18	0.278	0.0360	86.96						
			19	0.138	0.0001	99.93						
DOE, K25/ Oak Ridge, TN/ Low level mixed wastes	(39) Full	Quench Packed bed 2 stage IWS	1-1	0.0327						99.880	22	
			1-2	0.0244						99.915	23	
			1-3	0.0177						> 99.940	23	
DOE, K25/ Oak Ridge, TN Low level mixed wastes	(36) Full	Quench Packed bed 2 stage IWS	1	0.099	63	0.0190	99.970				8,950	
			2	0.045	113	0.1360	99.880				8,360	
			3	0.004	30	0.0090	99.970					7,940
			4	0.040	140	0.0140	99.990					7,910
			5	0.019	166	0.1660	99.900					7,610
			6	0.030	176	0.1760	99.900					7,740
			7	0.003	17	0.0120	99.930					7,520
DOE, K25/ Oak Ridge, TN Low level mixed wastes	(40) Full	Quench Packed bed 2 stage IWS	1	0.022								
			2	0.029								
			3	0.028								
			4	0.028								
			5	0.019								
			6	0.031								
			7	0.020								
			8	0.033								
			9	0.041								

extensively in the hazardous waste management, steel, nuclear, and pulp and paper industries. Lone Star Steel developed the technology in the late 1960s and has had systems operating in its plants for more than 15 years. Hydro-Sonic scrubbers have been installed to treat combustion gases from a total of 33 hazardous and low level mixed waste incineration systems.

The HSS scrubbers are enhanced venturi type devices for treating gases containing submicron particulates and acid gases. The HSS scrubbers extend the venturi principle into the free jet regime where the high velocity water droplets create a fine mist that promotes collection of fine particulates by the water droplets. These droplets are removed in a demister. The John Zink Company claims the HSS scrubbers can attain higher submicron particulate removal efficiencies at lower pressure drops than conventional venturi scrubbers.

John Zink markets three configurations of the HSS scrubber design: the Steam-Ejector Scrubber, the Tandem Nozzle Scrubber, and the Super-Sub Scrubber. Each configuration is discussed below and schematic diagrams of each are presented in Figure 7-3.

Steam Ejector Scrubber

In the Steam Ejector Scrubber, the energy from moving the gases through the system and cleaning the gases is provided by the flow of steam from a supersonic ejector nozzle. Steam Ejector Scrubbers can be applied where abrasion, corrosion, or vibration preclude the use of an ID fan. These units are also less expensive to purchase and install than fan-driven systems, however, they require large amounts of steam and operating costs can be very high.

The amount of steam added through the eductor is proportional to the mass of gas flowing through the system. Ratios of 0.2 to 0.3 pound of steam per pound of gas are normally used in a Steam Ejector Scrubber. Particulate collection efficiency is a function of the steam-to-gas ratio and can be increased by using a higher ratio of steam to gas. Overall turndown capacity of the system is extremely high because the eductor supplies the energy required to move the gases through the system.

Tandem Nozzle Scrubber

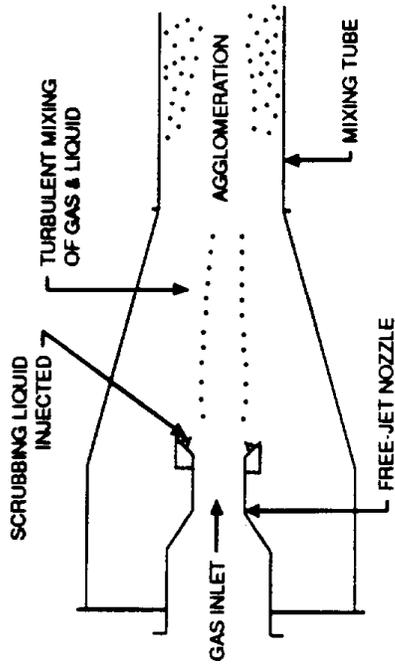
The Tandem Nozzle Scrubber is another version of a venturi-type device for the removal of sub-micron particulates and acid gases. In the Tandem Nozzle Scrubber two subsonic nozzles equipped with water sprays are used in series. An ID fan provides the prime motive force for the movement of gases through the system. The first subsonic section condenses vapors, removes large particulates, and promotes the agglomeration of small particles. The second section removes some of the agglomerated particulates and promotes additional condensation and agglomeration. Large water droplets containing particulates and acid gases are removed in an entrainment separator.

The performance of the Tandem Nozzle Scrubber is pressure-drop-dependent. Since the venturi nozzles have a fixed geometry, a gas recycle stream from the ID fan outlet to the scrubber inlet is used to maintain a constant gas flow through the scrubber. This gas cycle loop increases the turndown capacity of the system.

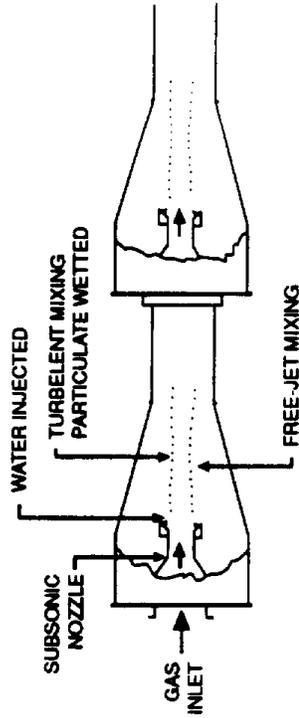
Super-Sub Scrubber

The Super-Sub Scrubber is an enhanced version of the Tandem Nozzle Scrubber. A small volume supersonic steam nozzle is added at the inlet of the first scrubber stage to atomize the scrubbing liquid and increase the overall particulate removal performance of the scrubbing system.

FAN-DRIVEN FREE-JET SCRUBBER



TANDEM NOZZLE FAN DRIVE



SUPERSUB FAN/EJECTOR DRIVE

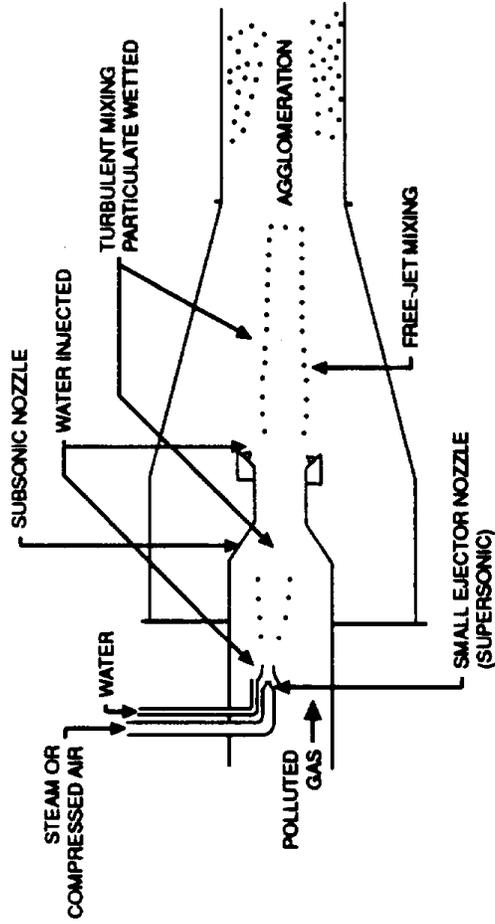


Figure 7-3. Hydro-sonic systems scrubber schematics (32).

The Super-Sub Scrubber typically operates at steam to gas ratios of 0.03 to 0.05 pound of steam per pound of gas. The Super-Sub Scrubber has better particulate and acid gas removal efficiencies than the Tandem Nozzle scrubber at a small increase in capital cost and a moderate increase in operating cost.

Table 7-3 presents measured emission data from seven Hydro-Sonic Scrubber in hazardous waste incinerators.

7.3 SYSTEM CAPABILITIES AND LIMITATIONS

Table 7-4 summarizes the particulate test data for all three advanced wet scrubber designs discussed in Section 7.2. Note that a significant number of the tests for all three designs showed particulate outlet emissions of 0.01 gr/dscf or greater. This is in contrast to the performance expected of a baghouse. In Section 5.1 it is noted that "Well designed and operated baghouses have been shown to be capable of reducing overall particulate emissions to less than 0.01 and in a number of cases as low as 0.001 to 0.005 gr/dscf."

A baghouse can be expected to provide at least an order of magnitude better particulate removal performance than even the best wet scrubbers. Wet scrubbers, however, have low capital costs, and can effectively handle upset conditions and start-up and shut-down modes. In addition, a wet scrubber system at Stanford University has achieved low TCDD equivalent dioxin emissions (less than 10 ng/kg-waste) and high dioxin control.

Data presented in Section 7.2 also shows that wet scrubbers provided at least 99.9 percent removal of HCl. Thus the wet scrubbers provide excellent acid gas removal for hospital waste incinerators provided some other means of removing particulate is included. One alternative system for removing dioxins, particulate, and acid gas simultaneously might be the system used at Hamot Medical Center in Erie PA. This system is described in detail in Section 11 was design by BECO and includes a baghouse for particulate control and a lime injection system and wet scrubber for acid gas control. This system has achieved 99.3% HCl removal efficiency, 0.001 gr/dscf at 7% O₂ particulate emissions, and a 2,3,7,8-TCDD DHS toxic equivalent emission factor of 0.92 ng/kg-waste.

TABLE 7-3. HYDRO-SONIC SYSTEMS PERFORMANCE DATA (32)

Owner/ Location/ Application	Ref. Scale	APC Configuration	Run No.	Particulate (gr/dscf)		HCI (lbs/hr)		Stack Temp. (F)	Stack Flow (acfm)	Stack Flow (acfm)	Pres. Drop (in. wc)			
				Quench Inlet	Stack Outlet	Quench Inlet	Stack Outlet					Effic. (%)	Effic. (%)	
PPG/ St. Charles, LA/ Chemical production waste	(41)	Pilot Quench Tandem Nozzle	1	0.0250							29			
			2	0.0190							40			
			3	0.0062								40		
			4	0.0140								49		
			5	0.0180								25		
			6	0.0140								35		
			7	0.0130								45		
John Zink Tulsa, OK/ Hazardous waste	(42)	Pilot Quench Super-Sub	4	1.160	0.0045	99.61					51.6			
			5	0.872	0.0037	99.58								
			6	3.410	0.0042	99.88								
			7	4.600	0.0068	99.85								
			8	1.700	0.0056	99.67								
			9	1.220	0.0025	99.80								
			10	1.280	0.0120	99.06	9.647	< 0.0100	> 99.90					
			11	1.250	0.0125	99.00	3.362	< 0.0100	> 99.70					
			12	1.330	0.0125	99.06	6.835	< 0.0560	> 99.20					
			Enasco/El Dorado, AR Commercial hazardous waste	(43)	Pilot Quench Steam Hydro	1	0.570	0.0690	87.89	16.63	0.3290	98.00		
						2	1.148	0.1370	88.07	21.98	0.2060	99.10		
						3	0.661	0.0870	86.84	23.22	0.1950	99.20		
4	1.260	0.3270				74.05	22.65	0.2940	98.70					
5	0.977	0.0900				90.79	30.84	0.6840	97.80					
6	1.415	0.0710				94.98	30.85	0.2810	99.10					
7	0.533	0.0650				87.80	21.73	0.3100	98.60					
8	0.683	0.1320				80.67	20.2	0.1170	99.42					
9	0.758	0.1090				85.62	20.13	0.1120	99.40					
Enasco/El Dorado, AR Commercial hazardous waste	(43)	Pilot Quench Tandem Nozzle	10	1.874	0.0790	95.78	29.37	1.3240	95.50					
			11	1.283	0.1260	90.18	22.61	1.3130	94.20					
			12	0.651	0.0870	86.64	19.28	0.3010	98.40					
			13	1.258	0.0930	92.61	39.51	0.0810	99.80					

TABLE 7-3. HYDRO-SONIC SYSTEMS PERFORMANCE DATA (CONTINUED)

Owner/ Location/ Application	Ref.	Scale	APC Configuration	Run No.	Particulate (gr/dscf)			HCl (lb/hr)			Pres. Drop (in. wc)	Stack Temp. (F)	Stack Flow (acfm)	Stack Flow (acfm)
					Quench Inlet	Stack Outlet	Effic. (%)	Quench Inlet	Stack Outlet	Effic. (%)				
Enasco/El Dorado, AR Commercial hazardous waste	(43)	Pilot	Quench Super-Sub	13	0.740	0.0310	95.81	17.88	0.2380	98.70				
				14	1.341	0.0320	97.61	27.45	0.6760	97.50				
				15	0.923	0.0260	97.18	18.55	0.3740	98.00				
				17	1.268	0.0360	97.16	27.83	0.3670	98.70				
18	0.684	0.0400	94.15	30.87	0.4870	98.40								
Ciba Geigy/ St. Gabriel, LA/ Chemical production waste	(44)	Full	Quench Super-Sub	1-1		0.0388		488.7	0.0247	99.995			12,695	
				1-2		0.0404		459.1	0.0387	99.992			12,945	
				1-3		0.0344		496.2	0.0181	> 99.996			13,058	
				2-1		0.0630		491.3	0.0953	99.980			13,476	
				2-2		0.0565		491.2	0.1074	99.980			13,377	
				2-3		0.0660		512.9	< 0.0174	99.997			12,291	
				3-1		0.0337		289.6	< 0.0109	> 99.996			7,710	
3-2		0.0263		300.2	< 0.0113	> 99.996			8,382					
3-3		0.0253		297.1	< 0.0111	> 99.996			8,282					
Texas Eastman/ Longview, TX Chemical production waste	(45)	Full	Quench Tandem Nozzle	3-1		0.0039					36			
				3-2		0.0061					36			
				3-3		0.0081					36			
				5-1				117	< 0.02	> 99.98				
				5-2				155	< 0.02	> 99.99				
				5-3				121	< 0.02	> 99.98				

TABLE 7-4. PARTICULATE EMISSION DATA SUMMARY

Vendor	APC Configuration	No. of Tests	Percentage of Runs with Emissions in Stated Range			
			Particulate Emissions Concentration (gr/dscf)			
			X < 0.01	0.01 < X < 0.02	0.02 < X < 0.03	X > 0.03
Calvert	Condenser/Absorber & Collision Scrubber	12	8	25	67	0
Ceilcote	2 stage IWS	118	45	13	9	33
	3 stage IWS	6	67	33	0	0
Hydro-Sonics	Super-Sub	23	26	13	13	48
	Tandem Nozzle	14	29	36	4	31
	Steam Hydro	9	0	0	0	100

8.0 DRY SCRUBBERS

8.1 THEORY OF OPERATION

Dry scrubbing is any process which involves contacting flue gas with an alkaline material, which results in a dry waste product for disposal. To date, nearly all commercial applications in the United States utilize a spray dryer as the contractor. A spray dryer is an apparatus in which a slurry or solution is sprayed or atomized into a hot gas, such that the hot gas is humidified and adiabatically cooled while the slurry or solution is evaporated to apparent dryness. Spray dryers have been used for many years to produce dried products such as instant coffee and dried milk.

Figure 8-1 schematically shows a spray dryer acid gas removal system. In this case, the flue gas is sprayed with an alkaline reagent, which reacts with the acid vapor in the flue gas, resulting in a dry solid product which is then filtered out with other particulate matter in a baghouse or ESP.

The alkaline reagent, termed sorbent or reactant, is often a calcium-based slurry or a sodium solution which reacts, both during and following the drying process, with sulfur and chlorine compounds in the flue gas.

Figure 8-2 is a schematic diagram of the basic elements of a typical spray adsorption/particulate collection process. The flue gas containing fly ash and acid gases enters the spray dryer and is contacted with a finely atomized alkaline slurry or solution. During the approximately 10 second residence time in the dryer, the flue gas is adiabatically cooled as the water in the slurry or solution is evaporated. Simultaneously, acid gas constituents of the flue gas react with the alkaline species to form solid salts such as calcium chloride and calcium sulfate. The solids formed are dried to generally less than 1 percent free moisture. The flue gas, which has usually been humidified within the dryer, goes into a downstream high efficiency particulate collection device. In most designs a portion of the solids drop out in the dryer, but the bulk of the solid salt products are collected with flyash in a fabric filter or an ESP. The reaction between the alkaline material and acid gases continues as the gas passes through the ductwork and the fabric filter or ESP.

