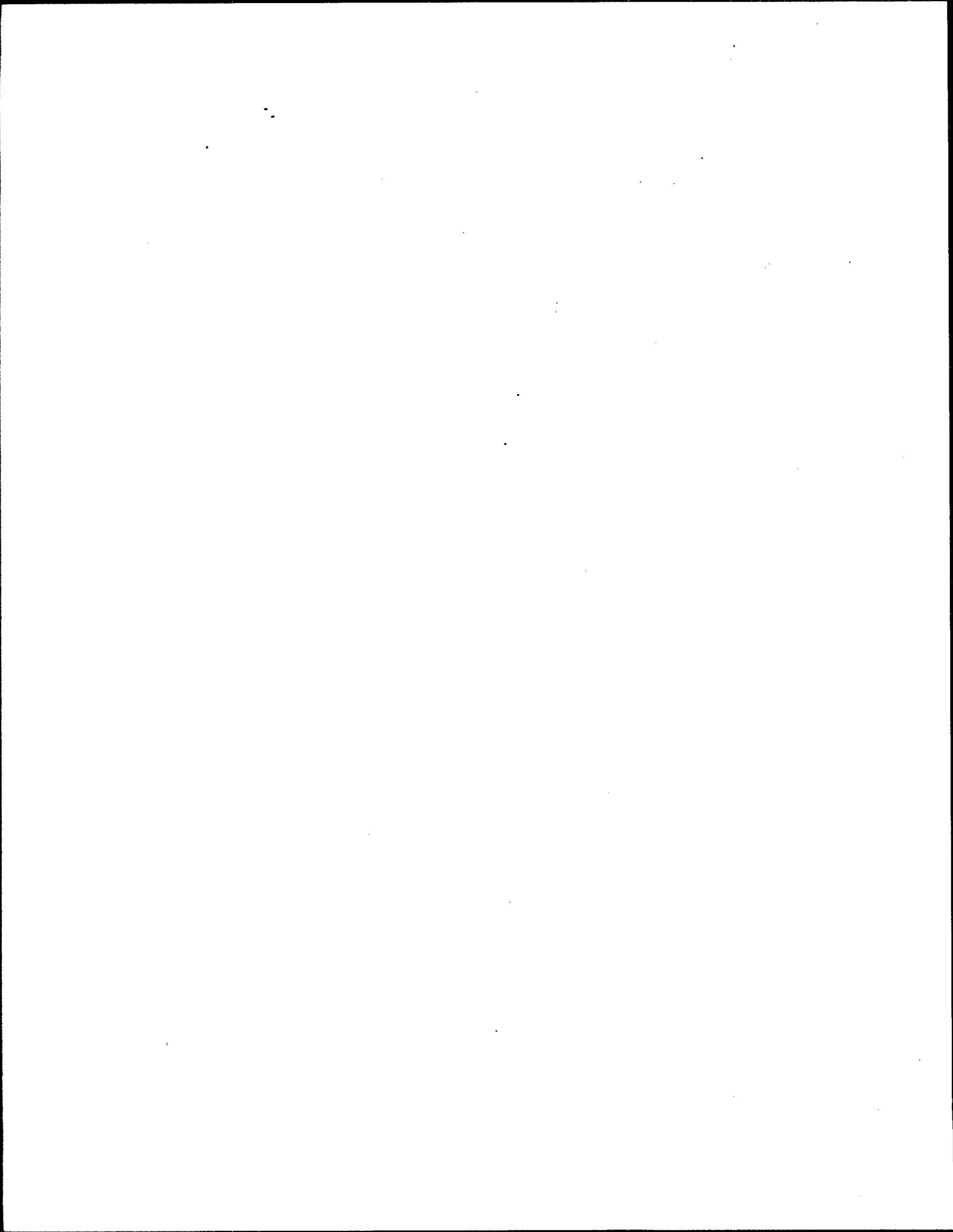


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**Medical Waste Incinerators-Background Information for Proposed
Standards and Guidelines:
Control Technology Performance
Report for New and
Existing Facilities**

July 1994

**U. S. Environmental Protection Agency
Office of Air and Radiation
Office of Air Quality Planning and Standards
Research Triangle Park, North Carolina**



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1.0 INTRODUCTION

The main objectives of this report are to describe the various emission control techniques used to control emissions from medical waste incinerators (MWI's), to summarize the emission test data generated during a comprehensive emission test program, and to provide an emission test data analysis that quantifies the performance of these techniques. Two general types of emission control techniques are described: combustion controls and add-on air pollution control systems (APCS's). Combustion controls refer to the control of the combustion process and the emission-generating mechanisms through proper design, operation, and maintenance to minimize the generation of emissions. Add-on APCS's control or remove pollutants from the exhaust gas stream after the gas stream exits the MWI system. This document is one of a series of reports written to provide background information used to develop emission standards and guidelines for MWI's under Section 129 of the Clean Air Act.

This report presents technical information on the emission control techniques available to control emissions from MWI's. Section 2.0 first describes the general approaches to combustion controls and subsequently describes specific designs and/or operational features that are employed to control the combustion process. Section 3.0 describes the add-on APCS's. Section 3.1 describes wet scrubbers including the venturi and packed-bed scrubbers in detail and briefly describes other types of wet scrubbers including the Rotary Atomizing™ scrubber, Ionizing Wet Scrubber™, the collision scrubber, and the Hydrosonic® scrubber. Section 3.2 describes fabric filters. Section 3.3 describes dry scrubbers including dry sorbent injection and spray dryer systems. Finally, Section 4.0 summarizes available emission test data and presents a test data analysis that quantifies the performance of APCS's (venturi/packed-bed scrubber, fabric filter/packed-bed scrubber, dry sorbent injection/fabric filter, spray dryer absorber/fabric filter), and three combustion controls (increased secondary chamber residence time, increased secondary chamber temperature, and proper charging procedures).

2.0 COMBUSTION: THEORY AND CONTROL

The emissions from an MWI are influenced strongly by the combustion process conditions. Consequently, combustion control can be an important element of MWI emission control measures. This section describes the MWI combustion process and discusses methods that are being used to control that process. Section 2.1 provides a brief overview of combustion theory and summarizes how the process characteristics affect emissions. Section 2.2 describes general approaches to combustion control and describes specific control practices that are typically used.

2.1 COMBUSTION THEORY

Combustion is defined generically as a chemical oxidation reaction characterized by the evolution of energy as light and heat. The medical waste combustion process is characterized by a complex combination of chemical reactions that involve the rapid oxidation of organic substances in the waste and auxiliary fuels. The goal of the process is to achieve complete combustion of the organic material, while minimizing the formation and release of undesirable pollutants.

This section presents a brief overview of the combustion process as it relates to medical waste incineration and describes the key physical and chemical phenomena that occur in combustion systems. It also identifies the key operating parameters and discusses their effect on the combustion process.

2.1.1 The Chemical Reactions

Because medical waste is a heterogeneous mixture of general refuse, pathological wastes, plastics, and laboratory wastes, the specific chemical composition is unknown and varies with time. However, the process can be described reasonably well by making some simplifying assumptions about the key chemical reactions. The organic portion of medical waste consists primarily of carbon (C), hydrogen (H), and oxygen (O), with other elements such as sulfur (S), chlorine (Cl), nitrogen (N), and a variety of metals being found to a lesser degree. Key combustion reactions involve these major waste constituents and the O₂ in the combustion air.

The simplified equilibrium reactions that characterize the MWI process are:

1. $C + O_2 \rightarrow CO_2 + \text{heat}$
2. $2 H_2 + O_2 \rightarrow 2 H_2O + \text{heat}$
3. $H + Cl \rightarrow HCl + \text{heat}$
4. $S + O_2 \rightarrow SO_2 + \text{heat}$

For equation 1, carbon monoxide (CO) also is formed if there is incomplete combustion. For equation 3, the available thermodynamic equilibrium data and bench-scale test data indicate that organic chlorine reacts almost completely to form hydrogen chloride (HCl) with small quantities of elemental chlorine (Cl₂) also produced. However, unless the H:Cl ratio in the feed is very low, and external hydrogen sources (e.g., water vapor) are unavailable, almost no Cl₂ is formed.¹ For equation 4, the organic sulfur is oxidized during the combustion process to form sulfur dioxide (SO₂). Because HCl is a stronger acid than SO₂, it will react more quickly with available alkaline compounds. Some SO₂ may react with available alkaline compounds; however, the amount of SO₂ involved in such reactions is expected to be negligible due to the high HCl content of the flue gas. Consequently, essentially all of the organic sulfur in the waste will leave the combustion chamber as vapor phase SO₂.

While these simplified reactions identify the major combustion products, they do not present a complete picture of the combustion process. Because of incomplete combustion, dissociation, and the formation of thermal and fuel nitrogen oxides (NO_x), the MWI exhaust gases will also contain trace amounts of CO, NO_x, methane (CH₄), Cl₂, and a wide range of organic compounds. Also, volatilization of inorganic compounds or entrainment of inorganic compounds in the combustion gases contaminate the exhaust gases with particulate matter (PM), including metals. A major goal of combustion controls is to minimize concentrations of compounds other than those identified in Equations 1-4 to levels as low as possible.

2.1.2 The Combustion Process

The primary objective of the MWI combustion process is the complete combustion of all organic material in the waste feed. As described in some detail in Section 2.2, MWI manufacturers and operators use a variety of specific design and operating techniques to achieve this goal. Despite this range of techniques, the basic combustion process and the factors that determine the ability of the process to achieve complete combustion are reasonably consistent. As a background for the more detailed discussion in Section 2.2, the paragraphs below provide a brief description of the typical MWI process and identify key factors that affect performance.

The basic MWI design typical of most newer systems is comprised of two, or possibly three chambers which are referred to as the primary, secondary, and tertiary chambers. Medical waste is fed into the primary chamber of these multiple-chamber units. This medical waste comprises a mixture of organic material (including volatile organics and fixed carbon), inorganic material (including metal compounds), and water. As this waste enters the primary chamber, it is exposed to a high-temperature heat source (either an ignition burner or the burning waste bed) and to combustion air. Key events that occur in the primary chamber are:

1. Moisture in the waste is evaporated from the waste and the water vapor temperature is raised to the temperature of the primary chamber exhaust gases;
2. Volatile organic materials in the waste are released and some amount of vapor-phase combustion occurs above the waste bed;
3. Fixed carbon is burned via surface oxidation reactions in the waste bed; and
4. Inorganic materials (particularly metals) are partitioned as entrained solids in the exhaust gas, vapors in the exhaust gas, and solid materials in the ash.