Several design and operating factors indicated by the schematic of the spray adsorption process are discussed in more detail below.

Using a spray dryer as a flue gas contactor involves adiabatically cooling the flue gas to within a specified number of degrees above saturation. With set conditions for inlet flue gas temperature and humidity for a specified approach to saturation temperature, the amount of water which can be evaporated into the flue gas is set by energy balance considerations. The sorbent quantity is varied by raising or lowering the concentration of a solution or weight percent solids of a slurry containing this set amount of water. While holding other parameters such as temperature constant, the obvious way to increase acid gas removal is to increase sorbent quantity. However, two major factors limit the effectiveness of attempts to raise the level of acid gas control by merely increasing sorbent quantity.

1. As the sorbent quantity increases, a smaller percentage of the sorbent may be utilized. The effectiveness of increasing the sorbent is limited by the comparatively small concentrations of unreacted acid gas.
2. The quantity of sorbent that can be added to the water is also limited. An upper limit is reached for the solubility in the solution, or for the weight percent of sorbent solids in a slurry.

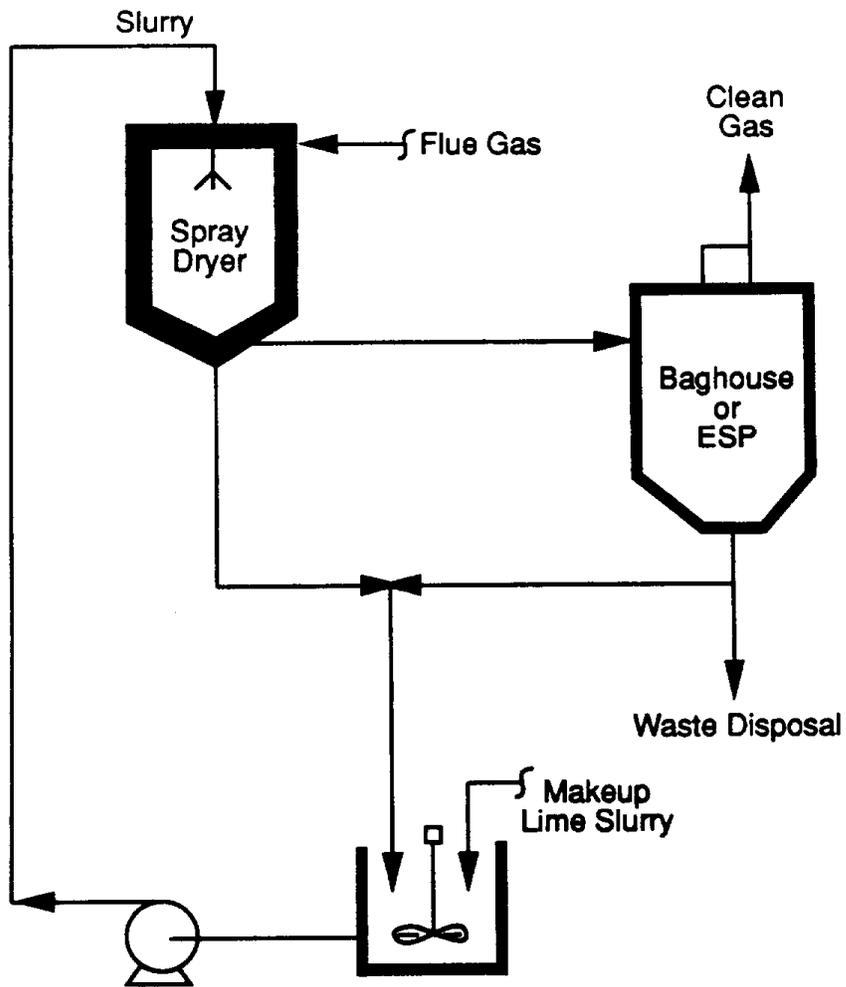


Figure 8-1. Schematic of spray adsorption system.

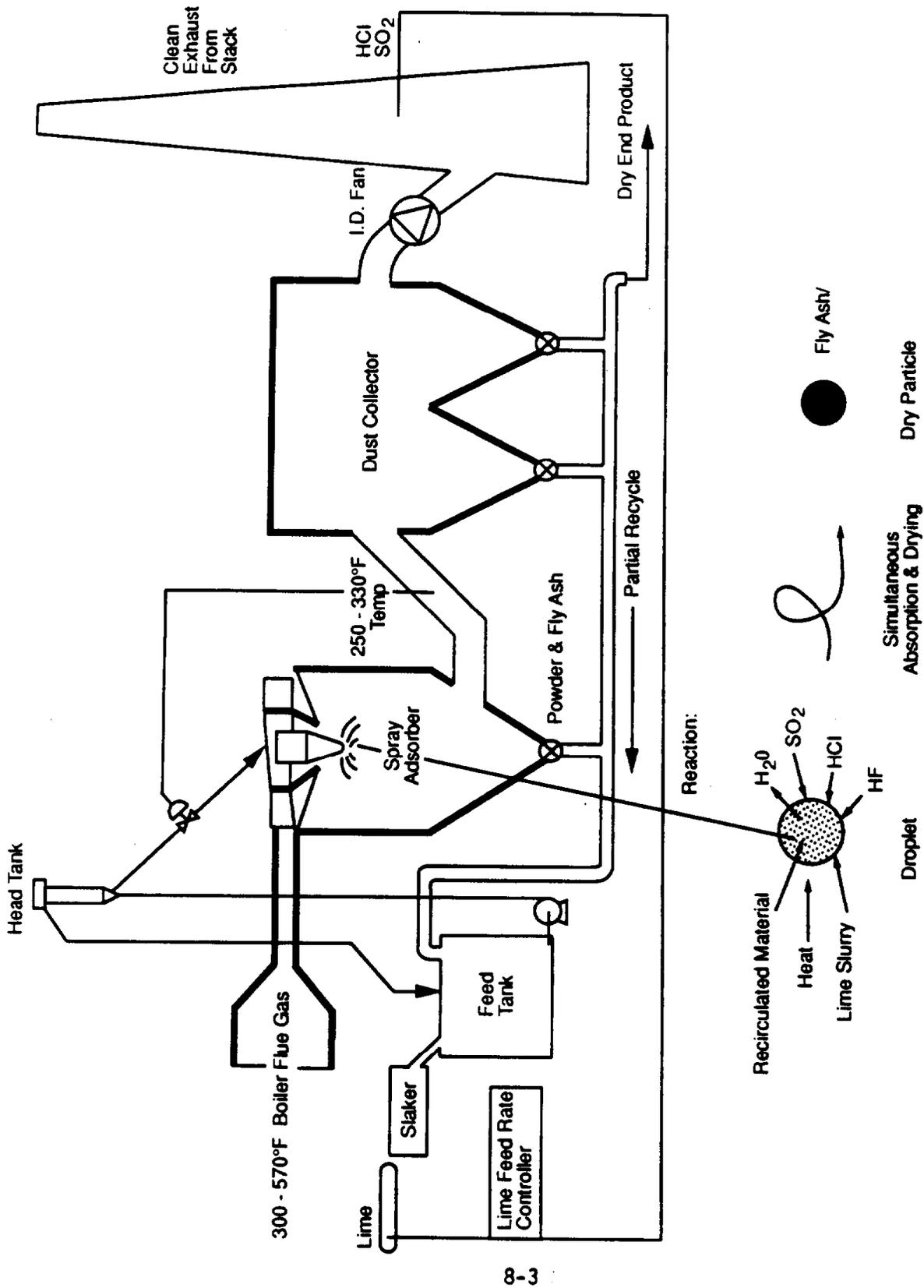


Figure 8-2. Typical spray adsorber/particulate collection flow diagram (46).

There are at least two methods of reducing the effects of these limitations. One method is sorbent recycle, which uses the solids that have either dropped out in the spray adsorber or have collected in the particulate emission controls device. Recycle increases sorbent utilization and can also increase utilization of any alkalinity in the fly ash. However, recycling also increases the weight percent of solids in the atomizer slurry if it is directly recirculated to the sorbent slurry tank as shown.

The second method of reducing the effect of the above limitations on acid gas removal is to operate the spray absorber at a lower outlet temperature. A closer approach to the saturation temperature has the effect of increasing both the residence time of the liquid droplets and the residual moisture level in the dried solids. As the approach to saturation decreases, acid gas removal rates and the sorbent utilization generally increase dramatically.

The approach to saturation at the spray adsorber outlet is limited by either the requirement for a margin of safety to avoid condensation in downstream equipment or by restrictions on stack temperature. The spray adsorber outlet can be operated at temperatures lower than these restrictions would otherwise allow if some warm or hot gas is bypassed around the spray adsorber to reheat the adsorber outlet gas. Warm gas from downstream of the boiler air heater entails no energy penalty, but bypassing this untreated gas for reheating does reduce overall acid gas removal efficiencies. Bypassing hot gas decreases the energy available for air preheating.

8.2 TYPES OF EQUIPMENT

There are several different, commercially-available spray adsorption systems which incorporate different variations of the basic system illustrated in Figure 8-2. System differences can be categorized in terms of four major areas:

1. Spray adsorber design and operation
2. Sorbent reagent preparation
3. Atomization
4. Particulate collector design and operation

8.2.1 Spray Adsorber Design and Operation

Variations in spray adsorber design include the difference in shape of the dryer, gas dispersion configurations, multiple or single rotary (or nozzle) atomizers per dryer, one - versus two-point flue gas admission to the spray adsorber and different methods of collecting solids from the spray adsorber. Each vendor claims his designs to be suitable for acid gas removal and to have certain advantages. Some important considerations in evaluating the various designs include:

1. Liquid/gas compact
2. Turndown capability
3. Potential for plugging or carryover of wet solids to the baghouse or ESP during upset conditions

Differences in spray adsorber operation includes variations in gas residence time and in the approach to saturation at the adsorber outlet. Gas resident times range from 7 to 12 seconds in most commercial designs, though most operate in the 10 to 12 second range.

Originally, spray adsorbers for removal of SO₂ from the flue gases of coal-fired boilers were designed to maintain dryer outlet temperatures within 30 to 50° F above saturation. However, many present system designs call for a closer approach to saturation of 18 to 25° F. These close approaches are common where acid gas removal efficiency requirements are 85 to 90

percent. Low temperature designs may also be used to decrease reagent requirements even in applications where lower removal efficiencies are acceptable.

In acid gas applications where HCl is the primary emission to be controlled, operation at 50 to 100° F above the adiabatic saturation temperature has been found to be necessary since the reaction product, calcium chloride, is hygroscopic. If operation at higher humidity levels were attempted, the calcium chloride would absorb an excess amount of water from the flowing gases resulting in a wet, sticky dust cake. Fortunately, the presence of calcium chloride also appears to catalyze the reaction of hydrated lime with SO₂ such that acceptable levels of SO₂ removal are possible at the higher temperature condition.

8.2.2 Sorbent Reagent Processing

Two basic reagents are considered for spray adsorption processes: sodium based compounds and calcium compounds. Of these, sodium compounds such as trona or nahcolite are the easiest to process since they are highly soluble. Processing is essentially a matter of metering a weighted amount of the dry compound into a known volume tank to produce a solution of known strength. This solution is then diluted for the atomizer feed. A two-step atomizer feed metering process is used, since the water flow rate is independently controlled to maintain the acid gas outlet loading at the desired level.

The more commonly used calcium compounds are more difficult to process. Because of their lower solubility, these compounds form a slurry instead of a solution. Calcium compounds are more commonly used because sodium-based reactant products leach more readily when disposed of in landfills than do the calcium-based reaction products. In addition, calcium compounds are cheaper and more readily available in most locations.

The calcium compound most commonly used in spray driers is pebble lime. The spray adsorber facility normally receives pebble lime of approximately 1/2 inch size which is normally pneumatically transferred from the delivery truck or railroad car to an on-site storage silo and then by gravity to the slaker. The slaker is a device for mixing the lime with water to produce calcium hydroxide.

An alternative to the use of pebble lime and on-site slaking, just as it is usually done in large spray dryers for coal burning electric utilities, is the procurement and use of lime that is already hydrated. The choice between pebble lime or hydrated lime is an economic question. The minimum cost choice has been shown to depend primarily on the lime use rate. Water treatment industry application experience can be used to determine the most economical type of lime system for a particular installation.

The economic questions reduce to a comparison of the costs of procuring, storing and metering dry hydrated lime, to the costs of procurement and storing of quick lime followed by slaking and metering the slurry into the spray adsorber. These questions are precisely those which have been faced by large water treatment plants for many years. In answering these questions, the following points should be considered:

1. Hydrated lime is more expensive than quick lime because it requires an additional step in manufacture.
2. Pure quick lime (CaO) has 0.714 pounds of calcium per pound of quick lime. Hydrated lime has 0.514 pounds of calcium per pound of hydrate [Ca(OH)₂].

3. Hydrated lime is a fine, low density (25-35 lb/ft³) powder compared to quick lime which is usually handled as 1/2 inch pebbles having a density of 55 to 60 lb/ft³. Both are delivered in closed trucks or railroad cars and transferred pneumatically to storage silos. The fine powdered hydrate requires live bottom silos.
4. The above items result in hydrated lime being at least 30% more expensive than quick lime, and having increased shipping costs. However, it requires less capital expense at the point of use. These two offsetting features have resulted in the use of hydrated lime by the water treatment industry for facilities requiring less than 100 to 125 tons of lime per month. Quick lime is used above that amount.

This experience from the water treatment industry was used together with a typical chlorine content for MSW of 0.5%, a typical sulfur content of 0.1%, and an assumed requirement of a stoichiometric ratio of 4 to make calculations that show that incinerators designed for capacities smaller than 125 to 150 tons per day (TPD) should consider purchasing hydrated lime. Conversely, incinerators above 150 TPD should be able to economically justify the use of pebble lime with on-site slaking.

8.2.3 Atomizers

Two types of atomizers are used for spray adsorbers, rotary atomizers and two-fluid nozzle-type atomizers. A third type, simple pressure spray nozzles, are not used due to problems of turndown capability and rapid nozzle erosion due to the abrasive nature of the injected slurry.

Rotary Atomizers

Rotary atomizers have been used for over 40 years in the spray dryer industry. Hence, they represent a well-developed technology. Figure 8-3 depicts a large, commercially available rotary atomizer. Figure 8-4 shows a sectional view of the cup-shaped atomizing wheel. Lime slurry is fed, at essentially zero pressure, to the inside of the rapidly rotating wheel. Centrifugal forces hold the slurry against the inner wall of the atomizer cup as the slurry is accelerated to wheel speed. The slurry is then forced out through the ceramic lined nozzles on the circumference of the wheel. Atomization results from the shear forces between the rapidly rotating wheel, peripheral speed in the order of 450 ft/sec, and the entering of flue gases.

In typical dry scrubber systems using recirculation of fly ash and sorbent, the design of the atomizer wheel must consider abrasiveness of the slurry and the fly ash particles in the adsorbent liquid. The wear resistant wheel, shown in Figure 8-4, is comprised of a stainless steel body with a bottom plate and inserts of silicon carbide. The inserts protrude within the wheel body to maintain a layer of stationary slurry which protects the inside of the wheel from abrasion.

The rotary atomizer is designed for continuous operation with routine maintenance. Rotary atomizers are capable of virtually infinite reagent flow turndown without significantly changing the particle size distribution of the atomized liquid. This feature provides uniform control of water evaporation rates and end-product characteristics over a wide range of gas flow rates.

Nozzle-type Atomizers

Although rotary atomizers are most commonly used for spray adsorption systems, two-fluid nozzles are also used by some manufacturers. The two-fluid nozzle has the primary virtue of simplicity, i.e., it has no moving parts. Figure 8-5 shows a sectional cut-away of a two-fluid

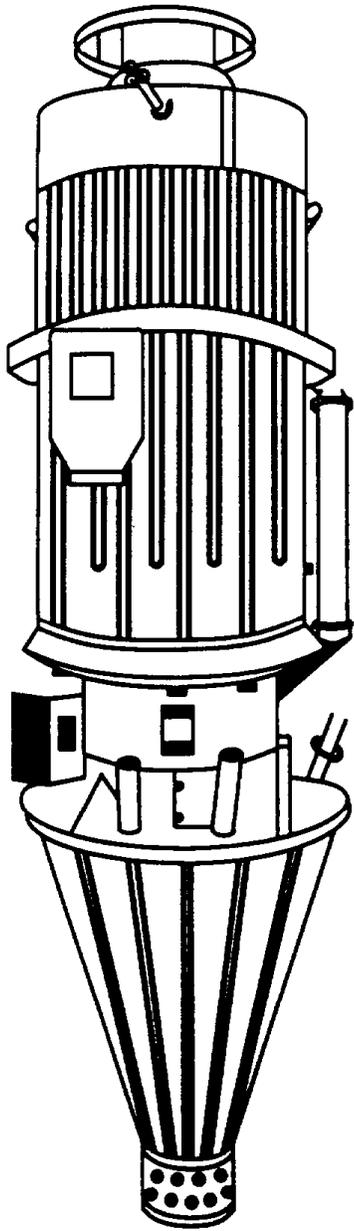


Figure 8-3. Niro Rotary Atomizer (46).

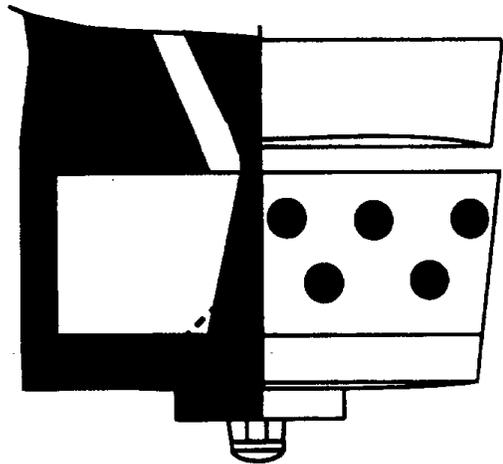


Figure 8-4. Abrasion Resistant Atomizer Wheel.

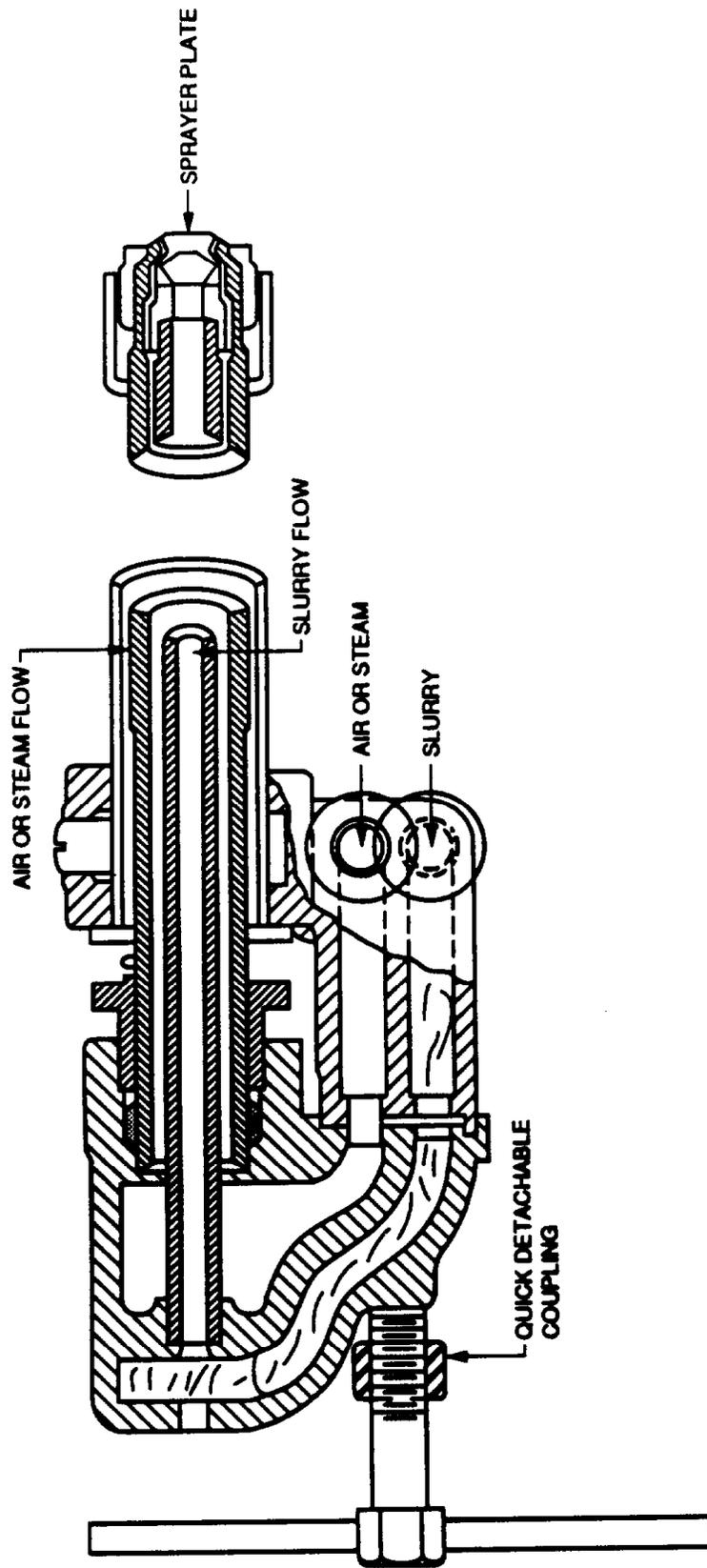


Figure 8-5. Y-jet slurry atomizer (47).

nozzle, termed the "Y" jet slurry atomizer. Design of these nozzles is based on extensive experience with similar designs for atomizing heavy liquid fuels for boilers.

Spray adsorber reactors using nozzle-type atomizers are typically quipped with 12 "Y" jet nozzles. The two-fluid atomizers use a concentric pipe to feed both the atomizing fluid, steam or air and the reagent, lime slurry. Two-fluid nozzles, particularly with multi-nozzle installations, have the advantage of easy replacement without system shutdown. However, they do require significant additional energy costs relative to rotary atomizers.

8.2.4 Vessels

The reaction vessel in a spray adsorption system is designed to adequately and uniformly mix the atomized slurry with the entering flue gases. Size of the vessel is determined primarily by "residence time," i.e. the volume of the reactant vessel divided by the volume flow rate of the flue gases. Assuming uniform flow, the residence time describes how long the flue gases are in the vessel. Gas residence times range from 7 to 12 seconds in most commercial designs although most systems operate in the 10 to 12 second range.

The spray adsorber vessels for rotary atomizers are normally vertical cylinders with length to diameter ratios near one since the slurry is introduced radially and must be dried before it reaches the vessel wall. Generally, two-fluid nozzle vessels, which can be either vertical or horizontal cylinders, have larger length to diameter ratios, usually greater than 2. The more axial introduction of the two-fluid nozzle spray permits the larger L/D vessel. Conventional insulation is used on the outside walls of the spray adsorber vessel to minimize heat losses and to prevent condensation on the internal vessel walls which could lead to corrosion.

8.2.5 Interaction Between the Spray Adsorber and the Particle Collector

Fabric filters have been chosen over ESP's in most commercial spray adsorption applications to date. Fabric filters are considered to have an advantage over ESP's in that unreacted alkaline in the solids and fly ash collected on the fabric surface can react with remaining HCl and SO₂. In some applications, however, an ESP has been chosen instead of a fabric. The factors important in making the choice between ESP's and fabric filters include:

1. Use of recycle (increases dust loading to particle collector).
2. Fly ash resistivity (high ash resistivity calls for larger, more expensive ESP's but has no effect on fabric filter design).
3. Pressure drop (an ESP has a lower pressure drop and related costs than a fabric filter).

Fabric filter designs for spray adsorber acid gas removal systems vary primarily with bag fabric type, cleaning frequency, and cleaning mode. Teflon-coated fiberglass bags have been selected for most spray adsorber systems, although acrylic bags are a low cost alternative that can be considered when gas temperatures are low.

Proponents of ESP's for spray adsorber systems claim that a closer approach to adiabatic saturation can be made when using an ESP since there need be no concern about the plugging of bags from condensation. This would increase the adsorber acid gas removal performance beyond the additional acid gas removal that would have occurred in the dust cake of a fabric filter. However, this claimed advantage might not be achieved in practice since the temperature must still

be maintained above saturation to minimize corrosion of ESP components due to acid gas condensation.

Besides performance, the principle interaction between the spray adsorber and a fabric filter is the moisture content of dust buildup on the fabric filter. Excessive moisture could result in reducing the cleanability of the dust cake causing the fabric filter pressure drop to rise excessively. Experience has shown successful operation of the fabric filter at a filter inlet temperature of 20° F above the adiabatic saturation point. Short duration excursions below this temperature caused by system upsets have been shown to be tolerated by the fabric filter. Apparently, the existing cake of dry dust protects the fabric, permitting it to clean successfully on the next cleaning cycle. An alternative explanation of the fabric filter tolerance of short durations of excessive moisture is that the cake is redried after the upset and prior to the next cleaning cycle.

8.3 SYSTEM CAPABILITIES AND LIMITATIONS

Dry scrubbers have, and are, making rapid progress relative to the previous wet scrubber technology for utility and MSW incinerator applications. The following comparison of dry scrubbing and wet scrubbing illustrates this progress.

1. A dry product is produced by the scrubber which can usually be disposed of simultaneously with the fly ash, thus, problems associated with the disposal of the wet sludges produced by wet scrubbers are avoided. The dry solid waste product can be handled by conventional fly ash handling systems, thus eliminating requirements for a sludge handling system. However, the dry waste solids from sodium-based systems are quite water soluble and can lead to leachability and waste stability problems. In contrast, waste solids from lime spray drying systems can be disposed of with similar environmental affects as waste from lime/limestone wet systems.
2. Dry scrubbing systems are inherently simple, hence, they have the potential of both lower costs and equally or more important, higher operating availability. Dry systems require less equipment than wet systems since the thickeners, centrifuges, vacuum filters, and mixers required to handle the wet sludge waste product from wet systems are eliminated. Also, slurry pumping requirements are much lower for spray drying. This is important because wet systems have reported high maintenance requirements associated with large slurry circulation equipment. Also, the scaling potential in wet limestone systems requires extra effort to maintain proper scrubber operation and possibly makes dry systems somewhat more flexible as far as their ability to adjust process operations to respond to variations in inlet acid gas concentrations and flue gas flow rates.
3. Although costs are quite site specific, dry scrubbing offers several possibilities for cost savings due to the reduction in equipment and operation and maintenance requirements relative to wet lime/limestone systems. Early studies have evaluated the costs of spray drying systems to be in the order of 20 to 30 percent less costly over the 35-year life of the plants than comparable wet systems. Reagent costs for sodium-based spray dryer systems will be considerably higher than for lime-based systems, although

vendors claim the capital costs, excluding waste disposal, will be lower for sodium-based systems.

4. Generally, dry scrubbing systems require a somewhat higher ratio of sorbent to entering acid flue gas to achieve the desired removal efficiency than for limestone wet scrubbing systems (2 to 4:1 for dry scrubbing, 1 to 1.5:1 for wet scrubbing). In addition, the reagents employed in spray drying (and dry injection) systems (soda ash, lime, and trona) are significantly more expensive than limestone. Consequently, limestone wet scrubbing systems will have an advantage with regard to reagent utilization and sorbent-related operating costs.
5. With regard to energy requirements, dry scrubbing systems have a significant advantage over wet systems due to savings in reheat and pumping requirements. Many wet scrubbing systems reheat the flue gas before it enters any downstream equipment to prevent corrosion. This reheat requirement is eliminated in most dry system configurations and results in considerable energy savings. Energy savings result from the fact that wet scrubbers may require liquid to gas (L/G) pumping rates of to 100 gallons per 1000 ACFM of gas whereas spray dryers only require an L/G rate of 0.2 to 0.3 gallons per 1000 ACFM.
6. Dry scrubbing vessels and ducts, with the exception of slurry preparation equipment, are dry, thus minimizing corrosion problems. Slurry preparation and injection equipment has less corrosion and scaling problems than wet scrubbing slurry handling equipment.

Therefore, dry systems do offer potential advantages over wet systems, especially in the areas of energy savings, equipment costs, and potential operational problems.

9.0 RETROFIT SYSTEMS FOR MEDICAL WASTE INCINERATORS

Many medical facilities now have an incinerator, however to meet new regulations they must consider the retrofit addition of emission control equipment to the present incinerator. This section addresses the particular problems of retrofitting and considerations of the use of experience on similar incinerators to guide the selection and operation of the new emission controls system.

9.1 CONSIDERATIONS IN COMBINING EQUIPMENT

Usually, it may not be possible or prudent to purchase the complete emission controls system from one source, hence the medical waste facility, or their technical representative, must consider the integration and interaction of equipment procured from several sources.

Careful preparation of the procurement specifications for each piece of equipment will assure proper system operation provided all installation and operational parameters are identified. This may seem obvious, however it is easy only once the specification preparer is familiar with both the system requirements and the details of the type of equipment being procured. Most applicants may want to contract with equipment vendors or engineering consultants for assistance with permit preparation. The contractor may also assist in the preparation of the authority to construct application, health risk assessment, and permit to operate. In addition, the contractor may assist in verifying compliance after installation of the air pollution control devices. The key to successfully retrofitting an existing incinerator is the assignment of one person responsible at the medical waste facility that is, or becomes, knowledgeable of the design and operation of the entire incinerator and the new emission controls system.

Three important considerations in defining, procuring and installing a retrofit system are:

1. Making sure that all components are compatible and that the overall system is as simple as possible.
2. The retrofit system must fit into available space.
3. Installation of the new system must be compatible with the necessary availability of the present incinerator; i.e., what do you do with the waste while the new emission controls equipment is being installed. Can most of the installation be accomplished prior to connecting to the incinerator?

9.2 SCALING AIR POLLUTION CONTROL DEVICES USED ON MSW INCINERATORS TO SMALL MEDICAL WASTE INCINERATORS

The technologies and principles used on large MSW systems to effectively reduce emissions should apply equally well to small medical waste systems. For instance, the key design factors that determine the performance of a baghouse are fabric material, weave pattern, cleaning mechanism, and cleaning frequency. Each of these design components will have performance which is independent of the baghouse size assuming the unit is operated correctly. Key operating parameters include the baghouse pressure drop and inlet temperature. Thus as long as appropriate design and operating practices are followed, a medical waste baghouse containing one hundred bags would be expected to perform no differently than a MSW baghouse containing one thousand bags.

Spray coolers operate by injecting a fine distribution of water droplets uniformly into the gas stream and providing sufficient time for evaporation. Scaling down spray cooler designs from MSW sizes to the small medical waste sizes can be accomplished by selecting smaller and/or fewer

spray generating nozzles and reducing the dimensions of the cooling vessel to accommodate the lower flow rate of exhaust gases. Smaller nozzles will aid in the evaporation process since these nozzles generally produce finer sprays which evaporate faster. In addition, the uniform distribution of the droplets into the gas stream is less difficult in small systems due to the reduced size of the cooling vessel.

Key parameters for wet scrubbers include the pressure drop across the device, liquid to gas ratio, reagent type, and reagent concentration in the injected solution. As long as the appropriate set points are maintained for each of these parameters and other parameters of importance specific to the particular system design selected, scaling a MSW wet scrubber down to a medical waste system should produce the same performance. This is because neither the efficiency of the reactions responsible for acid gas control nor the efficiency of the collisions responsible for particulate control in wet scrubbers depend on the device size (see Equation 1 in Section 5 of Volume I).