In most MWI systems, the combustion air supplied to the primary chamber is insufficient to complete the reactions described in Section 2.1.1. Consequently, a fuel-rich, exhaust

gas stream passes from the primary to the secondary chamber. Additional combustion air is supplied to the secondary chamber and the combustion reactions are carried towards completion.

How well this basic process achieves the goal of complete organic combustion with minimal release of undesirable pollutants is determined by three key factors that influence the combustion process. In simplest terms, these factors are usually referred to as time, temperature, and turbulence (or mixing). The combustion reactions described in Section 2.1.1 are equilibrium reactions. The degree to which these reactions move toward completion is a function of reactant availability, reaction rate, and time over which conditions are appropriate for the reaction to occur. The reaction rates for all combustion reactions are temperature dependent. The temperature at the point of combustion must be sufficiently high to initiate the reaction, and the degree of reaction completion depends on the time/temperature envelop to which the reactants are exposed. The key combustion reactions are oxidation reactions. Consequently, oxygen must be in close contact with the material being combusted for the reactions to proceed quickly. Turbulence is required to expose unburned material (in both the waste bed and in the secondary chamber) to the available oxygen in the incoming air. Without waste-bed turbulence, much of the unburned organic material (either volatile or fixed carbon) will be insulated under layers of ash and will not have sufficient oxygen available to complete the combustion process. The mixing created by turbulence in the waste bed ensures that all combustible materials contact the supply of oxygen at some point during the burning cycle. Turbulence in the secondary chamber ensures that volatiles and other unburned material are adequately mixed with combustion air (oxygen) to complete the combustion process begun in the primary chamber. Adequate secondary chamber temperature and gas-residence time are also required to complete combustion. Most combustion control measures described in Section 2.2 are related to time, temperature, and turbulence.

One other relationship that is an important prerequisite to understanding combustion controls is the relationship between combustion air and temperature. The stoichiometric amount of combustion air is the quantity of air needed to provide exactly the theoretical amount of oxygen for complete combustion of carbon and hydrogen in the waste. Theoretically, 100 percent stoichiometric air coincides with the condition of maximum temperature ($>1650^{\circ}\text{C}$ [3000°F]) in the chamber. A graphical representation of the relationship between combustion temperature and excess air level is shown in Figure 1. As the amount of combustion air is increased above the stoichiometric point (excess air), the combustion temperature is lowered because energy is used to heat the combustion air from ambient temperature to the combustion chamber temperature. The greater the volume of the excess air, the greater the "heat loss" due to raising the air temperature. As the amount of excess air is decreased, the combustion temperature increases until it becomes maximum at the stoichiometric point. Below the stoichiometric point, as the amount of combustion air is decreased, the temperature decreases because complete combustion has not occurred. Because the complete combustion reaction (which is exothermic) has not occurred, the maximum heat is not generated. Typically, the primary chamber of an MWI is operated in the substoichiometric region of the curve, while the secondary chamber is operated in the excess air region.

2.2 COMBUSTION CONTROL

Combustion controls are defined as any design features or operating practices that are used by MWI manufacturers and operators to reduce or limit the quantities of undesirable pollutants emitted with the MWI exhaust gases and to maximize the destruction, or burnout, of organic material in the solids bed. In addition to enhancing the quality of gaseous exhausts and solids discharge, the control measures are designed to minimize the operation and maintenance costs of the incineration system. These goals are often compatible in that the well-controlled combustion conditions that lead to low emission levels and good

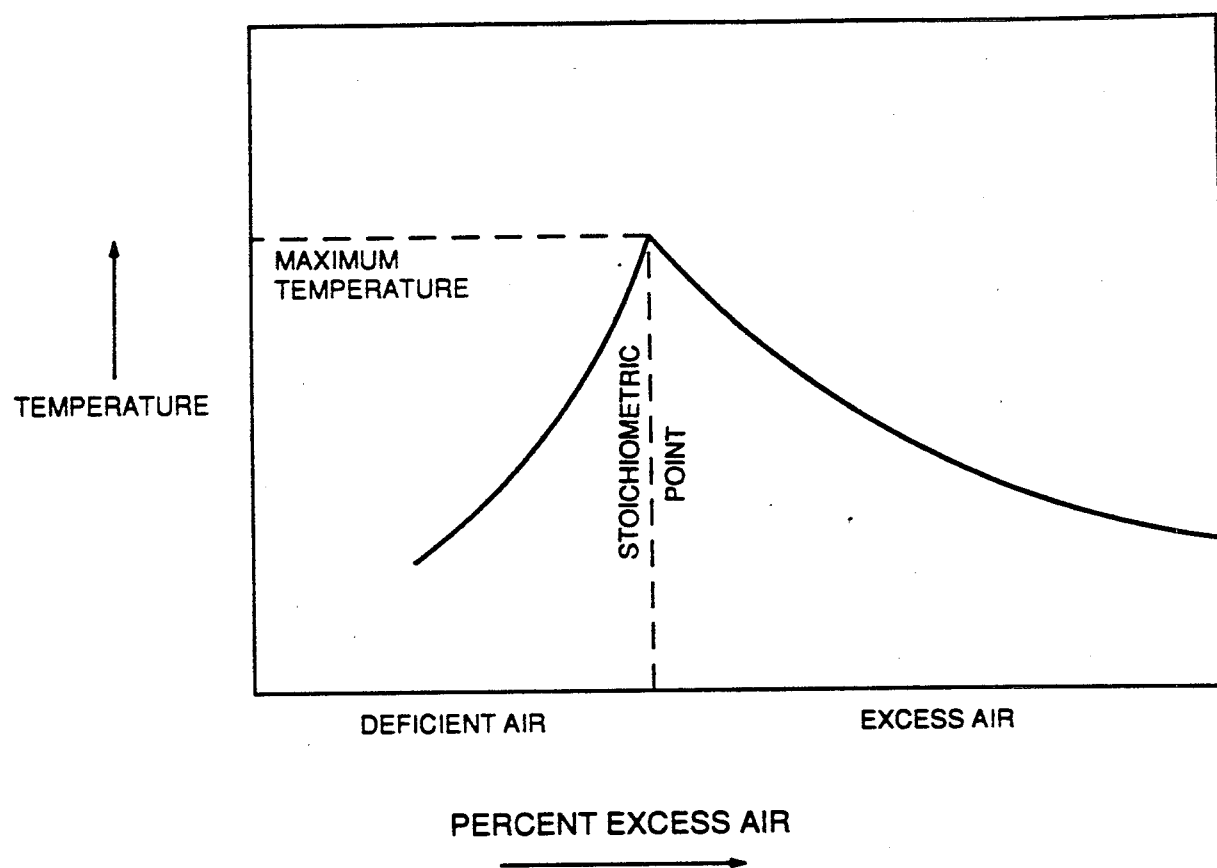


Figure 1. Relationship of temperature to excess air.²

ash quality' also tend to limit damage to the MWI system, thereby promoting lower operation and maintenance costs.

The remainder of this section discusses the combustion control mechanisms that have been implemented by different manufacturers and operators to control emissions from MWI's. The discussion is divided into three parts. The first provides a general overview of the different combustion control approaches that have been used. The second describes specific control practices and presents the available information on the effectiveness of these practices in controlling all pollutants of interest that are emitted from MWI's. The final subsection provides a brief overview of how these different specific control practices are related.

2.2.1 General Approaches to Combustion Control

Each MWI manufacturer has developed a package of features in its design that is aimed at controlling air emissions and ash quality. The mixture of controls varies among manufacturers, making each combustion system unique in its approach to combustion control. While each system is unique and a wide variety of specific practices are used, all of the systems comprise some combination of three general approaches:

(1) controlling the rate of primary chamber chemical reactions, thereby controlling the release rate of volatile organics and the degree of ash burnout; (2) controlling waste bed turbulence, thereby limiting entrainment of particles from the waste bed; and (3) controlling secondary chamber combustion conditions, thereby promoting the complete combustion of volatile organic material. These general approaches are implemented by including design or operating features that control some combination of the following parameters: temperature of the reactants and reaction products, residence time of reactants at reaction temperatures, and gas turbulence and solids mixing of the reactants in the primary and secondary chambers of the MWI.

When medical waste is charged to the primary chamber and is exposed to a high-temperature heat source, such as an already burning waste bed or auxiliary burners, numerous physical/

chemical reactions occur in and above the waste bed. These reactions include vaporization of moisture in the waste, the volatilization of organic material in the waste, both gas-phase and surface chemical reactions that involve pyrolysis and oxidation of organic material, volatilization of inorganic material in the waste, and the entrainment of solid materials in the combustion gases. Reactions continue in the secondary chamber for those gases and solid particles released from the waste bed. By controlling the key parameters of temperature, residence time, gas turbulence, and solids mixing of the reactants within each chamber, the rate and level of completeness of the physical/chemical reactions are also controlled.

Combustion control within an MWI is usually based on maintaining temperatures in both chambers within specified limits by controlling the combustion air rate to each chamber, the waste feed rate, and the auxiliary fuel burner operation. Limiting combustion air in the primary chamber to below stoichiometric conditions prevents rapid combustion, decreases the temperature, and allows a quiescent condition within the primary chamber that minimizes entrainment of PM. In the secondary chamber, however, high temperatures can be maintained in a turbulent condition with excess air (i.e., greater than stoichiometric levels) to ensure complete combustion of organics in the gases emitted from the primary chamber.

Combustion controls are generally aimed at reducing CO and organic emissions and limiting PM and metals emissions. Generally, these combustion control measures have little or no effect on emissions of HCl and SO₂. In both cases, most of the chlorine and sulfur will be converted to HCl and SO₂ under the entire range of combustion conditions which normally occur in an MWI.

There are varied degrees of combustion control for MWI's, depending not only on the manufacturer, but also on the type and size of the incinerator. Combustion control systems vary from simple, manually-controlled, manually-fed units to highly complex, automatically-controlled, automatically-fed, continuous

units. The specific combustion control practices used, their interrelationships, and their effects on the emission levels of specific pollutants are discussed below.