While it is expected on a scientific basis that the same performance can be expected from an air pollution control device scaled from MSW systems to medical waste systems, there have been only a few tests on a limited number of devices to corroborate this theory. A wet scrubber system at Stanford University in California and a dry injection system utilizing a baghouse and wet scrubber at Hamot Medical Center in Pennsylvania have both satisfied the 10 ng/kg-waste dioxin limit. Other tests, however, have not been as successful. Reasons for these failures are probably not a result of the inability of MSW systems to be scaled to medical waste systems. However, the actual reasons might include:

1. Differences between typical medical and municipal solid waste compositions and feed variability.
2. Insufficient incinerator exhaust gas for maintaining proper incinerator/control equipment draft.
3. Improper operation of the air pollution control devices.
4. Air pollution control device capabilities.

Each of these issues is addressed in more detail below.

9.2.1 Waste Composition and Feed Variability

The characteristics of medical wastes may vary; since each department generates and bags its own waste, each bag may have very different properties. However, surveys have summarized the average composition of medical waste. Information from these surveys (see Table 9-1) indicates that the bulk make-up of medical waste is similar to municipal waste. Thus it is not expected that waste type will have a significant effect on the performance of the scaled air pollution control devices.

While the average composition of medical waste is similar to the waste incinerated in MSW systems, the variability of the waste feed rate and composition in small hospitals is generally greater than that found in MSW systems. This is because of the large supply of waste present at MSW facilities and the high degree of specialization within different departments at hospitals. To limit upset conditions resulting from waste feed rates and compositions which are either well below or above those specified by the incinerator manufacturer, both the waste feed rate and waste composition should be carefully monitored and controlled by the operator. This would involve mixing high heating value wastes (plastics) with low heating value waste (liquid and glass wastes) and feeding the waste at a uniform rate.

TABLE 9-1. COMPARISON OF THE COMPOSITION OF MEDICAL AND MUNICIPAL WASTE (48)

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

9.2.2 Insufficient Exhaust Gas Flow

Due to the size and operational characteristics of small incinerators, situations may arise where insufficient exhaust gas is present to maintain proper operation of the air pollution control devices. To maintain appropriate system draft, a damper providing air and an induced draft fan could be mounted before and after the air pollution control devices, respectively. The fan operation and/or damper setting would be controlled to maintain the appropriate flow of gas through the air pollution control devices. To prevent the escape of untreated exhaust, the system would have to be maintained below atmospheric pressure.

9.2.3 Improper Operation

Differences in incinerator operational characteristics and operator training are two of the key issues involved with scaling air pollution control devices used on MSW installations to small medical waste installations. 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 the weekends. Fabric filters have characteristics which make their application under these conditions difficult. For instance, fabric filters can only accept flue gas in a relatively narrow temperature range. Upper temperature limits are set by materials of construction. Thus, baghouses will be damaged by direct exhaust from an incinerator. Lower temperature limits are set by the flue gas dewpoint. Wetting of the bags can cause bag blinding. Calcium-based sorbents turn to a cement-like material when exposed to water. In addition, any condensate will be highly acidic and attack the bag material. This severely reduces bag life. To assure proper performance of a baghouse it will be necessary to provide for daily cold start-up of the air pollution control devices. This will include bypassing the exhaust gases around the fabric filter or through the dump stack until the flue gas is well above the dewpoint. In addition to requiring a sophisticated control system to handle start-up and shut-down procedures and upset conditions, the effective operation of the air pollution control devices will require an operator who has received training and is familiar with the operation of each device in the system. A system incorporating a baghouse for particulate control and a lime injection system and wet scrubber for acid gas control at Hamot Medical Center in Erie, PA has met the current dioxin requirements established in California (see Section 11).

In contrast 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 system, installed at Stanford University, experienced some difficulty but subsequently has provided satisfactory dioxin control performance. The scrubber installed at Stanford was required primarily for acid gas control and is not designed for stringent particulate control.

9.2.4 Control Capabilities

Even if the air pollution control devices can be scaled, a control system can be devised to make the incinerator operating cycle compatible with the operation of the emission control devices, and the operator is intimately familiar with all system equipment, the incinerator emissions may still not be sufficiently reduced to satisfy the local regulations. Thus it is important that the facility or a hired consultant thoroughly research the different combinations of air pollution control devices and their capabilities before purchasing a system. In addition, once a system is selected the facility or its consultant should assure before purchasing the system that the equipment has been properly

scaled by the manufacturer accounting for all key design parameters which are provided in Volumes I and II of this report.

9.3 CONTROL SYSTEMS

The control of water or water-slurry flow rate to maintain the particle collector inlet temperature at a set value can be readily accomplished using state-of-the-art controllers and a variable speed pump with a modulating, recirculating valve. Such control systems are successfully used in spray dryer installations for both coal fired boilers and MSW systems. The temperature to be controlled, for example the baghouse inlet temperature, is sensed by a shielded thermocouple which feeds into a conventional process controller which, in turn, controls the slurry (or water) flow rate by either a variable speed pump or by a by-pass valve. Systems for spray dryers routinely maintain the baghouse inlet temperature to within less than 10° F of the set point. Except for the smaller pump or control valve, the control equipment required for the medical waste incinerator control system would be identical. Equipment required for implementation of such a system is available off-the-shelf at a total cost estimated to be less than \$5000 (49).

An advantage of using a wet scrubber instead of a dry scrubber or a spray cooler is that the scrubber outlet temperature is defined by saturation considerations; hence, a temperature control system is not required.

In large MSW spray dryer systems the reactant (slurry) flow rate is usually controlled by a second active control loop (the first being the temperature control). This loop senses the outlet SO₂ level and automatically adjusts the slurry solids concentration to maintain a set level of SO₂. It is assumed the HCl present will be preferentially reacted prior to the reaction of the SO₂. This is done primarily because of the unavailability of suitable HCl sensors. It is of note that this approach is satisfactory only if both HCl and SO₂ are present.

It is not recommended that an active control loop for reactant flow be used for the medical waste incinerator application. It is recommended that the reactant concentration be maintained constant, i.e. the percent of solids in the slurry water be maintained at a constant value sufficient to provide sufficient HCl removal under average levels of HCl. Although this approach wastes reactants, it is not felt that the amount wasted would justify the additional complexity of an active control loop.

10.0 ECONOMICS

An economic analysis should be useful for the selection between available systems and for prediction of future costs. For such an analysis to be meaningful, it must carefully and accurately compare available systems on the same basis.

The details of the specific installation for which the analysis is being made are the basis of the analysis and must include such factors as; incinerator outlet parameters, emission control requirements, allowable physical space for the installation, schedule, etc.

It is not possible for this report to define the specifics of any installation, hence the purpose of this report is to assist in narrowing the possibilities such that a reasonable number of technical alternatives can be identified for the economic analysis.

Subsequent paragraphs present information on the economics of two actual operating hospital waste incinerators using dry scrubbing/baghouse technology, and three proposed wet scrubber systems for a hazardous waste incinerator similar in size to typical hospital waste incinerators.

Great care must be exercised in comparing the cost analyses presented, since they have not been prepared on an identical basis. The purpose in presenting the examples is that they may assist the reader in establishing the items that must be considered in setting an order of magnitude for the costs involved.

10.1 ETS DRY REACTOR SYSTEM - FAIRFAX COUNTY HOSPITAL, VIRGINIA

An ETS Dry Reactor emission control system (50) was retrofitted to an existing medical waste incinerator at the Fairfax County Hospital. Start-up of the emission control system was in January 1987. It has been in continuous (one shift per day) operation since start-up. Acceptance testing was successfully completed in February 1987 and compliance testing was completed in February 1988.

Table 10-1 lists significant process and equipment information. Figure 10-1 is a schematic of the system. Internal configuration of the ETS reactor is illustrated in Figure 10-2. The reactor is designed for cyclonic flow of flue gas near a motor driven "slinger" which distributes dry hydrated lime in a commercially available dry chemical feeder. Directly above the slinger is the lighter fraction of the partially spent sorbent. Below the recirculation section of the reactor, a dropout of heavy particulate matter takes place before the gas flows to the baghouse particulate collector.

Table 10-2 lists a breakdown of costs for installing the Fairfax County Hospital/ETS Dry Reactor retrofit emission control system in 1987 on the existing 900 lb/hr incinerator. The total purchase cost for the equipment shown in Figure 10-1 was \$83,500. This includes the cost of ductwork connecting the quench tower, reactor and baghouse, and the cost of the system fan and compressor. The total cost to the hospital for the ETS system including the purchase and installation of equipment, and design and field engineering was \$136,000.

10.2 BECO'S "ALKA/SORB" PROCESS - HAMOT MEDICAL CENTER: ERIE, PA

The "Alka/Sorb" process is a dry/wet system comprising a lime injection/baghouse/wet scrubber as shown in Figure 10-3 (51).

For the Hamot Medical Center, BECO used a controlled flow rate of ambient air dilution to maintain the incinerator flue gases at 375°F as they enter the baghouse. Hydrated lime is metered

TABLE 10-1. FAIRFAX COUNTY HOSPITAL

I. PROCESS INFORMATION:

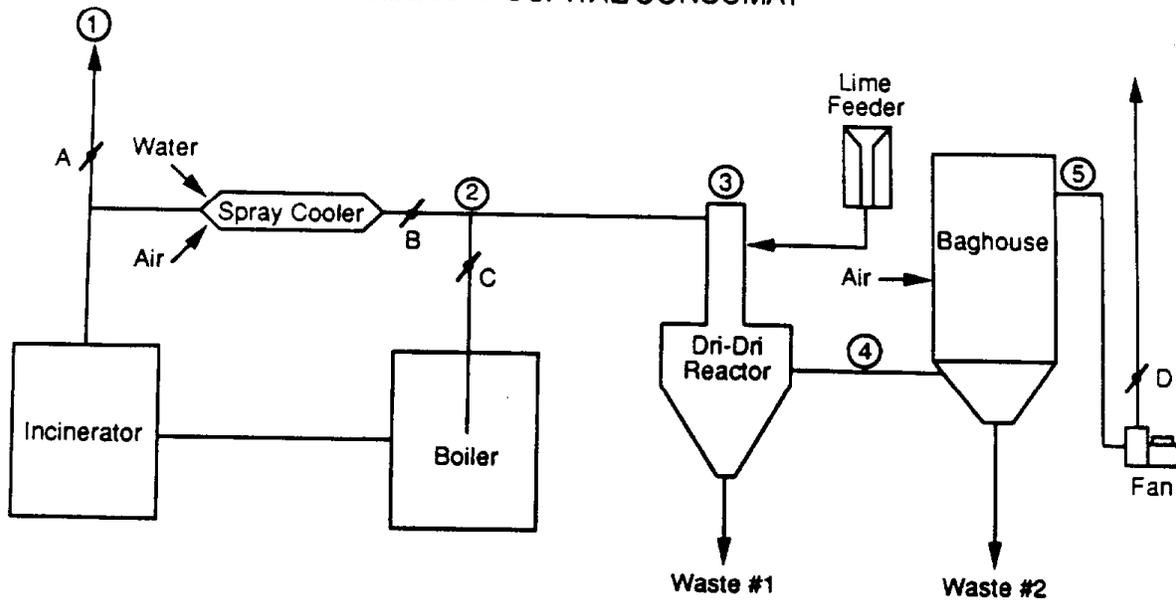
Incinerator	- Consumat model CS-325 with boiler
Rated Capacity	- 7.2 tons/day - batch fed
Operations Duty	- 16 hrs/day - 6 days/wk
Waste Type	- Hospital trash and infectious waste
Auxiliary Fuel	- Natural gas
Gas Volume	- 9748 acfm at 1800°F (1) 4000 acfm at 400°F (3)
HCL average	- 500 ppm (3)
Particulate	- 1.0 gr/scfd (3)
Emission Limit	- particulate - 0.08 gr/scfd at 12% CO ₂ (5)

II. APC EQUIPMENT:

a. Reactor	- ETS dry reactor model B-72
Rate	- 4000 acfm at 400°F (3)
HCL Conc	- 500 ppm (3) 50 ppm (4)
Reactant	- Lime
Stoichiometry	- 3/1
b. Baghouse	- Eastern Control - pulse jet
Bag Type	- woven glass
Filter Area	- 1350 sq ft
G/C	- 2.96/1
c. Quench Tower	- ETS/Consumat
Type	- horizontal flow, water spray
Water Rate	- 10 GPM at 40 psig
Temperature	- 1800°F (1), 400°F (2)

() - Numbers give the location of measurement point (see Figure 10-1).

FAIRFAX HOSPITAL/CONSUMAT



Component	Utilities Required
Spray Cooler	Air - 70 SCFM @ 100 psig, H ₂ O - 10 gpm @ 40 psig
Reactor	Lime - 0.5 - 1.0 cf/hr, Air - 5 SCFM @ 100 psig
Baghouse	Air - 20 SCFM @ 100 psig
Fan	12 H.P. @ 1800 rpm @ 12 in. W.C. Static Pressure
Lime Feeder	Hopper Capacity = 12 cf, Feed Rate = 0.5 - 1.0 cf/hr (12.5 - 25 lb/hr)
TOTAL POWER = 12 kW	

Average Design Conditions

Point	Temperature °F	Volume ACFM	Static Pressure In W.C.
1	1800	10,000	
2	402	3,525	-2
3	384	3,450	
4	365	3,375	-4
5	329	3,235	-10

Figure 10-1. Installation schematic of ETS dry reactor.

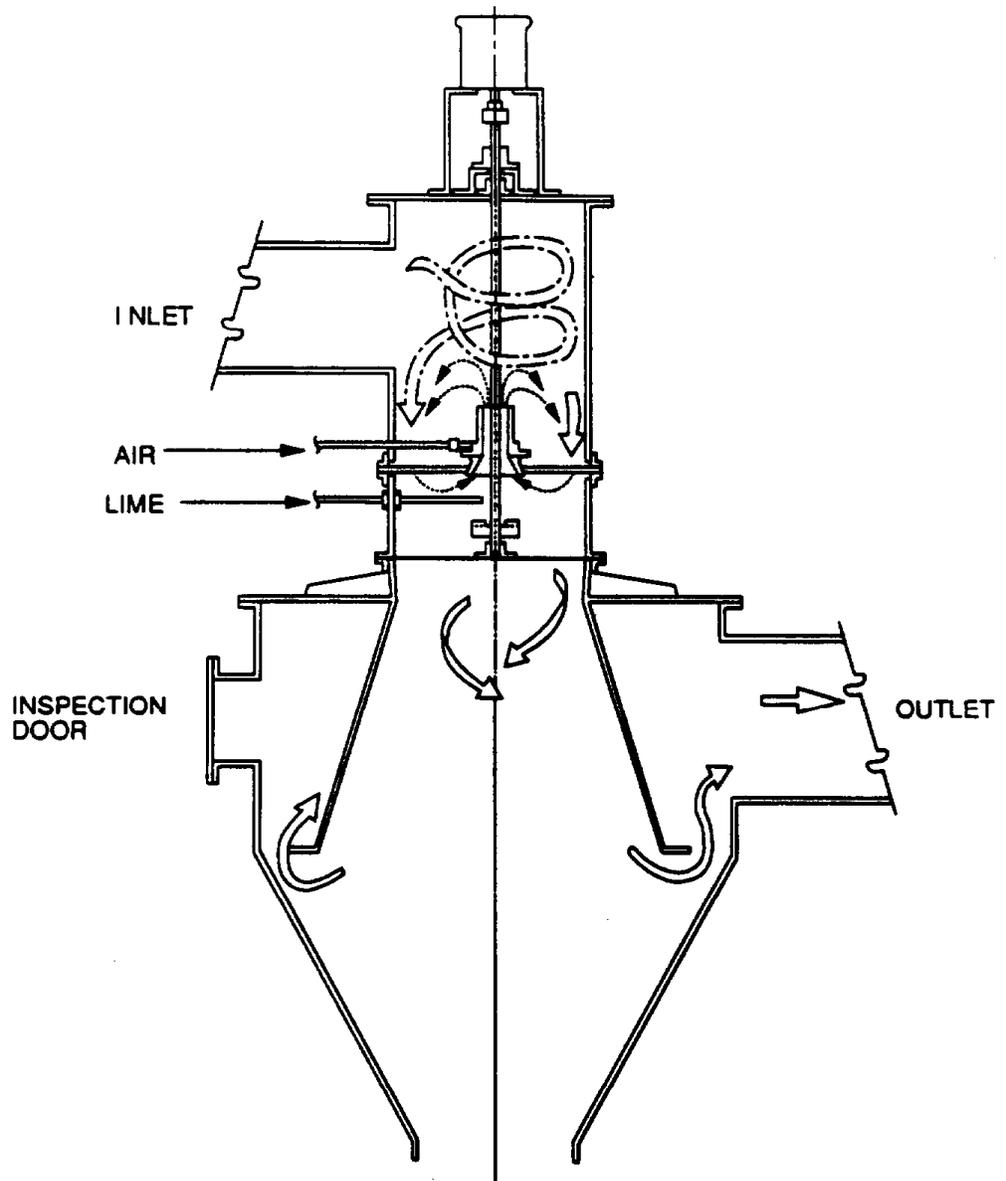


Figure 10-2. ETS dry reactor.