2.2.2 Specific Control Practices

Manufacturers and operators of MWI's use a variety of techniques to address the combustion control objectives identified in Section 2.2.1. The techniques that have been widely applied to MWI's include feed rate control, control of combustion air volumetric flow and distribution, temperature control in the primary and secondary chamber, control of solids retention time in the primary chamber and gas residence time in the secondary chamber, enhancement of gas mixing in the secondary chamber, control of solids mixing in the primary chamber, sizing and location of combustion air ports in the primary chamber, primary chamber steam injection, and operator training. The subsections below describe how each of these techniques is implemented and present qualitative assessments of the effect of the different techniques on pollutant emissions.

2.2.2.1 Control of Feed Rate. Each incinerator system is designed for a particular thermal input rate with the thermal input coming from the waste feed and, when necessary, auxiliary fuel burners. Under ideal conditions, the incinerator operates with a constant thermal input. Under actual conditions, however, the medical waste feed is a heterogeneous mixture with variable volatile content, fixed-carbon content, ash content, moisture content, and heating value. Incinerator operating conditions are varied to the extent possible with changing waste characteristics in order to promote controlled combustion and minimize pollutant emissions. Rates of thermal and volatiles release from the waste feed are controlled by controlling the combustion air rates in combination with control of waste feed quantity and frequency. This section describes waste feed control measures, while the combustion air control measures are described in Section 2.2.2.2.

The effects of waste feed rates on combustion conditions and emissions are closely tied to waste feed characteristics. Increasing the feed rate with low-density, high-heating-value

wastes (plastics, rubber, paper) results in higher gas-phase and solid-phase combustion rates, higher temperatures, higher volatiles release rates, and higher gas velocities in the primary chamber. Also, the higher temperature and resulting increase in volatiles release rates generate gas volumes that are likely to exceed the excess air capacity and volumetric capacity of the secondary chamber. All of these effects of increased waste feed rates raise the potential for high-PM emissions from entrainment, lower secondary chamber residence times, and the discharge of incomplete combustion products to the environment. Increasing the feed rate with high-density, low-heating-value wastes (fluids, tissue, bones) generally creates lower primary chamber temperatures due to the heat required to vaporize moisture and the low amount of heat being released from the waste. With wastes of this type, auxiliary fuel burners must often be operated to maintain the temperatures in both chambers. The large volume of water vapor and the small amount of combustible gases coming from the waste bed coupled with lower primary chamber temperatures increase the likelihood of the discharge of incomplete combustion products.

The methods used to control the feed rate for MWI's differ between batch-duty units and intermittent- or continuous-duty units. Batch-duty MWI's are designed to accept a single load of waste at the beginning of the incineration cycle, and feed rate control is simply a matter of how much waste is loaded into the primary chamber at that time. If the waste being charged has a significantly higher heating value than that specified for design purposes, the primary chamber must be loaded at less than volumetric capacity to decrease the thermal input from the batch charge. These units range in size from 331 to 1,724 kg/batch (150 to 3,800 lb/batch) and typically are loaded manually. Some batch MWI's also have options for charge door lock-out tied to a preset timer or to the primary chamber temperature to prevent the operator from opening the door before the cycle is complete.

The intermittent- and continuous-duty MWI's typically have a mechanical charging device (ram feeder) that permits waste

charging while the MWI is operating. Some small intermittent units, however, do not have a mechanical loading device but are charged manually, and some manufacturers offer a continuous mechanical charging device (auger feeder) for charging their continuous-duty MWI's. The ram feeder loading device feeds small charges of waste material to the primary chamber at regularly timed intervals. The size of each waste charge is controlled by the size of the hopper and the amount of waste the operator places into the hopper. The charging frequency can be controlled manually or by a preset timer on the control panel. Also, the charging cycle can be locked out or overridden by a control loop that responds to temperature in the primary chamber or the temperatures in both the primary and secondary chambers. To approach a steady thermal input, manufacturers recommend a charging procedure consisting of multiple charges at equally timed intervals. The recommended charge size is 10 to 25 percent of the rated hourly capacity, charged at 5- to 15-minute intervals. The charging frequency may then need to be adjusted to respond to variations in the waste composition.

2.2.2.2 Control of Combustion Air. For most MWI's, the primary combustion controls are driven by control loops that maintain the temperatures in the primary and secondary chambers of the incinerator within specified limits. The control parameter of greatest importance in maintaining these temperatures within setpoints is the combustion airflow rate in each chamber.

The combustion air in the primary chamber is typically controlled to below stoichiometric amounts. As stated in Section 2.1.2, limiting the combustion air in the primary chamber to below stoichiometric conditions (generally 40 to 70 percent of stoichiometric) limits the combustion rate by limiting the amount of oxygen available for both solid-phase and gas-phase oxidation reactions. By limiting these combustion reactions, the heat release rate to the primary chamber is reduced with a corresponding decrease in temperature. Also, limiting the combustion airflow and the resulting combustion rate allows a

quiescent condition to exist within the primary chamber that limits the entrainment of PM in the combustion gases exiting to the secondary chamber.

The combustion air in the secondary chamber is typically controlled to greater than stoichiometric amounts (generally 150 to 250 percent of stoichiometric [i.e., 50 to 150 percent excess air]). Consequently, the secondary chamber is said to operate with excess air. Combustion gases are maintained at higher temperatures in a turbulent condition with excess oxygen to ensure complete combustion of the volatile organic compounds and CO emitted from the primary chamber. Because the secondary chamber temperature is operating in an excess air mode, increasing the amount of combustion air to the secondary chamber decreases the secondary chamber temperature.

Controlling the combustion air in an MWI permits a staged combustion system for minimizing pollutant emissions from the combustion process. By limiting the combustion air and the temperature in the primary chamber, the formation of fuel NO_x and thermal NO_x and the entrainment of particulate matter are limited. Enough combustion airflow is maintained to ensure minimum temperatures for the destruction of pathogens in the waste and fixed-carbon burnout in the primary chamber. In the secondary chamber, the combustion air is controlled at levels that permit enough excess air for the required temperature, gas turbulence, and residence time of the combustion gases both to ensure the destruction of pathogens that have been entrained in the primary chamber exhaust and to complete the reaction of organics in the exhaust gas stream.

The conversion of fuel-bound nitrogen to NO_x (fuel NO_x) depends in large part on the local availability of oxygen to react with the volatile species, the amount of fuel-bound nitrogen, and the chemical structure of the fuel-bound nitrogen. Because of the substoichiometric amount of combustion air in the primary chamber with the fuel, the formation of fuel NO_x is minimized. Combustion air control affects organics destruction, metals volatilization, thermal NO_x generation, and ash burnout

only through the effects of combustion air on temperature and turbulence. The effects of temperature and turbulence on these phenomena are described in subsequent sections.

Combustion air control is usually based on the temperatures of the primary and secondary chambers. Thermocouples within each chamber are used to monitor the temperatures continuously; this information is then used to adjust the combustion air rate to maintain the desired temperatures. Many manufacturers also use timers and information about the loading and burndown cycles to control the combustion air. Some manufacturers have also used parameters such as gas flow, opacity, and oxygen concentration to control combustion air, but these mechanisms are not typical.⁸

The level of combustion air control varies from manually setting the combustion airflow dampers for each chamber to fully modulating the combustion airflow over the entire operating range. On some systems, the control settings are actuated by the feedback from a monitored parameter (e.g., temperature), by a specified time in a cycle (e.g., charge-door opening), or by a control timer. The more advanced, elaborate combustion air control systems offer more control of the temperature and hence the combustion rate in the incinerator, but they are also more complicated and more costly. The simple, manually set combustion airflow dampers are generally set for an average charge of medical waste with a typical composition. As the waste composition varies and the combustion of the waste charge proceeds, the combustion airflow through these dampers remains constant. Consequently, over the duration of a burn cycle, the percentage of stoichiometric air varies constantly in both chambers, resulting in changes in the combustion rate, temperature, turbulence, residence time, and pollutant emissions. In contrast, the automatically controlled, fully modulated, combustion air control systems permit continuous monitoring of the chamber temperature and the control of the combustion airflow rate according to that temperature. These changes in the combustion airflow rate also modulate the combustion rate and tend to smooth out temperature swings in both the primary and

secondary chambers. The increased stability tends to minimize the increases in pollutant emissions that can result from these temperature swings found in less automated MWI's.

Many of the newer, automatically controlled systems also stop the combustion airflow to the primary chamber when the charging door is opened, thereby compensating for the amount of combustion air that enters through the charge door with the charge. Many of these systems also operate with the combustion airflow damper to the secondary chamber fully open at the time of charging to ensure maximum excess air to combust the initial release of volatiles that accompanies a fresh charge.

2.2.2.3 Control of Primary Chamber Temperature. Combustion control for the primary chamber of an MWI is typically based on controlling the temperature in that chamber. A thermocouple within the primary chamber is used to monitor the temperature continuously. Feedback from the monitoring is then used on some systems to control the combustion air rate at levels that maintain a specific setpoint temperature within the chamber. Control of the incinerator feed rate, use of auxiliary fuel burners, and water injection are other methods that may be used to control the primary chamber temperature.

The primary chamber must be operated at a temperature sufficient to sustain combustion and to combust the fixed carbon in the waste bed. The temperature in the primary chamber is maintained by the combustion of the fixed carbon within the waste bed, the combustion of a portion of the combustible gases in the primary chamber just above the waste bed, and, when necessary, auxiliary fuel burners. The typical operating ranges noted in the literature are 400° to 980°C (750° to 1800°F).^{2,4,5} The lower setpoint is needed to maintain fixed-carbon combustion and volatiles release from the waste bed, while temperatures below the upper setpoint minimize slagging and refractory damage.

The volatiles release rate and the gas- and solid-phase combustion rate are temperature dependent. Controlling the temperature level in the primary chamber also controls the combustion rate and the volatiles release rate from the waste bed

at the time of charging. If the temperature in the primary chamber is not controlled, the resulting rapid volatiles release immediately increases the volume of combustion gases leaving the chamber, promotes the entrainment of both organic and inorganic materials, reduces the gas residence time, and increases the requirement for combustion air in the secondary chamber. Taken together, these phenomena are likely to result in increased PM, CO, metals, and trace organics emissions.