TABLE 10-2. FAIRFAX HOSPITAL *

APC DATA

History:

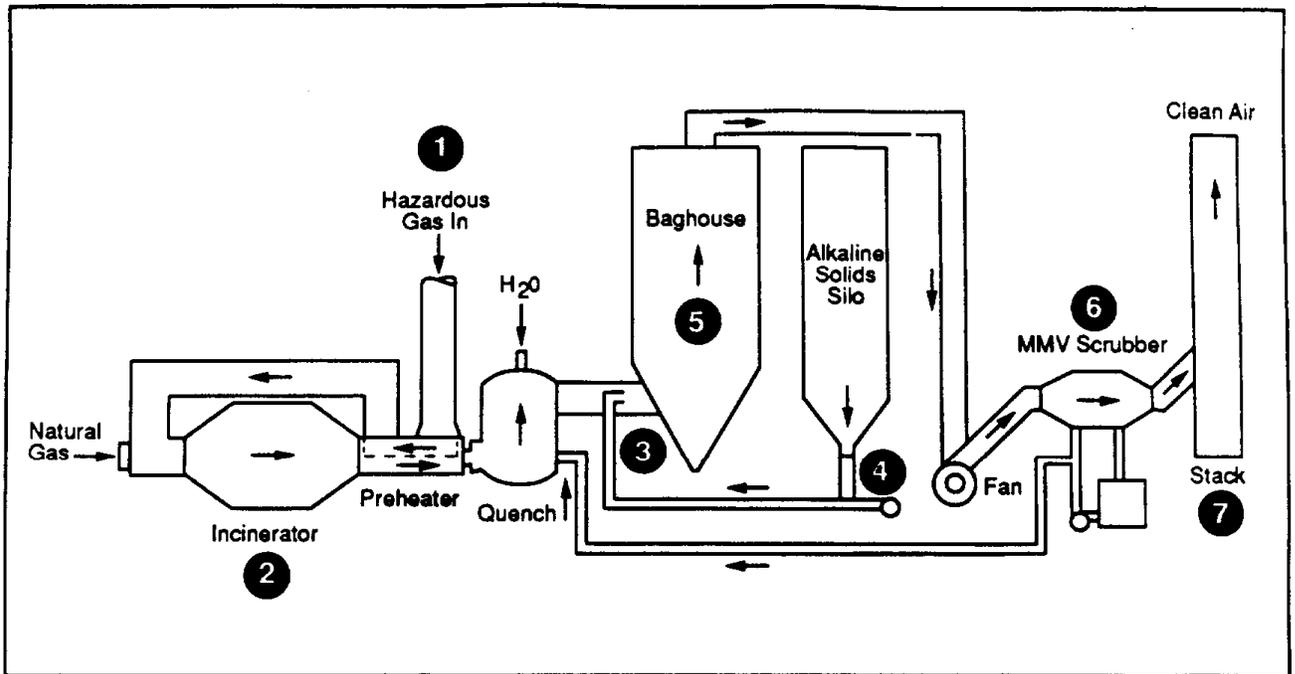
Ordered	1985
Started up	Jan. 1987
Acceptance test	Feb. 1987
Compliance test	Feb. 1988

Cost Information:

a. <u>Major equipment:</u>	
Quench tower	21,000
Ductwork	10,000
Compressor	7,500
Reactor	20,000
Baghouse	20,000
Fan	<u>5,000</u>
total	83,500
b. <u>Installation:</u>	
Foundations	3,500
Piping & Electrical	6,000
Erection	<u>18,000</u>
	27,500
c. <u>Design & field engineering:</u>	
	<u>25,000</u>

TOTAL \$136,000

* Cost information is from 1985.



BECO SYSTEM DESCRIPTION

- 1 Air containing hazardous solvents and toxic vapors enters the disposal train at a rate of 30,000 CFM. Gas is preheated to 1100°F by exchange with incinerator off-gas.
- 2 Incinerator heats gases to 1400°F, destroying VOC's and forming submicron tin oxide fume, HF plus HCl. The off-gases flow through preheater, exiting at 550°F then enter evaporative quench, and are further cooled to 280°F.
- 3 Sodium bicarbonate powder is injected into the quenched gas to neutralize the HF and HCl and to serve as pre-coat on the bag filters for sub-micron fume and ash removal.
- 4 Sodium bicarbonate is pneumatically transferred from the silo to the baghouse inlet under control of a solids feeder. The sodium bicarbonate thermally dehydrates to high-surface-area sodium carbonate which rapidly dry-reacts with the acid gases.
- 5 The baghouse filters serve to remove the sub-micron metal oxide fume and the reacted halide salts. Baghouse residence times are designed to provide both adequate bicarbonate/carbonate conversion time and acid-gas reaction time. The inert solids discharge from the baghouse is suitable for landfill disposal.
- 6 A downstream high-velocity Beco MMV "guard scrubber" is used as secondary protection against process upsets and bag leaks. The wet scrubber uses recycle bicarbonate solution as absorbent. The scrubber blowdown is evaporated in the incinerator off-gas quench, meeting a zero-liquid-discharge specification.
- 7 Stack testing at full load has verified that final stack discharge is in total compliance with all local, state and EPA emission standards for VOC, particulate solids and acid gases.

Figure 10-3. BECO's ALKA/SORB system.

by a screw feeder and pneumatically fed into the inlet of a pulse jet baghouse using felted bags. After the baghouse, a wet scrubber is used for further removal of acid gases. Sodium hydroxide is introduced to maintain the scrubber liquor at a pH between 8.5 and 9.5.

The injection of dry hydrated lime upstream of the baghouse serves several purposes:

1. It reduces the caustic consumption in the downstream wet scrubber. The reagent cost per pound of HCl absorbed is approximately \$0.04 for lime compared to \$0.40 for sodium hydroxide solution.
2. The lime provides additional surface area for condensation of metal oxides, dioxins and furans.
3. The lime allows better release of the collected flyash when pulsing the baghouse.
4. The lime coats the internal surfaces of the baghouse and acts as a corrosion inhibitor in the event of acid condensation on shutdown.

A 8.5 cubic foot bag dump station holding up to 250 pounds of lime is provided. A volumetric screw feeder powered by a variable speed motor meters the flow of hydrated lime from the dump station into a 2 hp, 90 SCFM, 2.5 psi pneumatic injection blower.

The baghouse is a reverse pulse jet collector operating at a filter rate of approximately 5:1. Aluminum venturis are used. Bags are 4.5 inch diameter by 10 foot length spaced on 8 inch centers. Goyen diaphragm pulse valves triggered by ASCO solenoid valves are used.

The wet scrubber is a BECO Engineering high velocity horizontal flow two-stage Multi-MicroVenturi (MMV) scrubber. Liquor is recycled at a total rate of approximately 7 gal/MCF from a recycle/separator tank in which the pH is maintained at 10-12 by addition of 50% NaOH makeup solution. Blowdown is taken off the recycle pump discharge at a fixed rotameter setting, to maintain a constant dissolved solids concentration in the liquid. Makeup water, to compensate for evaporation and blowdown, is added to the liquid system in two streams. One stream is provided to the air-atomizing nozzle in the quench section at a constant flow rate, while the second stream is added to the recycle liquid under automatic level control. Softened water is used for makeup to the scrubber to prevent precipitation of calcium salts in the scrubber.

Table 10-3 is BECO's projection of various size emission control systems similar to the installation at the Hamot Medical Center in Erie, PA. Note that this table includes budgetary estimates for the vendor supplied equipment only, thus engineering would be in addition to these costs. Cost estimates for individual system components are not available.

10.3 WET SCRUBBERS

Occidental Chemical Company (OCC) submitted a report titled Evaluation of Liquid Waste Incineration Air Pollution Control System Alternatives in April 1990 to the New York State Department of Environmental Conservation detailing an evaluation of emission control alternatives for their planned expansion of a hazardous waste incinerator facility (32). Specifically, the Occidental report describes pilot scale testing on a liquid waste incinerator equipped with a Ceilcote air pollution control system which includes a quench chamber, pre-scrubber, and two-stage ionizing wet scrubber. The report also provides an assessment of different air pollution control technologies and their associated costs. These technologies include those described in Section 7.0. The following sections outline the cost analysis presented in the Occidental report.

TABLE 10-3. COMPARISON OF VARIOUS BECO EMISSION CONTROL SYSTEMS *

DWG. TAG	BECO WET-DRY SYSTEM EVALUATION										6/12/1990		
	OPERATING CONDITIONS & UTILITY REQUIREMENTS												
INLET TEMPERATURE = 450°F.													
1	BOILER EXHAUST FLOW (SCFM)	700	1000	1250	1500	2000	2750	3500	4400	5000	6500	8000	10000
	INLET PARTICULATE (PPH)	.432	.417	.771	.926	1.234	1.697	2.160	2.715	3.086	4.011	4.937	6.171
	OUTLET PARTICULATE (PPH)	.058	.063	.104	.125	.166	.229	.291	.366	.416	.541	.666	.832
	INLET HCl (PPH)	4.270	6.100	7.625	9.150	12.201	16.776	21.351	26.941	30.501	39.652	48.802	61.003
	OUTLET HCl (PPH)	.214	.305	.381	.458	.610	.839	1.068	1.342	1.525	1.983	2.440	3.050
	MAXIMUM OPERATING TEMPERATURE (°F)	500	500	500	500	500	500	500	500	500	500	500	500
	MAXIMUM BLIND TEMPERATURE (°F)	550	550	550	550	550	550	550	550	550	550	550	550
	DESIGN PRESSURE (W.C.)	-20	-20	-20	-20	-20	-20	-20	-20	-20	-20	-20	-20
2	AMBIENT AIR BLEED (ACFM)	340	486	608	730	973	1337	1702	2432	2432	3161	3891	3891
3	LINE CONSUMPTION (AIR)	9	13	16	19	25	35	44	55	62	81	99	124
	LINE FEED SYSTEM (AIR)	3	3	3	3	3	3	3	3	3	3	3	3
	BAGHOUSE MODEL NO.	PR36-10	PR36-10	PR54-10	PR54-10	PR81-10	PR106-10	PR144-10	PR180-10	PR225-10	PR270-10	PR324-10	PR400-10
	BAGHOUSE BAG MATERIAL	PMA AROMATIC POLYIMIDE											
	AIR-TO-CLOTH RATIO	3.099	5.567	4.646	5.574	4.953	5.107	4.877	4.459	4.459	4.830	4.954	5.016
4	PLANT AIR USAGE (CFM @ 100 PSIG)	7.5	7.5	7.5	12	16	13	13.5	19.5	27	37.9	44	55
5	SOLIDS TO DISPOSAL (AIR)	11	15	19	23	30	41	52	65	74	96	118	147
6	WATER CONSUMPTION (CFM @ 70°F)	.097	.711	.888	1.066	1.421	1.954	2.487	3.127	3.553	4.169	5.685	7.106
	CALCULIC FEED PUMP (HP)	1/8	1/8	1/8	1/8	1/8	1/8	1/8	1/8	1/8	1/8	1/8	1/8
7	NACH CONSUMPTION (CFM AS 20% SOLN.)	.104	.263	.329	.394	.526	.723	.920	1.157	1.315	1.709	2.103	2.629
	RECYCLE RATE (CFM)	20	20	20	20	25	30	40	55	55	75	90	110
	RECIRCULATION PUMP MODEL NO.	CFPY-300	CFPY-300	CFPY-300	CFPY-300	CFPY-300	CFPY-300	CFPY-300	CFPY-300	CFPY-300	CFPY-300	CFPY-300	CFPY-300
	RECIRCULATION PUMP (HP)	2	2	2	2	2	2	2	2	2	2	2	2
8	BLOWDOWN RATE (CFM)	.002	.046	.068	.069	.069	.127	.162	.204	.231	.301	.370	.463
	% SOLIDS IN BLOWDOWN	0	0	0	0	0	0	0	0	0	0	0	0
9	OUTLET GAS (ACFM)	1325	1893	2366	2839	3786	5205	6625	8328	9464	12303	15142	18928
	OUTLET TEMPERATURE (°F)	126	126	126	126	126	126	126	126	126	126	126	126
	PRESSURE DROP (W.C.)	12	12	12	12	12	12	12	12	12	12	12	12
	L.D. PAN MODEL NO.	CF-194DH	CF-194DH	CF-194DH	CF-194DH	CF-224DH	CF-264DH	CF-294DH	CF-334DH	CF-334DH	CF-404DH	CF-454DH	CF-504DH
	L.D. PAN (HP, INCL. 5" W.C. EXT. S.P.)	10	10	15	15	20	25	30	40	40	50	75	100
A	BAGHOUSE OVERALL HEIGHT (IN.)	200.25	200.25	308.25	308.25	314.25	326.25	325.25	342.25	342.25	361.25	362.25	373.25
B	BAGHOUSE LENGTH (IN.)	56	56	77	77	77	96	96	96	117	138	138	152
C	BAGHOUSE WIDTH (IN.)	56	56	56	56	56	77	77	77	96	117	138	152
D	SCREENER DIAMETER (IN.)	12	12	12	12	12	16	16	16	24	30	36	36
E	SCREENER FLOW AREA HEIGHT (IN.)	12	12	16	16	16	24	24	30	36	36	48	54
F	SCREENER FLOW AREA WIDTH (IN.)	16	16	20	24	21	30	36	36	36	48	54	66
G	SCREENER FEED LENGTH (IN.)	120	120	132	132	132	136	144	150	150	150	156	156
	FOOTPRINT DIMENSIONS (L. x W. x H)	SEE DIMENSIONS ABOVE											
	APPROXIMATE SHIPPING WEIGHT (LBS.)	5600	5700	6300	6400	9000	11900	15600	22400	22900	28100	31800	35000
	PRICE (F.O.B. FT. OF MPRL)	\$100,100	\$104,300	\$110,100	\$111,300	\$124,000	\$133,200	\$145,900	\$159,200	\$178,100	\$200,500	\$224,100	\$243,900
	ADDITIONAL PRICE, L.D. PAN & DAMPER	\$3,120	\$3,120	\$3,480	\$3,480	\$4,560	\$5,880	\$7,080	\$9,720	\$9,720	\$12,240	\$14,760	\$14,760
	ADDITIONAL PRICE 1-1/2 TRUCK SILO	\$45,750	\$45,750	\$45,750	\$45,750	\$45,750	\$45,750	\$45,750	\$45,750	\$45,750	\$45,750	\$45,750	\$45,750

* Cost information is from 1990.

10.3.1 Capture Cost Estimates

In the following examples two cases are evaluated. For Case 1, the gas cleaning train must contain a quench chamber, particulate removal equipment, acid gas removal equipment, an induced draft fan, stack, ducting between APC devices, and instrumentation. For Case 2, the gas cleaning train must include the items listed above plus a heat exchanger, recycle pumps, strainer, slumps, valves, and piping.