The formation of NO_x from nitrogen in the combustion air (thermal NO_x) is limited in both chambers by limiting the peak flame temperatures to less than 1649°C (3000°F), typically through combustion air control. The formation of thermal NO_x is highly temperature dependent and proceeds rapidly at temperatures in excess of 1649°C (3000°F) (see Figure 2). The theoretical flame temperature is the maximum flame temperature attainable with a stoichiometric amount of air and no heat losses and is typically in the range of 1649° to 1927°C (3000° to 3500°F) (see Figure 3). The actual flame temperatures, however, for substoichiometric and excess air conditions with the typical heat losses due to radiation, convection, conduction, and dissociation, are expected to be in the range of 1260° to 1371°C (2300° to 2500°F). Temperatures in this range are less conducive to thermal NO_x formation than the peak temperatures associated with stoichiometric air supply.^{6,7}

Primary chamber temperatures affect both the amount of metals being volatilized and the amount of metals being entrained in the exhaust gases leaving the primary chamber. Increasing primary chamber temperatures shifts the metals partitioning towards the volatile fraction and the entrained particle fraction and away from the ash fraction. Further, metals that volatilize at primary combustion chamber temperatures tend to selectively condense on small particles in the flue gas, a phenomenon known as fine particle enrichment. Also, higher primary chamber temperatures usually occur with conditions that cause increased particle entrainment (i.e., increased waste bed turbulence, increased combustion airflow, and increased volatiles release

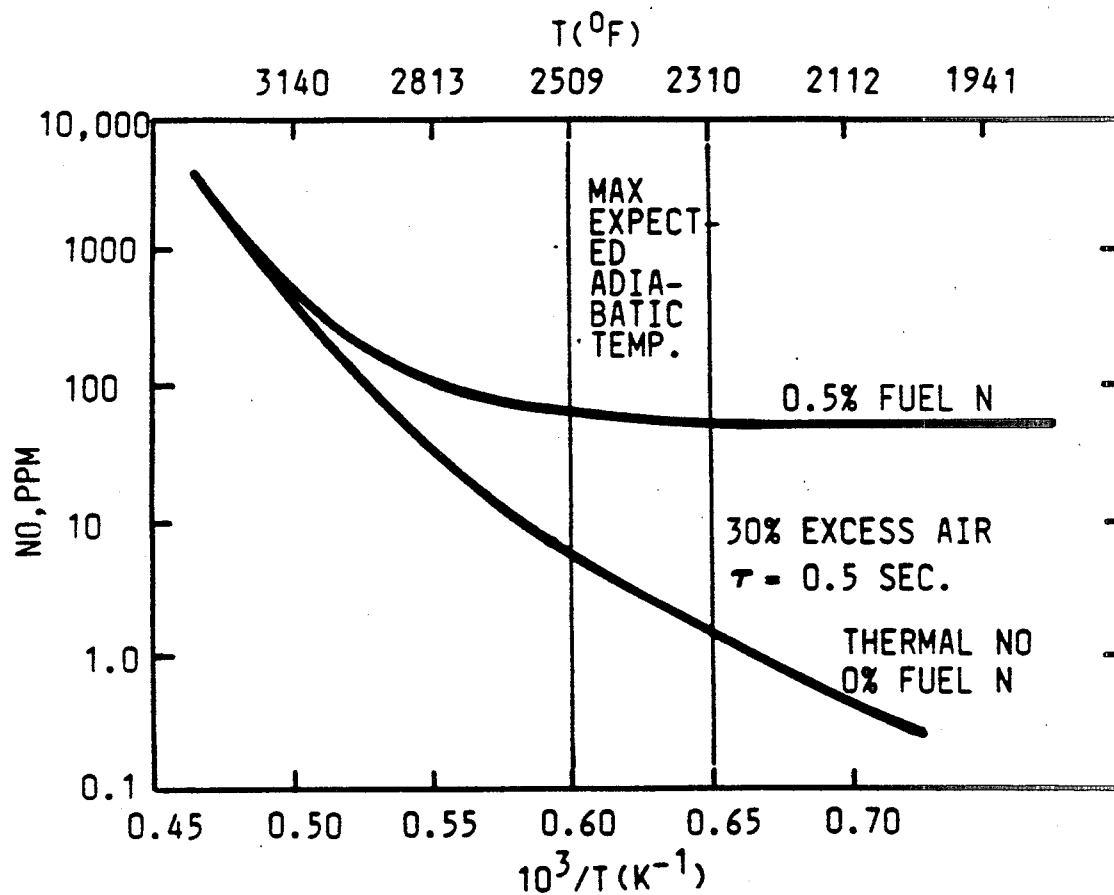


Figure 2. Impact of temperature and fuel nitrogen on NO_x emissions for excess air conditions (calculated using EER kinetic set).⁷

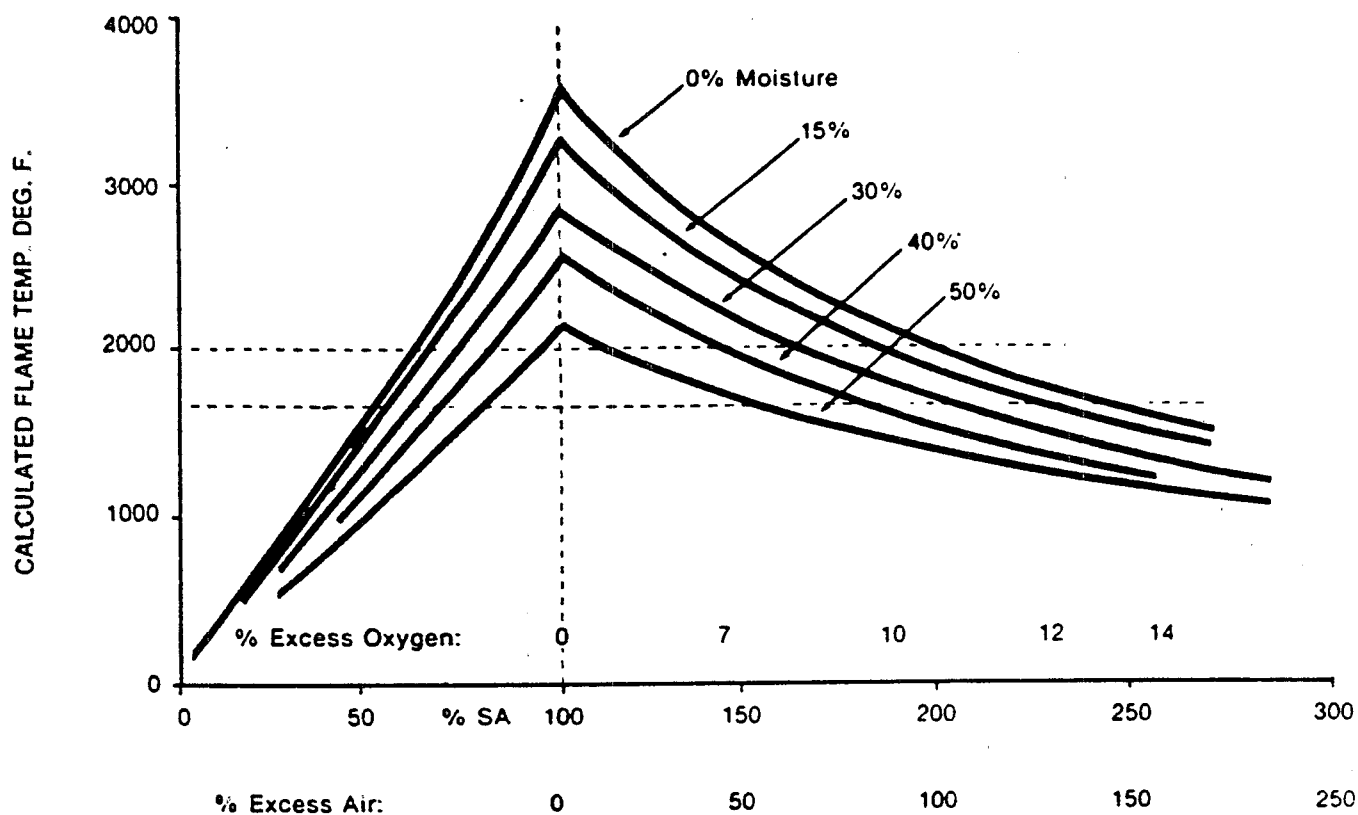


Figure 3. Theoretical temperature of the products of combustion calculated from typical municipal solid waste properties, as a function of refuse moisture and excess air or oxygen.⁸

(Reproduced from a paper titled "Minimizing Trace Organic Emissions from Combustion of MSW by Use of Carbon Monoxide Monitors" by Floyd Hasselriis presented at the ASME Solid Waste Processing Division Conference in 1986.)

rates). Hence, the amount of entrainment, volatilization, and enrichment of metals in the smaller-diameter PM is expected to increase if primary chamber temperatures are raised.

Typically, the primary chamber temperature is controlled by controlling the feed rate and the combustion air as described in previous sections. Other alternatives include using auxiliary fuel burners and/or water injection. For systems that rely primarily on airflow control, auxiliary fuel burners may be used as necessary to maintain a minimum setpoint temperature. The control of the auxiliary fuel burners varies substantially from unit to unit. The least complex systems consist of simple on/off switches that activate the burner or shut it off as setpoints are reached. More sophisticated systems fully modulate the burners from low fire to high fire based on the primary chamber temperature. Some manufacturers also offer a water injection system for rapidly decreasing primary chamber temperatures that exceed specific maximum setpoints. These systems are generally simple on/off switches.

For batch-type MWI's, manufacturers control the temperature by switching the burners and combustion air between high/low or on/off settings based on a series of timers.^{9,10}

2.2.2.4 Control of Secondary Chamber Temperature. The key secondary chamber combustion control parameter for MWI's is temperature. Typically, a thermocouple is used to monitor the temperature continuously near the secondary chamber outlet. That information is then used to modulate the amount of combustion air supplied to that chamber and, in some cases, to modify primary chamber operations to control the volatiles release rate. Because the secondary chamber is operated in an excess-air condition, increasing temperatures trigger an increase in the combustion airflow rate to bring temperatures back to the setpoint. (See Figure 1.) This increased combustion air reduces the secondary chamber temperature because energy is required to heat the excess air from ambient to flue-gas temperatures.

The primary function of the secondary chamber is to complete the combustion process initiated in the primary chamber. This

function is best accomplished if the secondary chamber is operated within a specified temperature range. If temperatures are too low, the gaseous and solid organics may not be completely destroyed. Consequently, the system may emit excessive levels of PM, CO, and organic emissions. If the temperatures are too high, refractory damage may occur, residence time may be decreased, and auxiliary fuel may be wasted. The limited data on pathogen destruction indicates that pathogens can be destroyed at the temperatures achievable in MWI's. Experimental work at the University of Dayton Research Institute indicates that temperature is the primary factor that affects the decomposition of organics and that a threshold temperature exists above which an organic compound rapidly combusts. The threshold temperature found for polychlorinated dibenzo-p-dioxin (CDD) and polychlorinated dibenzofurans (CDF) and potential precursors (e.g., hexachlorobenzene) is near 930°C (1700°F).⁷ Thermal NO_x formation is highly temperature dependent but only becomes significant at temperatures in excess of 1650°C (3000°F). As stated in Section 2.2.3, thermal NO_x formation is limited by limiting the peak flame temperatures within the secondary chamber to less than 1650°C (3000°F). Typically, upper setpoint temperatures in the MWI secondary chamber (about 1200°C [2200°F]) keep flame temperatures below those levels, thereby limiting thermal NO_x formation, and prevent refractory damage. In summary, a secondary chamber temperature operating range of 980° to 1200°C (1700° to 2200°F) promotes effective destruction of the organics and pathogens, conserves auxiliary fuel, prevents refractory damage, and avoids thermal NO_x formation.

The methods used to control the temperature in the secondary chamber include controlling the feed rate and combustion air (See Sections 2.2.2.1 and 2.2.2.2) and the use of secondary chamber auxiliary fuel burners. The temperature in the secondary chamber is typically controlled by modulating the combustion airflow. Also, when necessary, the auxiliary fuel burners are operated to maintain a minimum setpoint temperature. Auxiliary burner control varies from a single on/off switch driven by the lower

setpoint to fully modulating burners that range continuously over low-fire to high-fire in response to secondary chamber temperature. Also, since instantaneous peaks in the flow of combustion gases generated in the primary chamber can occur, a recommended operating practice is to keep the secondary chamber auxiliary burner on at all times to ensure that the volatile gases from the primary chamber combust completely during these peak conditions.¹¹

2.2.2.5 Control of Primary Chamber Retention Time. The nonvolatile combustible portion of the waste (fixed carbon) is burned on the primary chamber hearth at high temperatures. The fixed carbon is burned in surface oxidation reactions. This solid-phase reaction requires higher temperatures and longer exposure times than do the gas-phase reactions that occur above the bed in the primary chamber and continue in the secondary chamber.

After the volatilization of the waste material in the primary chamber is complete, sufficient time must be provided for the remaining fixed carbon combustion in the waste bed to be completed. For batch and intermittent duty incinerators, there is typically a burndown cycle that is controlled by a preset timer and temperature feedback from the primary chamber. During this cycle, the amount of fixed carbon remaining in the waste slowly decreases. To combust this remaining fixed carbon, a preset minimum temperature is maintained for a predetermined time period. The thermal input needed to maintain temperature during this time is supplied by fixed-carbon combustion and, when necessary, auxiliary fuel burners. The desired burndown time is preset by a timer, and the burndown cycle is initiated either manually by a switch or through an automatic system that "initiates" the burndown cycle automatically by restarting the burndown cycle every time the charge door is opened. In this automatic system, burndown is tied to the last charge. A typical burndown period for batch and intermittent units is in the range of 2 to 4 hours.^{10,12}

For continuous-duty incinerators there is no distinct burndown period since the waste is continuously moving through the system. However, during shutdown, some continuous-duty incinerators with stepped hearths and internal transfer rams use a distinct burndown procedure. After the last charge in a given campaign, each ram goes into a sequential burndown mode. The internal ash rams, starting with the initial or drying hearth, are operated in a mode that progressively increases the distance of each stroke over a prescribed time period until all the waste has been transferred to the next hearth. At this point, the underfire air to the initial or drying hearth is shut off, and the same sequence of operations is applied to the next hearth until all waste material is discharged to the ash pit. This burndown sequence is usually preset by the manufacturer but can be changed if ash quality is poor.

Three alternatives to the fixed-hearth systems described above are the rotary kiln, the Pulse-Hearth™ and the stoker. For the rotary kiln the retention time of the waste for burndown is determined by the rate of rotation and the angle of incline or rake of the kiln. One manufacturer of continuous-duty MWI's uses a Pulse-Hearth™ for moving waste material through the primary chamber. The retention time of the waste for burndown in this system is controlled by the frequency of the hearth pulses that move the waste along the hearth. Another manufacturer provides a stoker system to move waste through the primary chamber. The stoker comprises a series of overlapping, alternating stationary and movable grates. While a movable grate positioned over a stationary grate is advancing, a movable grate positioned under that stationary grate retracts to form a step 15 inches high. This action causes waste to fall and mix as it moves across the length of the stoker.

2.2.2.6 Control of Secondary Chamber Gas Residence Time.

In the modern MWI, the secondary combustion chamber serves as a reaction vessel to complete conversion of the organic materials released from the primary chamber. Although some of the carbonaceous material in entrained particulate matter may

combust, most of the chemical reactions in the secondary chamber are gas-phase reactions that involve volatile organic materials released from the waste and oxygen in the secondary combustion air. The specific reaction chains by which the organic material is converted to CO_2 and H_2O are not fully understood and are likely to be quite complex. However, they are generally assumed to behave according to first order reaction kinetics. Under such an assumption, the rate of conversion of organic material to CO_2 and H_2O is a function of the temperature/time envelope provided by the secondary combustion chamber. If the residence time is not sufficient, given the system's operating temperature, complete combustion of the organics and conversion of CO to CO_2 will not be accomplished.

The residence time in the secondary chamber is a function of the size of the chamber and the volumetric flow through the chamber. In its simplest form, the average residence time can be calculated as:

$$\Delta t_s = \frac{V_s}{Q_s},$$

Eq. 1

where:

Δt_s = secondary chamber residence time, sec;

V_s = secondary chamber volume, m^3 ; and

Q_s = combustion gas flow rate at secondary chamber conditions, m^3/sec .

The primary mechanism used to control residence time is appropriate sizing of the secondary chamber during the design process. Information collected from manufacturers indicates that systems are sized to have secondary chamber residence times of 0.25 to over 2 seconds under normal operating conditions. The two approaches that have been used to increase residence time are to increase the size of a single chamber or to construct two smaller chambers in series. For this latter approach, the two chambers are typically called the secondary and tertiary chamber, respectively. In theory, the two approaches should provide

equivalent residence times and emission reductions. No data that demonstrate differences have been identified.

Volumetric flow also affects residence time. Typically, this flow is not controlled directly in MWI's. Rather, it is a function of the feed rate, combustion air, and temperature control systems described earlier. Consequently, controlling these parameters to levels that are within design specifications is the key to achieving design secondary chamber residence times.

Secondary chamber residence times affect the control of organic emissions, CO concentrations, and, to a lesser extent, PM emission rates. Residence time does not affect metals or acid gas emissions. Increases in residence time at a given temperature decreases emissions of CO and organic pollutants, if properly mixed, by giving the oxidation reactions more time to move to completion. Increased residence time can also decrease PM emissions by providing additional time for the fixed carbon in entrained particles to combust and by allowing more complete combustion of condensible hydrocarbons.

2.2.2.7 Control of Secondary Chamber Mixing. The reaction rate for organic materials in the secondary chamber is a function of the temperature/time envelope provided by the chamber, but the reaction will proceed toward completion only if the gas phase organics from the primary chamber are well-mixed with the oxygen from the secondary chamber combustion air. Hence, complete combustion of the organics and CO in the secondary chamber requires turbulent mixing of the primary chamber exhaust and secondary chamber combustion air. As described in the paragraphs below, manufacturers have used a variety of techniques to promote turbulent mixing in the secondary chamber.

Two general types of techniques are used by manufacturers to promote secondary chamber mixing. First, all manufacturers use the location, direction, and velocity of the secondary air ports to promote turbulent flow, although specific designs vary among the different manufacturers. In addition, some manufacturers use constrictions or physical barriers such as baffles in the secondary chamber to increase gas velocity and create turbulent

flow. Note that both types of techniques are related to the design rather than the operation of the facility. However, the system operation does play a key role in maintaining turbulent conditions in that the different mechanisms designed to promote mixing are related to combustion air and combustion gas velocities. If the system operating rate drops to the point that gas velocities drop below minimum design specifications, insufficient mixing can result.

Each manufacturer has a unique system for introducing combustion air to the secondary chamber. Most MWI's contain a short, narrow passage between the primary and secondary chambers that is known as the flame port. Many designs introduce most of the secondary air into this flame port at a direction perpendicular to the flow of the primary chamber exhaust gases. The high gas velocities in this area are purported to generate a well mixed stream. While many systems introduce the major portion of secondary combustion air into the flame port, other designs introduce the air at different locations in the secondary chamber. Common designs include high-velocity air jets at multiple axial locations that introduce combustion air in a direction perpendicular to the gas flows at velocities sufficient to penetrate to the center of the chamber and airports near the flame port opening that introduce air tangential to the gas stream to promote cyclonic flow. One system introduces secondary combustion air through a device known as a thermal exciter.¹³ Although these designs have different geometries, they are all designed to achieve complete penetration of the primary chamber exhaust gas cross-section by the combustion air and to promote gas turbulence throughout the secondary chamber.

In addition to careful introduction of secondary air, some manufacturers use physical restraints in the secondary chamber to promote turbulence. One manufacturer uses a long, narrow, cylindrical secondary chamber to increase gas velocities and thereby promote turbulence. Other designs include locating baffles at multiple positions along the chamber and using a refractory choke ring about halfway along the cylindrical chamber

to generate turbulent flow. No quantitative measures of the effect of these physical measures on gas turbulence are available.