A short list of wet scrubber vendors was prepared. These vendors were asked for equipment cost estimates from which capital, annual operating, and total annual cost estimates were prepared. The selected vendors were:

1. Calvert Collision Scrubber
2. Ceilcote Ionizing Wet Scrubber
3. Hydro-Sonic Systems Super-Sub Scrubber

A bid package was prepared to obtain equipment purchase cost budgetary quotes from vendors. The bid package included the following items:

1. Scope of equipment supply
2. Results of previous pilot test
3. Results of waste characterization studies
4. Heat and material balances around the liquids incinerator
5. Equipment performance specifications
6. Equipment, instrumentation, electrical, piping, and utility specifications
7. Vendor startup assistance requirements
8. Vendor process engineering, installation, maintenance, and operating manual preparation requirements

A list of process conditions and limitations required by regulations were described in the bid package. Examples of these types of parameters include the maximum gas flow at the entrance to the APC system, stack gas flow limits, and stack height requirements. Vendors were asked to recommend all other operating parameters required for their equipment to meet the performance specification. Examples of operating parameters specified by each vendor included pressure drops across unit operations, makeup water flows, recycle water flows, and cooling water flows.

Vendor bid packages specified that OCC would be responsible for design engineering and installation of the equipment. Vendor quotations were based on equipment F.O.B. the manufacturing facility.

A battery limits installed capital cost estimate was prepared for each alternative using a factored cost estimating method. The battery limits are defined as the area within 15 feet of the process equipment. Costs for items outside of the battery limits, such as cooling water supply piping, river water supply piping, scrubber blowdown sewer lines, and electrical power distribution systems are not included in the battery limits capital cost estimates. The installed cost estimates assume that the existing caustic supply system and continuous emission monitoring system will be used for the new APC system.

The factored cost estimating method is based upon developing factors expressed as a percentage of the equipment purchase cost to estimate total installed costs. Installation costs were estimated for the following items:

1. Unidentified equipment allowance
2. Freight
3. Site preparation
4. Site improvements
5. Structural steel
6. Buildings
7. Above ground piping
8. Above ground electrical
9. Instrumentation
10. Insulation
11. Painting
12. Paving
13. Contractor's fees
14. Sales tax
15. Engineering
16. Contingencies

Installation factors were derived based upon historical cost records for similar equipment and vendor estimates for some items such as piping. Installed cost factors were generally within guidelines recommended in the U.S. EPA Economic Analysis Branch Cost Control Manual (52). An installed capital cost estimate for each alternative is presented in Table 10-4.

10.3.2 Operating Cost Estimate

A detailed operating cost estimate including the following elements was developed for each alternative:

1. Labor
2. Utilities
3. Chemicals
4. Waste disposal
5. Maintenance and operations

Table 10-5 represents a summary of annual operating cost estimates.

10.3.3 Total Annual Cost Estimate

A TAC was calculated for each alternative to compare alternatives on a basis that includes the time value of money. The TAC includes annual operating costs and capital recovery cost components.

Capital recovery was based on a 10 year process equipment life and a 10 percent interest rate as follows:

$$\text{CAPREC} = \text{CAPITAL} \times \text{CRF}$$

where:

CAPREC	=	Capital recovery (\$/year)
CAPITAL	=	Equipment installed capital cost (\$)
CRF	=	Capital recovery factor (0.1628/year)

TABLE 10-4. CAPITAL COST ESTIMATE (32) *

Case (a) Number	Vendor	Equipment Purchase Cost (\$)	Installed Cost Factor	Estimated Installed Capital Cost (\$)
Case 1	Calvert	580,000	2.61	1,507,900
	Ceilocote	567,000	2.65	1,504,265
	Hydro-Sonics	720,000	2.57	1,628,497
Case 2	Calvert	800,000	2.69	2,146,344
	Ceilocote	783,000	2.76	2,177,963
	Hydro-Sonics	860,000	2.66	2,262,216

(a) Case 1 - Once through water

Case 2 - Recirculated water with heat exchanger

* Cost information is from 1990.

TABLE 10-5. ANNUAL OPERATING COST ESTIMATE (32) *

Category	Calvert Case 1	Calvert Case 2	Ceilcote Case 1	Ceilcote Case 2	Hydrosonics Case 1	Hydrosonics Case 2
Labor Operator	42,000	42,000	42,000	42,000	42,000	42,000
Utilities						
Electricity	4,747	8,592	794	5,508	7,942	10,416
Steam	0	0	0	0	74,103	86,839
Cooling Water	0	51,377	0	101,861	0	54,058
River Water	<u>198,361</u>	<u>11,571</u>	<u>408,955</u>	<u>21,489</u>	<u>97,198</u>	<u>23,803</u>
Subtotal	203,109	71,541	409,749	128,859	179,242	175,117
Chemicals NaOH (100% Basis)	197,287	197,287	197,287	197,287	197,287	197,287
Effluent Disposal: Sewer Charges	292,190	20,837	594,325	38,359	142,070	32,676
Maintenance and Oper.						
Maintenance	75,395	107,317	75,213	108,898	81,425	113,111
Taxes, Ins., Admin.	<u>30,158</u>	<u>42,927</u>	<u>30,085</u>	<u>43,559</u>	<u>32,570</u>	<u>45,244</u>
Subtotal	105,553	150,244	105,299	152,457	113,995	158,355
Annual Operating Cost	840,139	481,909	1,348,660	558,962	674,594	605,435

(a) Case 1 - Once through water.

Case 2 - Recirculated scrubber water with heat exchanger.

* Cost information is from 1990.

The TAC is calculated as follows:

$$\text{TAC} = \text{OPCOST} + \text{CAPREC}$$

where:

TAC	=	Total annual cost (\$/year)
OPCOST	=	Annual operating cost (\$/year)
CAPREC	=	Capital recovery (\$/year)

Table 10-6 summarizes the estimated installed capital cost, operating cost, and TAC for each alternative. The preferred alternative, from an economic standpoint, is the alternative with the lowest TAC. This analysis indicates that the Case 2 is significantly less expensive than Case 1 for Calvert and Ceilcote. The difference in the annual cost between Case 1 and Case 2 for each of these vendors indicates that the saving in fresh river water cost and sewer charges for Case 2 relative to Case 1 more than offset the higher costs.

For Hydro-Sonic Systems, the total annual cost for Case 1 is \$34,000 per year less than for Case 2. Hydro-Sonic Case 1 and Case 2 use less river water and cooling water than the respective Calvert and Ceilcote cases. The savings in river water and sewer costs for Hydro-Sonic Systems Case 1 relative to Hydro-Sonic System Case 2 do not offset the higher capital costs.

Based solely on a total annual cost analysis, Calvert Case 2, Ceilcote Case 2, and Hydro-Sonic Systems Case 1 are preferred over the other three alternatives. The difference in the total annual cost between the least expensive and the most expensive for the three alternatives listed above is less than 13 percent. Considering the accuracy range of the capital and operating cost estimates, these three alternatives should be considered essentially equivalent from an economic standpoint.

TABLE 10-6. TOTAL ANNUAL COST ESTIMATE (32) *

a Case Number	Vendor	Installed Capital Cost (\$)	Annual Operating Cost (\$/yr)	b Total Annual Cost (\$/yr)
Case 1	Calvert	1,507,900	840,139	1,085,625
	Ceilcote	1,504,265	1,348,660	1,593,554
	Hydro-Sonics	1,628,497	674,594	939,713
Case 2	Calvert	2,146,344	481,909	831,334
	Ceilcote	2,177,963	558,962	913,534
	Hydro-Sonics	2,262,216	605,435	973,724

(a) Case 1 - Once through water.
Case 2 - Recirculated water with heat exchanger.

(b) Based on 10 year equipment life, 10 percent interest.

* Cost information is from 1990.

11.0 AVAILABLE DATA BASE

11.1 MEDICAL WASTE INCINERATORS

Only a few medical waste incinerators with emission controls have been in use for sufficient time to provide meaningful operational experience. Limited test data for these incinerator emission control systems are available.

Volume I of this report lists more than 12 operational medical waste incinerators. Two of these installations, and available test data, are described in subsequent paragraphs. Note that these installations differ quite a bit in equipment detail but both include the three key steps previously described as necessary for control of the emissions of concern from medical waste incinerators.

11.1.1 ETS Dry Reactor System - Fairfax County Hospital, Virginia

An ETS Dry Reactor emission control system was retrofitted to an existing medical waste incinerator at the Fairfax County hospital. Start-up of the emission control system was in January 1987. It has been in continuous (one shift per day) operation since start-up. Acceptance testing was successfully completed in February 1987 and compliance testing was completed in February 1988. This facility is presented as an example of a medical waste incineration system only. No dioxin or heavy metal tests have been carried out.

Table 11-1 lists important process and equipment information. Figure 11-1 is a schematic of the system. Internal configuration of the ETS reactor is illustrated in Figure 11-2. The reactor is designed for cyclonic flow of flue gas near a motor driven "slinger" which distributes dry hydrated lime in a direction countercurrent to the flue gas flow. Hydrated lime is fed to the slinger with a commercially available dry chemical feeder. Directly above the slinger is the lighter fraction of the partially spent sorbent. Below the recirculation section of the reactor, a dropout of heavy particulate matter occurs before the gas flows to the baghouse particulate collector.

Figure 11-3 shows ETS test results for HCl removal at Fairfax County Hospital using the Dry Reactor. ETS data is compared with data from Environment Canada for similar conditions using dry lime. Figure 11-4 compares the ETS test results with available data for several spray dryer systems. This comparison shows that the dry lime injection system produces very comparable HCl removals to that attained with the lime slurry injection systems.

Testing of the ETS system to date has only been sufficient to prove the capability of maintaining particulate emissions below the limit of 0.08 gr/DSCF corrected to 12% CO₂ and HCl emission below 1.52 lb/hr.

11.1.2 BECO'S "ALKA/SORB" PROCESS - Hamot Medical Center, Erie, PA

The "Alka/Sorb" process is a dry/wet system comprising a lime injection/baghouse/wet scrubber, shown in Figure 11-5.

For the Hamot Medical Center, BECO used a controlled flow rate of ambient air dilution to maintain the incinerator flue gases at 375° F as they enter the baghouse. Hydrated lime is metered by a screw feeder and pneumatically fed into the inlet of a pulse jet baghouse using felted bags. After the baghouse a wet scrubber is used for further removal of acid gases. Sodium hydroxide is introduced to maintain the scrubber liquor at a pH between 8.5 and 9.5.

An 8.5 cubic foot bag dump station, holding up to 250 pounds of lime, is provided. A volumetric screw feeder powered by a variable speed motor meters the flow of hydrated lime from

TABLE 11-1. FAIRFAX COUNTY HOSPITAL

I. PROCESS INFORMATION:

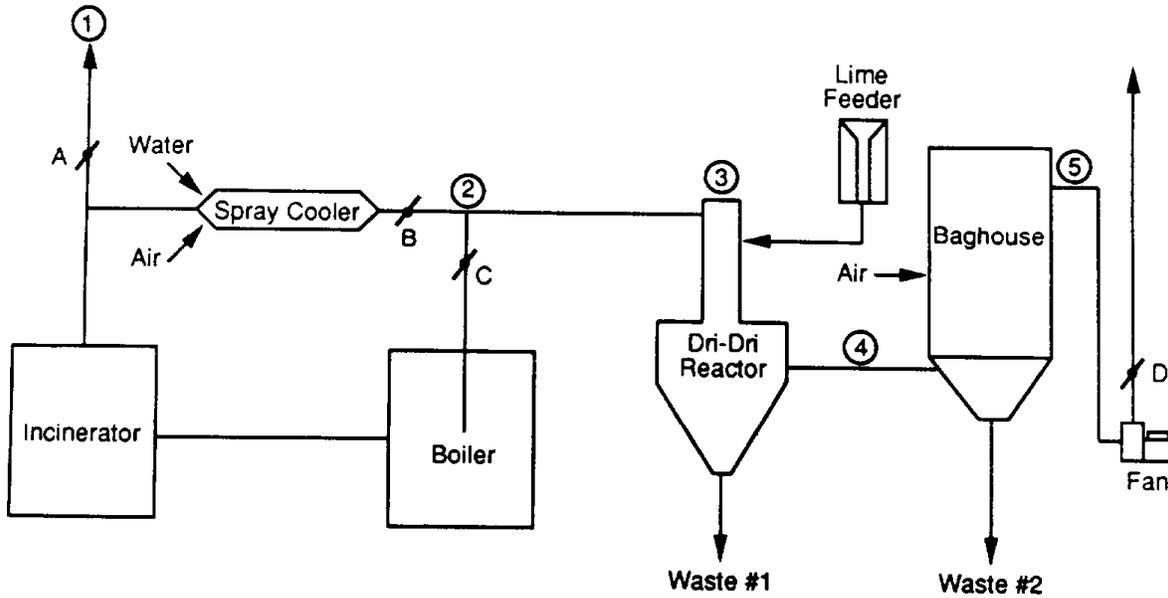
Incinerator	- Consumat model CS-325 with boiler
Rated Capacity	- 7.2 tons/day - batch fed
Operations Duty	- 16 hrs/day - 6 days/wk
Waste Type	- Hospital trash and infectious waste
Auxiliary Fuel	- Natural gas
Gas Volume	- 9748 acfm at 1800°F (1) 4000 acfm at 400°F (3)
HCL average	- 500 ppm (3)
Particulate	- 1.0 gr/scfd (3)
Emission Limit	- particulate - 0.08 gr/scfd at 12% CO ₂ (5)

II. APC EQUIPMENT:

a. Reactor	- ETS dry reactor model B-72
Rate	- 4000 acfm at 400°F (3)
HCL Conc	- 500 ppm (3) 50 ppm (4)
Reactant	- Lime
Stoichiometry	- 3/1
b. Baghouse	- Eastern Control - pulse jet
Bag Type	- woven glass
Filter Area	- 1350 sq ft
G/C	- 2.96/1
c. Quench Tower	- ETS/Consumat
Type	- horizontal flow, water spray
Water Rate	- 10 GPM at 40 psig
Temperature	- 1800°F (1), 400°F (2)

() - Numbers give the location of measurement point (see Figure 11-1).

FAIRFAX HOSPITAL/CONSUMAT



Component	Utilities Required
Spray Cooler	Air - 70 SCFM @ 100 psig, H ₂ O - 10 gpm @ 40 psig
Reactor	Lime - 0.5 - 1.0 cf/hr, Air - 5 SCFM @ 100 psig
Baghouse	Air - 20 SCFM @ 100 psig
Fan	12 H.P. @ 1800 rpm @ 12 in. W.C. Static Pressure
Lime Feeder	Hopper Capacity = 12 cf, Feed Rate = 0.5 - 1.0 cf/hr (12.5 - 25 lb/hr)
TOTAL POWER ~12 kW	

Average Design Conditions

Point	Temperature °F	Volume ACFM	Static Pressure in W.C.
1	1800	10,000	
2	402	3,525	-2
3	384	3,450	
4	365	3,375	-4
5	329	3,235	-10

Figure 11-1. Installation schematic of ETS dry reactor.