A well-mixed gas stream is needed to ensure intimate contact of organics in the gas stream with oxygen. Mixing also provides a more uniform temperature profile throughout the chamber and minimizes potential "short-circuiting" by portions of the gas stream. Good mixing reduces both organic and CO emissions and may provide some reduction in PM emissions. However, no quantitative measures of mixing are available.

2.2.2.8 Control of Solids Mixing in the Primary Chamber.

Solids mixing can have conflicting impacts on the control of emissions from MWI's. On the one hand, good mixing of the solids in the bed is needed to promote uniform temperatures in the bed, enable release of all volatile organic materials, and provide contact between all solid surfaces and the primary combustion air to ensure complete fixed carbon burnout. In contrast, excessive bed turbulence can lead to increased particle entrainment and, consequently, increased PM and metals emissions. Consequently, bed mixing or turbulence must balance these effects.

The two principal types of mechanisms that are used to control solids mixing are the physical processes that are used to move the waste along the primary chamber hearth and turbulence generated by injection of primary combustion air into the bed. Primary combustion air injection systems are discussed in Section 2.2.2.9. The paragraphs below discuss the physical mechanisms used to promote appropriate bed turbulence in three types of units--the fixed-hearth system (both single and multiple hearth), the pulse-hearth system, and the rotary kiln system. The basic concepts for these three systems are described in Section 2.2.2.5; the discussion below focuses on system parameters that affect solids mixing.

The most common MWI configuration is the fixed-hearth system. Historically, these systems were constructed with a single hearth and had either no ram (smaller, batch-fed units) or a single feed/ash ram. Feed/ash ram systems are found on larger

MWI's both to move waste/ash through the MWI effectively and to provide solids mixing. Newer designs contain multiple (three to four) hearths with a separate ram for each hearth. Single-hearth systems may have only a feed ram where new waste charges provide solids mixing. In general, these multiple-hearth systems mix solids in the bed better than do the single-hearth systems. The degree of turbulence in the bed of these systems can be controlled by controlling ram speed and ram stroke length. An increase in either of these parameters is likely to increase turbulence in the bed.

One alternative to the fixed-hearth design is the pulse-hearth design. Solids on these hearths are mixed via the pulsing action used to move the solids along the hearth. The degree of solids turbulence is a function of the pulse intensity. The manufacturer of this system claims to achieve better solids mixing than is achieved in fixed hearth units, but no data have been received to support this claim.

In the past 3 years, a limited number of rotary kiln MWI's have been installed in the United States. The rotary action generates substantially greater solids mixing than is achieved in either the fixed-hearth or the pulsed-hearth system. Within a given kiln, the degree of turbulence in the waste bed is a function of the rotational speed of the kiln, the angle of incline or rake of the kiln, waste characteristics, and the waste feed rate.

Ideally, control of solids mixing (or turbulence) in the primary chamber should be optimized to address conflicting objectives--maximizing ash burnout and minimizing particle entrainment in the exhaust gas from the primary chamber. In general, increasing mixing increases burnout, but it also generates higher concentrations of particles in the exhaust gas.

2.2.2.9 Sizing and Location of Combustion Air Ports in the Primary Chamber. The sizing and location of primary chamber combustion air ports are designed to address three objectives concurrently--to provide uniform airflows in the bed to control volatiles release, to promote complete fixed-carbon burnout, and

to minimize particle entrainment in the primary chamber exhaust gas. Also, systems are designed to maintain bed temperatures at levels that limit clinker formation and refractory damage.

Generally, combustion air is introduced to the primary chamber as "underfire" air, but some systems introduce the majority of primary chamber air through ports located immediately above the waste bed. While most systems do introduce underfire air into the side or bottom of the waste bed, the designs vary widely with respect to location of the injection ports, port size and geometry, and distribution of airflows along the combustion zone. Locations of the air ports include the side walls below bed levels, openings in the hearth itself, and the centerline of the ash ram. Geometries range from thin slots in the side walls that run the length of a hearth to small-diameter, circular openings in the hearth and the side walls to large-diameter low-velocity openings in the side walls and ash rams. Manufacturers also have different methods for distributing air along the hearth. Some systems introduce air uniformly along the total length of the hearth or along all hearths in a multiple hearth system (with the possible exception of the first hearth). Other systems vary the flow rates along the length of the hearth, with some systems providing higher flows at the charging/drying hearth and others providing higher flows at the discharge end.

Irrespective of the specific mechanism employed, the underfire air system design has three key impacts on emissions. First, the degree to which the system can operate in a consistent fashion without plugging or malfunctioning, affects how well the release of volatiles to the secondary chamber can be controlled. Controlling the release of volatiles to the secondary chamber affects CO and organic pollutant emissions. To reduce the potential for air port plugging, some continuous MWI's are designed with a mechanism that allows combustion air ports to be rodded or cleaned out while the MWI is in operation. Intermittent and batch MWI's require that the air ports be rodded out on a daily basis prior to the start of the burn. Second, the degree to which the system provides good oxygen contact with ash

surfaces as the ash moves toward the discharge end of the chamber affects ash burnout. Finally, the turbulence generated by the combustion air system affects particle entrainment and PM emissions.

2.2.2.10 Steam Injection in the Primary Chamber. Some manufacturers use steam injection into the ash bed to facilitate burnout of fixed carbon in the ash bed and at the same time help prevent hot spots and clinker formation on the hearth.^{14,15} The steam is injected into the ash bed through the underfire air ports. The steam reacts with the fixed carbon in the waste/ash bed to produce CO and hydrogen (H_2). This reaction is an endothermic reaction (absorbs heat), thus reducing the temperature in the ash bed. (The normal oxidization reaction of oxygen with carbon is exothermic and evolves heat, causing the ash bed temperature to rise and potentially resulting in hot spots adjacent to the air ports). The steam injection promotes complete burnout of the ash, and also helps to prevent hot spots in the ash bed adjacent to the air ports which might promote slagging.

Different techniques are used by different manufacturers for injecting steam. One manufacturer uses a series of staged hearths in its large incineration designs. The steam is injected through underfire ports in the last hearth in lieu of air.¹⁵ Another manufacturer of an intermittent-duty incinerator mixes the steam with the underfire air, which is distributed throughout the entire area of the hearth.¹⁴ During operation, steam injection is not used during the first part of the incineration cycle. Once an ash bed is developed, the steam injection is activated, and the steam is injected with the combustion air; the amount of air injected is reduced by the volume of steam injected.

2.2.2.11 Operator Training. Previous sections identify key operating parameters for the incineration systems and indicate the relationship between these parameters and potential emissions. No studies have been conducted to determine the effect of operator training (or the lack thereof) on emission

levels. Nonetheless, it is reasonable to presume that operator training can result in the reduction of emissions. An operator who understands how the key operating parameters affect emissions and who knows the preferred operating procedures can operate and maintain the incinerator and APCS in a manner that minimizes emissions.

Using proper waste charging procedures for an incinerator is an example of an operation that can affect emissions. Training of the operator responsible for charging of the incinerator helps to ensure that the incinerator is charged in such a manner as to minimize emissions. The operator should be trained in the proper handling procedures and steps for charging the unit to minimize fugitive emissions during charging. These procedures typically are provided by the manufacturer in the MWI operation manual. Also, maintaining the proper frequency and size of each charge insures that the proper charge rate (heat input rate) is maintained, thereby enhancing controlled combustion. Many newer incinerators use sophisticated controls that result in an automated operation with few functions under the direct control of the operator. For example, the system may include the automatic control of the secondary burner and combustion air rates as a result of temperature output from the secondary chamber thermocouple. Also, some newer systems include an automated feed system which controls the frequency and weight of the charges. However, using automated controls does not alleviate the need for operator training; it simply refocuses the areas in which training is required. Although the operator may not need to understand the theoretical aspects of how the automated control system operates, someone responsible for the operation of the unit must understand how the system is designed and intended to operate, how to establish proper setpoints, and how to recognize the telltale signs of a malfunction or need for calibration/adjustment.

Operator training with respect to proper maintenance and operation is important. If the incinerator and its combustion control system are not properly maintained, then the system will

not operate properly. The result is likely to be increased emissions. For example, if the primary chamber underfire air ports are not maintained such that they remain clear of debris, the combustion air distribution will be affected and will affect the primary chamber temperature and, ultimately, emissions and ash quality.

3.0 ADD-ON AIR POLLUTION CONTROL SYSTEMS

Many APCS's consist of one add-on control device to control particulate matter (PM) and another to control acid gases (primarily hydrogen chloride [HCl] gas). These add-on control devices can be wet scrubbers, dry scrubbers, or fabric filters. The following sections describe these add-on control devices. Each section contains a general description of the control device physical characteristics (i.e., the various pieces of equipment and how they fit together), how the control device cleans the flue gas of its primary pollutant(s) and its effectiveness, the key operating parameters, and a qualitative discussion of how much co-control of other pollutants can be achieved. Additionally, each section contains a qualitative discussion of the factors that affect the performance of the control device in controlling PM, acid gases, metals, and CDD/CDF, including specific design features and gas stream characteristics.

This section describes wet scrubbers, dry scrubbers, and fabric filters and their application to MWI's. Section 3.1 describes venturi, packed-bed, and other types of wet scrubbers. Section 3.2 describes pulse-jet fabric filters. Section 3.3 describes dry sorbent injection and spray dryer dry scrubbers.

3.1 WET SCRUBBERS

A venturi scrubber in combination with a packed-bed scrubber is the most common wet scrubber system used to control emissions from MWI's. Venturi scrubbers are used primarily for PM control and packed-bed scrubbers are used primarily for acid-gas control. However, both scrubber types achieve some degree of control of both PM and acid gases. A large amount of information and emission test data are available for these scrubber types. Other types of wet scrubbers that have found limited application to

control emissions from MWI's include the Rotary Atomizing™ scrubber, the Ionizing Wet Scrubber™, the Calvert collision scrubber, and the steam-ejector scrubber.

Section 3.1.1 describes wet scrubbing mechanisms. Venturi and packed-bed scrubbers are described in detail in Sections 3.1.2 and 3.1.3. The other scrubbers mentioned above with potential application to MWI's are briefly described in Section 3.1.4.

3.1.1 Wet Scrubbing Mechanisms

Wet scrubbers collect particles primarily through the mechanisms of impaction and diffusion and remove gaseous pollutants primarily through absorption. The following subsections describe these mechanisms.