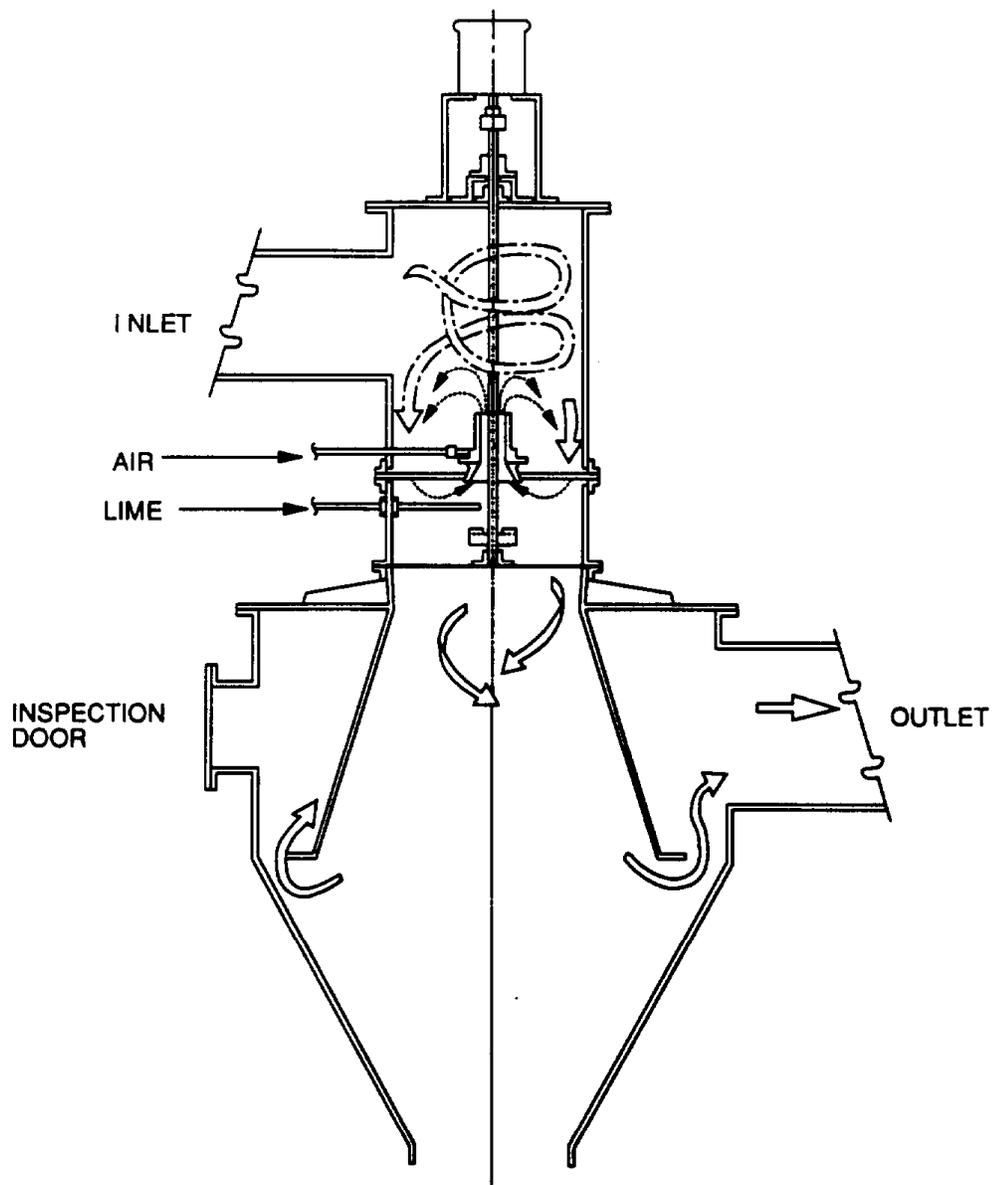
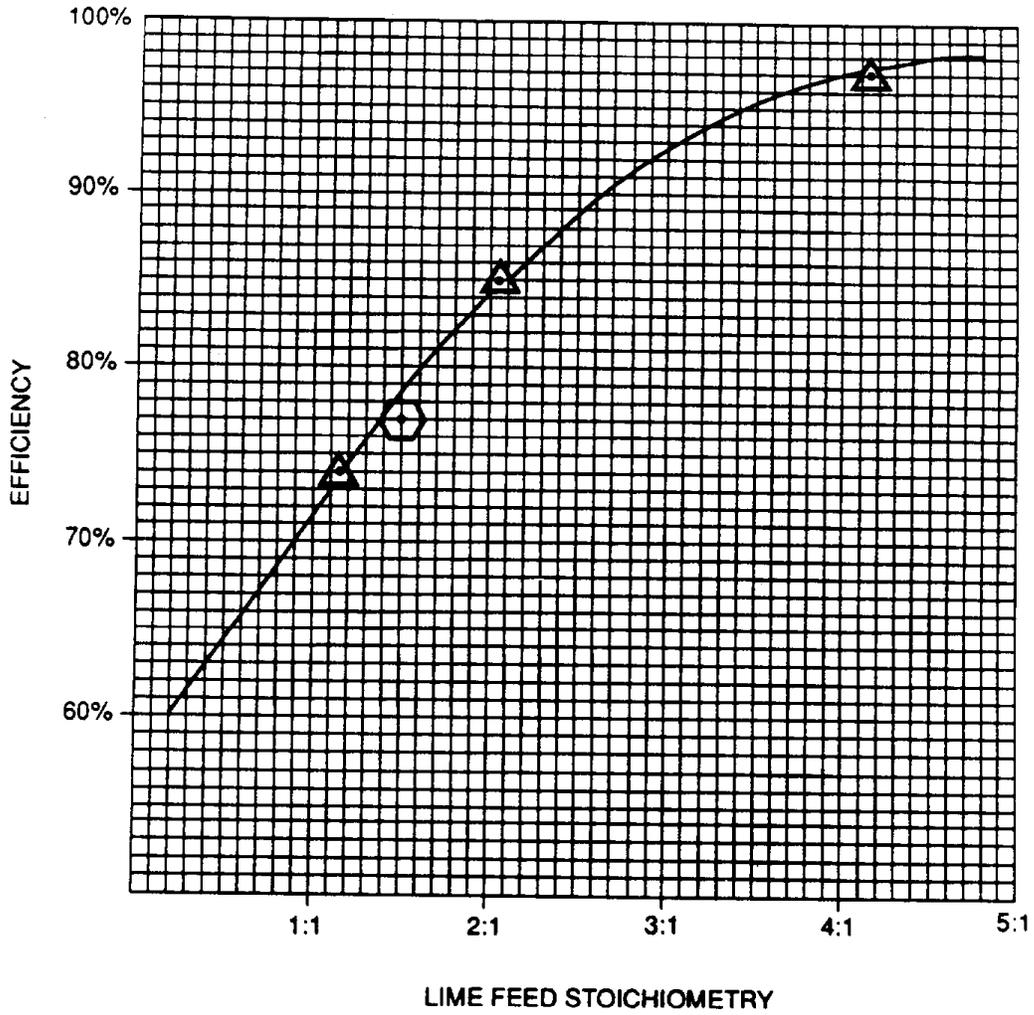


Figure 11-2. ETS dry reactor.

SYSTEM EFFICIENCY vs. LIME FEED
USING WET TEST METHOD



△ ETS DATA AT 440° F
⬡ CANADIAN DATA AT 410° F

Figure 11-3. ETS dry reactor test results.

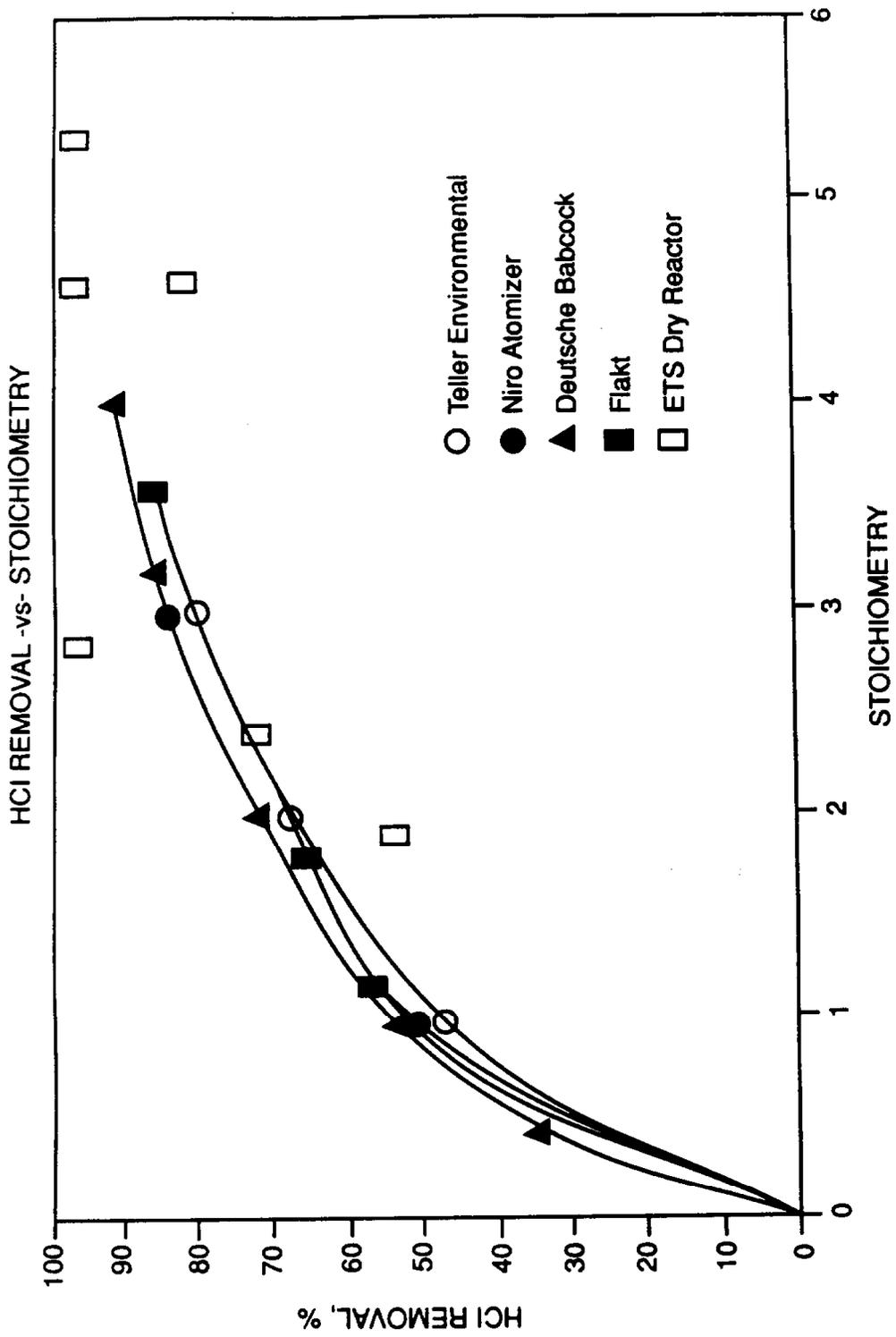
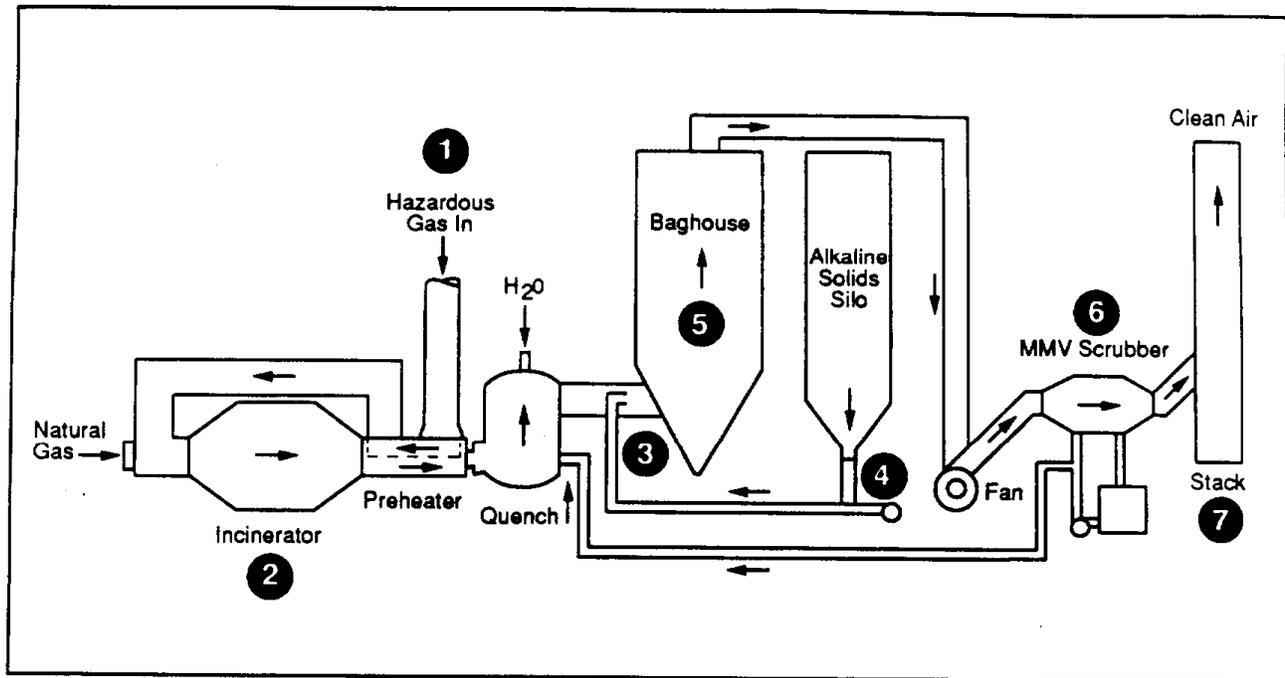


Figure 11-4. Comparison of wet and dry removal of HCl.



BECO SYSTEM DESCRIPTION

- 1 Air containing hazardous solvents and toxic vapors enters the disposal train at a rate of 30,000 CFM. Gas is preheated to 1100°F by exchange with incinerator off-gas.
- 2 Incinerator heats gases to 1400°F, destroying VOC's and forming submicron tin oxide fume, HF plus HCl. The off-gases flow through preheater, exiting at 550°F then enter evaporative quench, and are further cooled to 280°F.
- 3 Sodium bicarbonate powder is injected into the quenched gas to neutralize the HF and HCl and to serve as pre-coat on the bag filters for sub-micron fume and ash removal.
- 4 Sodium bicarbonate is pneumatically transferred from the silo to the baghouse inlet under control of a solids feeder. The sodium bicarbonate thermally dehydrates to high-surface-area sodium carbonate which rapidly dry-reacts with the acid gases.
- 5 The baghouse filters serve to remove the sub-micron metal oxide fume and the reacted halide salts. Baghouse residence times are designed to provide both adequate bicarbonate/carbonate conversion time and acid-gas reaction time. The inert solids discharge from the baghouse is suitable for landfill disposal.
- 6 A downstream high-velocity Beco MMV "guard scrubber" is used as secondary protection against process upsets and bag leaks. The wet scrubber uses recycle bicarbonate solution as absorbent. The scrubber blowdown is evaporated in the incinerator off-gas quench, meeting a zero-liquid-discharge specification.
- 7 Stack testing at full load has verified that final stack discharge is in total compliance with all local, state and EPA emission standards for VOC, particulate solids and acid gases.

Figure 11-5. BECO's ALKA/SORB system.

the dump station into a 2 hp, 90 SCFM, 2.5 psi pneumatic injection blower.

The baghouse is a reverse pulse jet collector operating at a filter rate of approximately 5:1. Aluminum venturis are used. Bags are 4.5 inch diameter by 10 foot length spaced on 8 inch centers. Goyen diaphragm pulse valves triggered by ASCO solenoid valves are used.

The wet scrubber is a BECO Engineering high velocity horizontal flow two-stage Multi-MicroVenturi (MMV) scrubber. Liquor is recycled at a total rate of approximately 7 gal/MCF from a recycle/separator tank in which the pH is maintained at 10-12 by addition of 50% NaOH makeup solution. Blowdown is taken off the recycle pump discharge at a fixed rotameter setting, to maintain a constant dissolved solids concentration in the liquid. Makeup water, to compensate for evaporation and blowdown, is added to the liquid system in two streams. One stream is supplied to the air-atomizing nozzle in the quench section at a constant flow rate while the second stream is added to the recycle liquid under automatic level control. Softened water is used for makeup to the scrubber to prevent precipitation of calcium salts in the scrubber.

Emission testing was carried out at the Hamot Medical Center on February 27 through March 3, 1990 by CAE. These results demonstrated a very low, three test average particulate emission of 0.001 gr/DSCF corrected to 7% O₂ based on the front half filter catch. The total 2,3,7,8-TCDD DHS toxic equivalent emission factor at the scrubber outlet was well below the required limit of 10 ng/kg-waste, averaging 0.92 ng/kg-waste for three runs. HCl removal for the dry lime/baghouse averaged 91.4%. The wet scrubber increased the average HCl removal to 99.3%. Average cadmium emission was 7.5 E-4 mg/DSCM.

11.2 MUNICIPAL WASTE INCINERATORS

More data is available for municipal waste incinerators. Table 11-2 summarizes the data from a variety of municipal waste incineration devices. Emissions cover a wide range. However, when modern units which make use of the principles discussed above are considered, the emissions are uniformly low. The two units included in Table 11-2 which make use of these principles are the facility at Marion County, Oregon, and the City of Commerce facility operated by the Los Angeles County Sanitation Districts.