3.1.1.1 Collection of PM. Wet scrubbers capture relatively small dust particles with relatively large liquid droplets. These droplets are produced by injecting liquid at high pressure through specially designed nozzles, by aspirating the particle-laden gas stream through a liquid pool, or by submerging a whirling rotor in a liquid pool. These droplets collect particles through two primary collection mechanisms: impaction and diffusion. With both of these mechanisms, PM collection increases with an increase in relative velocity (liquid- or gas-phase input) and a decrease in liquid droplet size.¹⁶

In a wet scrubbing system, dust particles with diameters greater than 1.0 micrometer (μm) tend to follow the streamlines of the exhaust stream. However, when liquid droplets are introduced into the exhaust stream, particles cannot always follow these streamlines as they diverge around the droplet (Figure 4). The particle's mass causes it to break away from the streamlines and impact on the droplet. Impaction is the predominant collection mechanism for scrubbers with a gas stream velocity greater than 0.3 m/sec (1 ft/sec), which is well below the gas stream velocity experienced in most scrubbers.^{17,18}

Very small particles (less than 0.1 μm in diameter) experience random movement in an exhaust stream. These particles are so tiny that they are "bumped" by gas molecules as they move

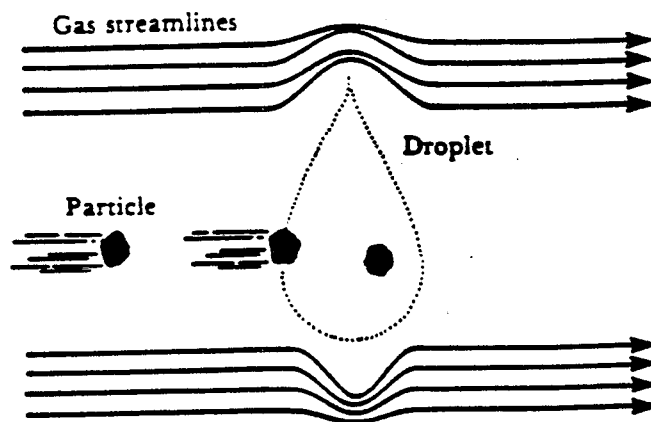


Figure 4. Impaction.¹⁸

in the exhaust stream. This bumping, or bombardment, causes the particles to move first one way and then another in a random manner, i.e., to diffuse through the gas. This irregular motion (or diffusion) can cause the particles to collide with a droplet and be collected (Figure 5).¹⁹ The rate of diffusion depends on relative velocity, particle diameter, and liquid droplet diameter. Collection by diffusion increases as particle size decreases. This mechanism enables certain scrubbers to remove the very tiny particles (smaller than $0.1 \mu\text{m}$) effectively.¹⁹

In summary, impaction is the predominant PM collection mechanism for particles greater than $1.0 \mu\text{m}$ while diffusion is the predominant mechanism for particles smaller than $0.1 \mu\text{m}$. For particles between 0.1 and $1.0 \mu\text{m}$, neither mechanism dominates; particles in this size range are collected by both mechanisms. However, particles in this size range are not collected as efficiently as are either larger particles by impaction or smaller particles collected by diffusion.^{18,19}

3.1.1.2 Absorption of Gaseous Pollutants. The process of dissolving gaseous pollutants in a liquid is referred to as absorption. Absorption occurs when mass is transferred as a result of a concentration difference between the liquid and the gas from which the contaminant is being removed. Absorption

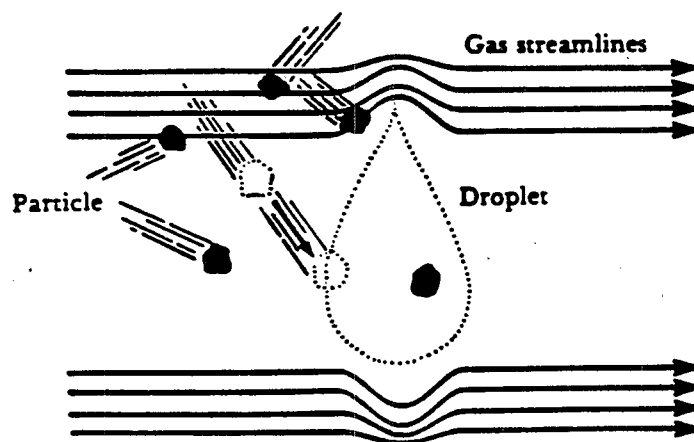


Figure 5. Diffusion.¹⁹

continues as long as a concentration differential or lack of equilibrium exists. In absorption, equilibrium depends on the solubility of the pollutant in the liquid.²⁰

To remove a gaseous pollutant by absorption, the exhaust stream must be brought into contact with a liquid. Figure 6 illustrates the three step process involved in absorption. First, the gaseous pollutant diffuses from the bulk area of the gas phase to the gas-liquid interface. Second, the gas molecule moves (transfers) across the interface to the liquid phase. This step occurs extremely rapidly once the gas molecules (pollutant) arrive at the interface area. Third, the gas molecules diffuse into the bulk area of the liquid, thus making room for additional gas molecules to be absorbed.

The rate of absorption depends on the diffusion rates of the pollutant in the gas phase (first step) and in the liquid phase (third step). Gas diffusion and, therefore, absorption can be enhanced by:

1. Providing a large interfacial contact area between the gas and liquid phases;
2. Providing good mixing of the gas and liquid phases (turbulence), and

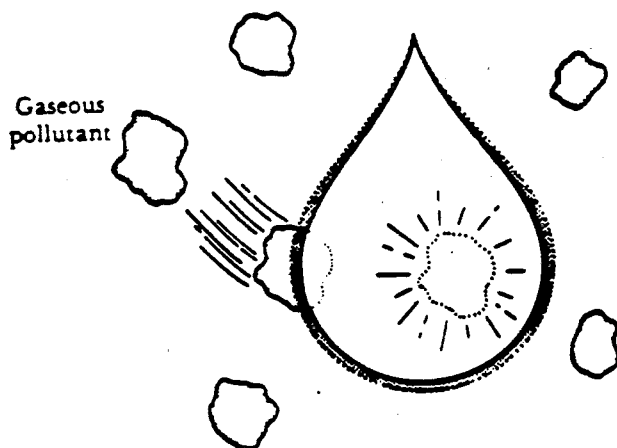


Figure 6. Absorption.²⁰

3. Allowing sufficient residence, or contact, time between the phases for absorption to occur.²⁰

A very important factor affecting the amount of a pollutant that can be absorbed is its solubility. The solubility of the pollutant governs the amount of liquid required and the necessary contact time. More soluble gases require less liquid. Also, more soluble gases will be absorbed faster. (For example, HCl is absorbed more rapidly than SO₂ in water because HCl is much more soluble.) Solubility is a function of both the temperature and, to a lesser extent, the pressure of the system. As temperature increases, the amount of gas that can be absorbed by a liquid decreases. For this reason, some absorption systems use inlet quench sprays to cool the incoming exhaust stream, thereby increasing absorption efficiency. Pressure affects the solubility of a gas in the opposite manner. When the pressure of a system is increased, the amount of gas absorbed generally increases.²¹

3.1.2 Venturi Scrubbers

This section provides a general description of a venturi scrubber system including equipment components, the gas cleaning process, and key operating parameters followed by a discussion of the factors affecting the performance of the venturi.

3.1.2.1 General Description. A venturi scrubber system typically is made up of the following components:

1. Scrubber vessel;
2. Cyclonic separator;
3. Induced-draft (ID) fan;
4. Liquid recirculation system; and
5. System controllers.

These components are described in the following paragraphs.

Venturi scrubbers are designed to remove PM primarily by impaction through high-energy contact between the scrubbing liquid and the suspended PM in the gas stream.²² Figure 7 illustrates a simplified venturi scrubber vessel consisting of a converging section, a throat section, and a diverging section.²³ The high-energy contact is achieved by directing the scrubbing liquid and the gas stream to the throat section. The gas stream to be scrubbed enters the converging section (or quench) and as the gas flows towards the throat and the cross-sectional area decreases, the gas velocity and turbulence increase.^{23,24} The exhaust gas, pulled through the throat by the system's ID fan and forced to move at extremely high velocities in the throat, shears the liquid from the throat walls and atomizes the liquid into a large number of small droplets.^{23,24} (Another method of producing droplets is to atomize the liquid by supplying high-pressure liquid through spray nozzles with small orifices).²⁴ Impaction of the PM on the droplets occurs in the venturi throat and the exhaust stream exits through the diverging section where it is forced to slow down.²³

In venturi applications on MWI's, either a special quench section and/or the converging section of the scrubber vessel acts as a quench, both to saturate and to cool the gases prior to the venturi throat. The hot MWI exhaust gas is cooled by evaporating the quench liquid to an equilibrium temperature that, for most incinerator applications, lies between 66° and 85°C (150° and 185°F).²⁵

Two types of venturi scrubbers may be installed in MWI applications--wetted- and nonwetted-approach venturis. Wetted-