TABLE 11-2. PCDD/PCDF EMISSIONS FROM MUNICIPAL WASTE INCINERATORS

Facility	Facility Type	Flue Gas Cleaning Device	TCDD Toxic Equivalents, (ng/kg)
Chicago	Mass Burn/Water Wall	ESP	499
Hampton (84)	Mass Burn/Water Wall	ESP	31,170
Peekskill	Mass Burn/Water Wall	ESP	225
Tulsa	Mass Burn/Water Wall	ESP	61
Wurtzburg	Mass Burn/Water Wall	WSH/DI/FF	67
Commerce	Mass Burn/Water Wall	SD/FF	2
Marion County	Mass Burn/Water Wall	SD/FF	3
Red Wing	Starved Air	ESP	49,047
Albany	Refuse Derived Fuel	ESP	1,388
Wright Patterson	Refuse Derived Fuel	Cyc/ESP	311



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APPENDIX A

A Typical Calculation for the Sizing of a Cooling Vessel

CALCULATION DESCRIPTION

This calculation was provided by EnviroCare for this project. It provides design and operating requirements for a cooling vessel sizing for a set conditions which are applicable to a medical waste incinerator. These conditions include an inlet volume flow rate and temperature of 30000 acfm and 1800 F, respectively. The required outlet temperature is specified as 300 F to be consistent with baghouse operation requirements and the California Air Resources Board regulations. Based on the input conditions, the program computed that three micromist nozzles with a combined water flow rate of 24.8 gpm and a cooling vessel with a length to diameter of 6.749 will give an outlet temperature of 300 F with a gas residence time of 1.9 seconds.



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ENVIROCARE EVAPORATIVE GAS COOLING
COMPUTER WORK SHEET

DATE: 08/08/90

ENVIROCARE REFERENCE NUMBER:

CUSTOMER NAME: STATE OF CALIF.
CUSTOMER CONTACT: DALE FURLONG

PROCESS: INCINERATOR
LOCATION: CALIFORNIA

GIVEN INFORMATION

	ENGLISH	METRIC
INLET TEMPERATURE.....	1800 (F)	982 (C)
OUTLET TEMPERATURE.....	300 (F)	149 (C)
INLET VOLUME.....	6963 SCFM	10978 Nm ³ /HR
INLET VOLUME.....	30000 ACFM	50970 Am ³ /HR
PLANT ELEVATION.....	100 FEET	30 METERS
DRAFT (H ₂ O).....	3 IN.	76 mm
WATER TEMPERATURE.....	60 (F)	16 (C)
DUST LOAD.....	10 GR/ACF	23 GRAM/Am ³

GAS COMPOSITION BY VOLUME

AIR.....	90 %
CARBON DIOXIDE.....	10 %

CALCULATED INFORMATION

TOTAL WATER FLOW.....	25 GPM	94 LPM
MASS FLOW.....	549 LB/MIN	
COMBINED SPECIFIC HEAT.....	32.12 BTU/SCF	
BTU-STEAM.....	1161.5 BTU/#	
STEAM SPECIFIC VOLUME.....	30.53 FT ³ /LB	
PRESSURE CORRECTION.....	1.010	
INLET DENSITY.....	0.018 LB/ACF	0.293 Kg/Am ³
OUTLET DENSITY.....	0.046 LB/ACF	0.742 Kg/Am ³
GAS DENSITY @ 70 F AND SEA LEVEL.....	0.079 LB/SCF	1.264 Kg/Am ³
GAS DENSITY @ 0 C AND SEA LEVEL.....	0.073 LB/SCF	1.173 Kg/Am ³
INLET VOLUME.....	30000 ACFM	50970 Am ³ /HR
OUTLET VOLUME.....	16028 ACFM	27232 Am ³ /HR
AVERAGE VOLUME.....	23014 ACFM	39101 Am ³ /HR
PERCENT WATER BY VOLUME.....	36.7 %	
PERCENT WATER BY WEIGHT.....	26.0 %	



ENVIROCARE EVAPORATIVE GAS COOLING
COMPUTER WORK SHEET

PAGE 2

DATE: 08/08/90

CUSTOMER NAME: STATE OF CALIF.
LOCATION OF PROJECT: CALIFORNIA

ENVIROCARE PROPOSAL NUMBER:

EQUIPMENT SELECTION

ENVIROCARE MICROMIST NOZZLES...SIZE MM 10
BASED UPON A NOZZLE SAFTEY FACTOR OF 1.1
THIS SYSTEM WILL REQUIRE..... 3 NOZZLES

SYSTEM REQUIREMENTS	ENGLISH	METRIC
TOTAL WATER FLOW.....	24.8 GPM	93.8 LPM
TOTAL AIR FLOW.....	177 SCFM	279 NM3/HR

MICROMIST NOZZLE REQUIREMENTS

WATER FLOW PER NOZZLE.....	8.3 GPM	31.3 LPM
MAXIMUM AIR FLOW PER NOZZLE.....	65 SCFM	102 NM3/HR
EFFECTIVE DROPLET SIZE.....	141 MICRONS	
THEORETICAL EVAPORATION TIME.....	0.89 SEC.	



ENVIROCARE EVAPORATIVE GAS COOLING
COMPUTER WORK SHEET

DATE: 08/08/90

CUSTOMER NAME: STATE OF CALIF.
LOCATION OF PROJECT: CALIFORNIA

ENVIROCARE PROPOSAL NUMBER:

DOWNFLOW TOWER PARAMETERS
CONICAL TYPE HOPPER

BASED UPON A SAFETY FACTOR OF 2.12

	ENGLISH	METRIC
CYLINDER DIAMETER (A)	5 FT. 2 IN.	1.57 M
CYLINDER HEIGHT (B)	34 FT. 10 IN.	10.62 M
HOPPER HEIGHT (C)	3 FT. 7 IN.	1.10 M
INLET HEIGHT (D)	7 FT. 11 IN.	2.41 M
SPRAY LANCE ELEV. (E)	3 FT. 6 IN.	1.07 M
CLEARANCE TO GRADE (F)	6 FT.	1.83 M
OVERALL HEIGHT (G)	52 FT. 4 IN.	15.95 M
INLET DIAMETER (H)	3 FT. 1 IN.	0.94 M
OUTLET DIAMETER (J)	2 FT. 3 IN.	0.69 M
INLET CONE ANGLE	7.5 DEGREES	
HOPPER ANGLE, DEGREES FROM VERT.	30 DEGREES	

GENERAL TOWER INFORMATION

TOTAL SURFACE AREA	696 SQ. FT.	65 SQ. M
APPROXIMATE TOWER WEIGHT	5327 LBS.	2416 Kg
PLATE THICKNESS	3/16 INCH	4.77 mm
BASED ON SCRAP FACTOR OF 0.8		
TOWER WEIGHT	4320 LBS.	1960 Kg
INLET CONE WEIGHT	784 LBS.	356 Kg
HOPPER WEIGHT	222 LBS.	101 Kg

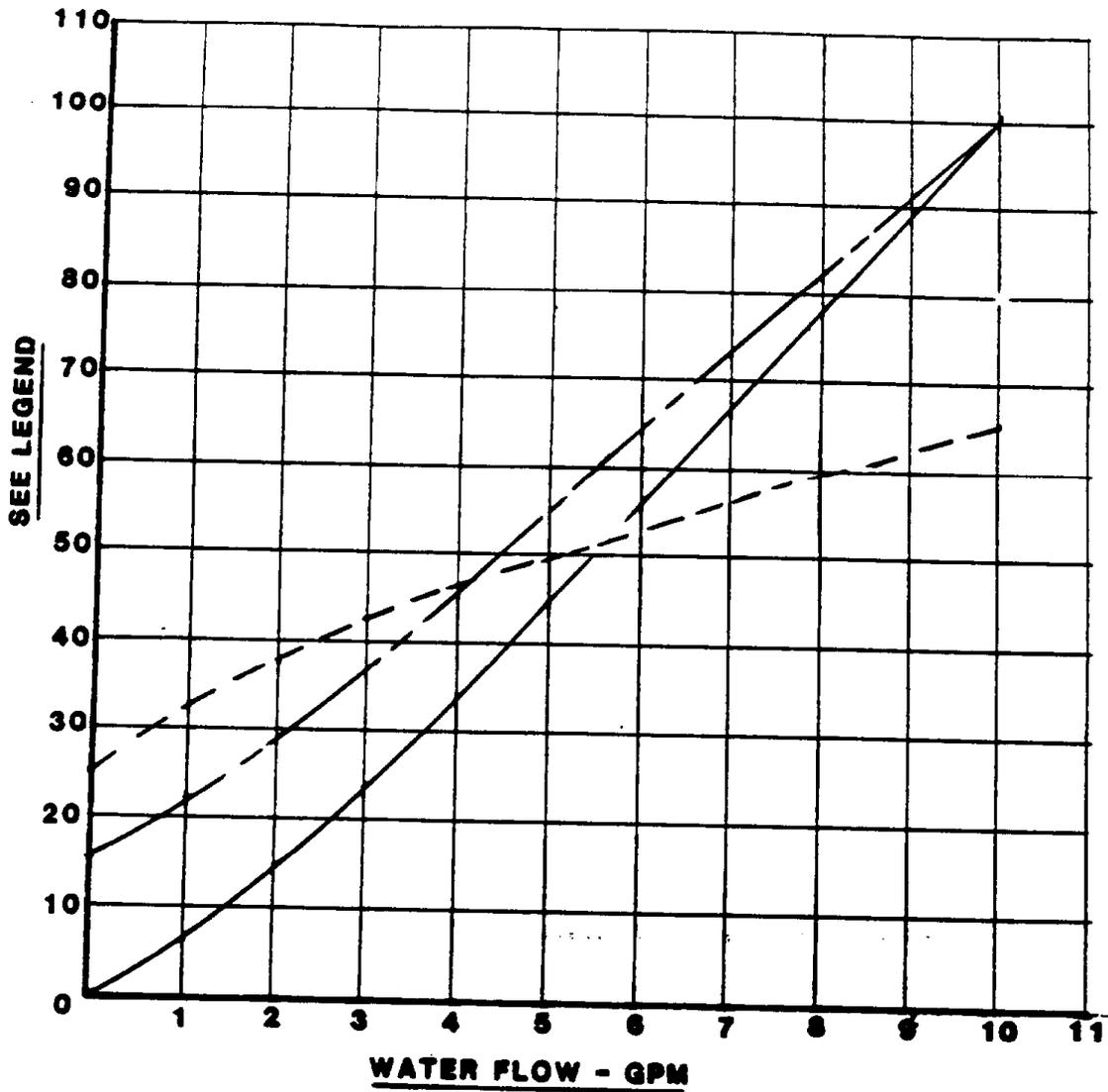
ENGINEERING FACTORS INVOLVED IN THE SELECTION OF THE

ENVIROCARE EVAPORATIVE COOLING TOWERS

L/D	6.749	
REQUIRED RESIDENCE TIME	0.89 SEC.	
AVAILABLE RESIDENCE TIME	1.90 SEC.	
VELOCITY	1100 FT/MIN	5.61 M/S
STATIC PRESSURE LOSS	0.40 IN. W.C.	
REYNOLDS NUMBER	125558	10 mm

LEGEND:

AIR(PSIG) 
 WATER(PSIG) 
 AIR FLOW(SCFM) 



NEXT ASSY NO.

△			
△			
△			

SYM REVISION DATE BY AP

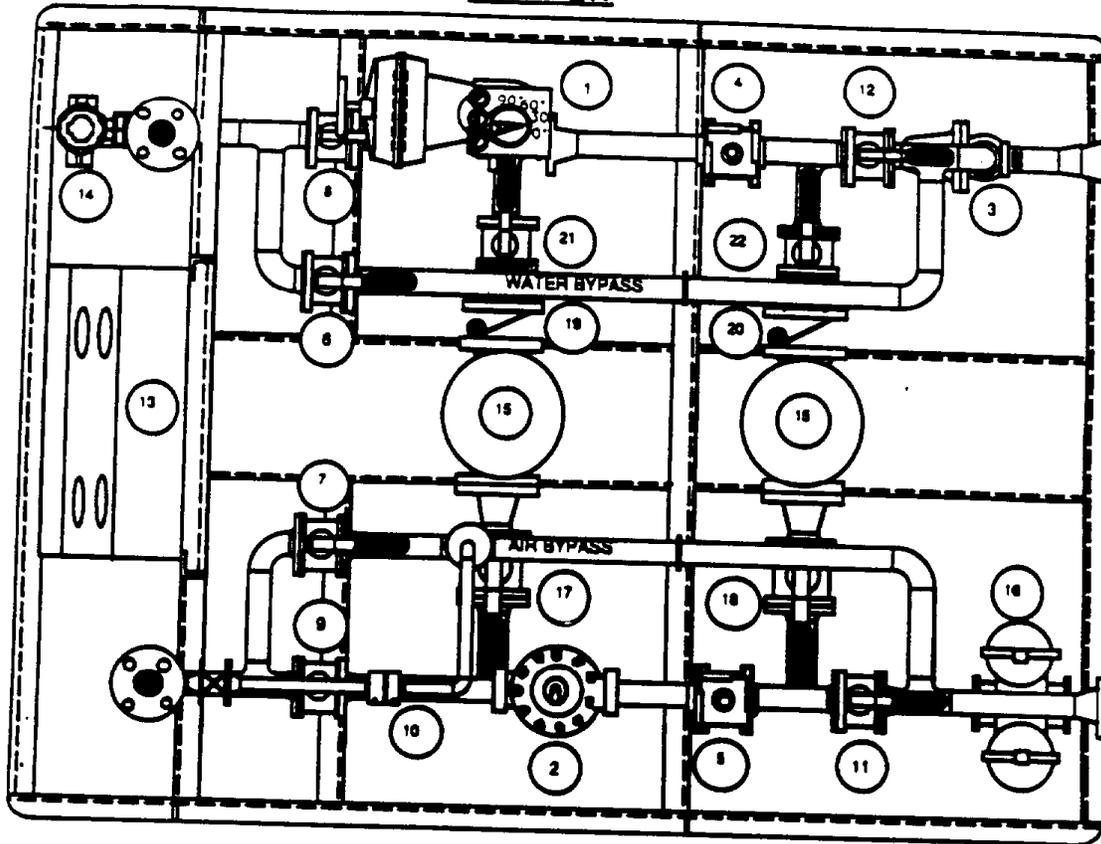
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TITLE **ENVIROCARE MM-10 MICROMIST PERFORMANCE CURVE**

DRAWN <i>SK</i>	DATE <i>9/13/88</i>	CLIENT	STANDARD	
DESIGN <i>JJS</i>	DATE <i>1/17/85</i>	PROJECT		
CHECK	DATE	CONTR NO.	QTY	RI
APPR	DATE	DWG NO. MMG-10	SHT	
SCALE NONE				

SINGLE VALVE RACK
COMPONENT IDENTIFICATION
TOP VIEW



- | | |
|-----------------------------------|---------------------------------|
| 1- WATER FLOW CONTROL VALVE | 12- INLET WATER BLOCK VALVE |
| 2- AIR PRESSURE CONTROL VALVE | 13- CONTROL CABINET |
| 3- BACK-PRESSURE REDUCING VALVE | 14- WATER FLOWMETER |
| 4- AUTOMATIC WATER BLOCK VALVE | 15- VERTICAL WATER PUMP |
| 5- AUTOMATIC AIR BLOCK VALVE | 16- INLET WATER BASKET STRAINER |
| 6- WATER BYPASS BLOCK VALVE | 17- INLET PUMP BLOCK VALVE |
| 7- AIR BYPASS BLOCK VALVE | 18- INLET PUMP BLOCK VALVE |
| 8- OUTLET WATER BLOCK VALVE | 19- CHECK VALVE |
| 9- OUTLET AIR BLOCK VALVE | 20- CHECK VALVE |
| 10- PURGE AIR RESTRICTING ORIFICE | 21- OUTLET PUMP BLOCK VALVE |
| 11- INLET AIR BLOCK VALVE | 22- OUTLET PUMP BLOCK VALVE |