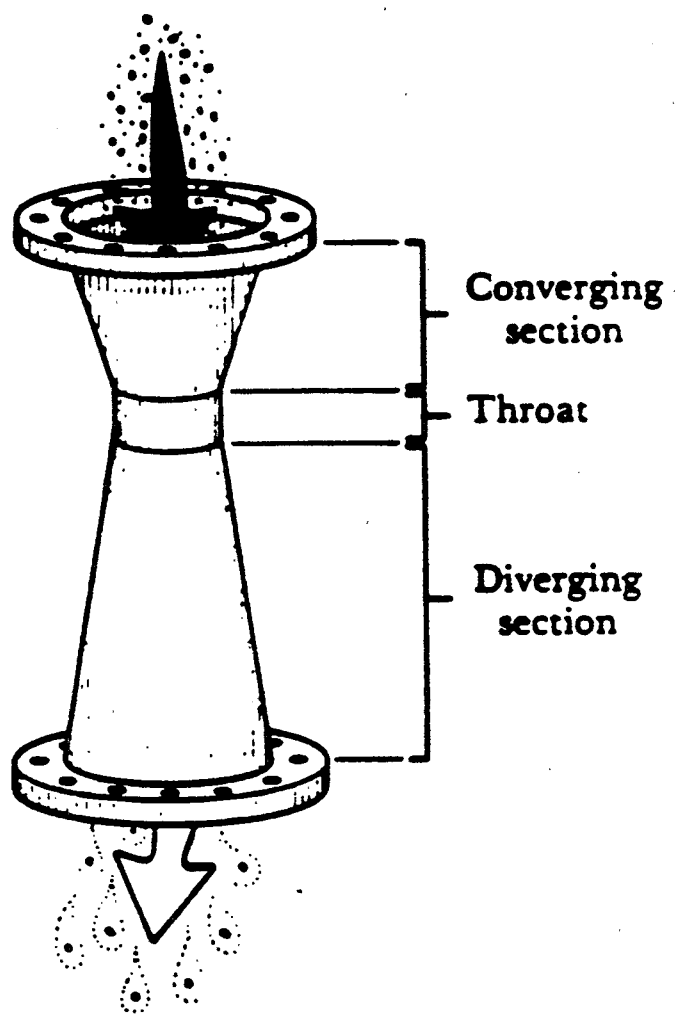


Figure 7. Simplified venturi scrubber configuration.²³

approach venturis are the most common. The primary difference between these two types is that in a wetted-approach venturi, which is illustrated in Figure 8, the scrubbing liquid is introduced through nozzles located at the top of the converging section to wet the scrubber walls. In a nonwetted-approach venturi, the liquid is injected through nozzles that direct the liquid directly into the throat without wetting the walls. Wetted-approach venturis are used when inlet gas streams are at temperatures greater than 93°C [200°F]. Coating the scrubber walls and throat with liquid reduces the tendency for PM to abrade or cake on the walls or throat.²⁶⁻²⁸

Because of the variations in MWI gas flow rate caused by waste charging and combustion air modulation, most venturi installations, in addition to being wetted-approach venturis, are variable throat venturis. Figure 9 illustrates a wetted-approach, variable throat, venturi scrubber.²⁹ Variable throat venturis use either a throat insert or an adjustable plate to decrease or increase the cross-sectional area of the venturi depending on the gas flow conditions.³⁰ The purpose of the variable throat is to maintain constant gas velocity across the throat, thereby maintaining venturi PM collection performance. Although a variable throat venturi can create restrictions in gas flow that cause the MWI draft to become positive, a venturi installed with a variable speed ID fan maintains negative draft in the MWI. As shown in Figure 9, scrubbing liquid also can be introduced through the throat insert.

The scrubbed gas from the venturi throat passes into the diverging section where the gas slows down.²³ Typically, the base of the diverging section is submerged in a pool of liquid to prevent abrasion of the metal surfaces by the collected PM.^{31,32} This configuration is called a wetted or flooded elbow and is illustrated in Figures 9 and 10.

The PM entrained in the droplets from the venturi scrubber subsequently is collected either in the packed-bed scrubber or in a cyclonic separator. Typically, in MWI applications, the gas passes from the wetted elbow to the base of a packed-bed scrubber

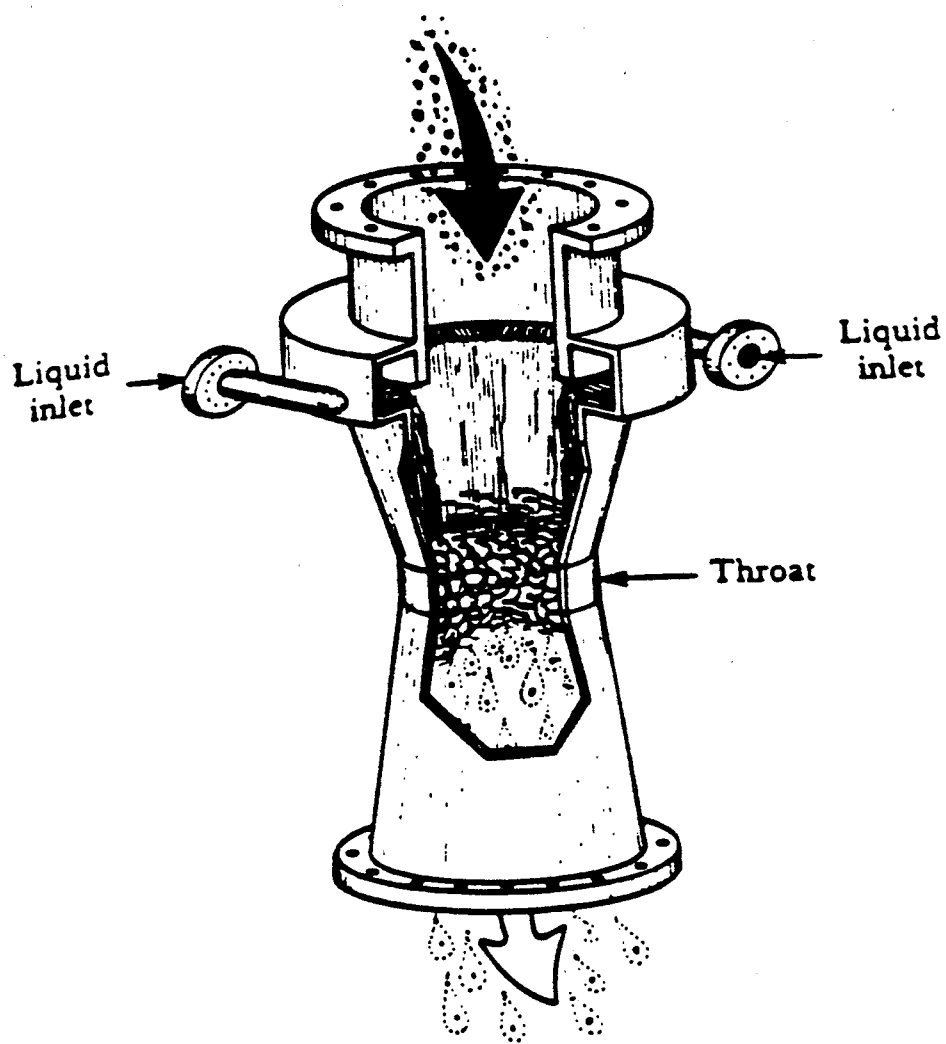


Figure 8. Schematic of wetted-approach venturi scrubber.¹⁶

VARIABLE VENTURI SCRUBBER WITH WETTED ELBOW

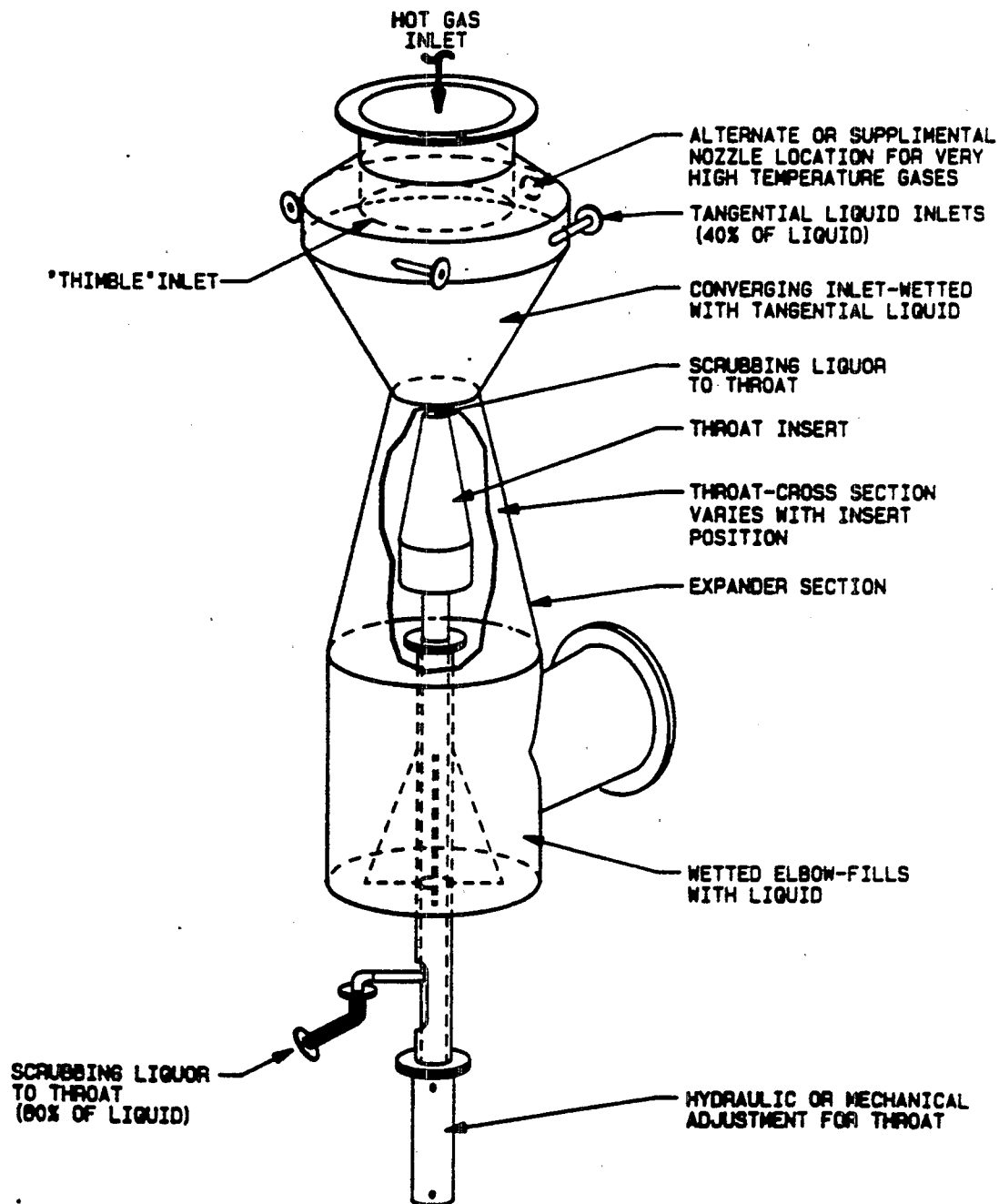


Figure 9. Schematic of wetted-approach, variable throat venturi scrubber.²⁹

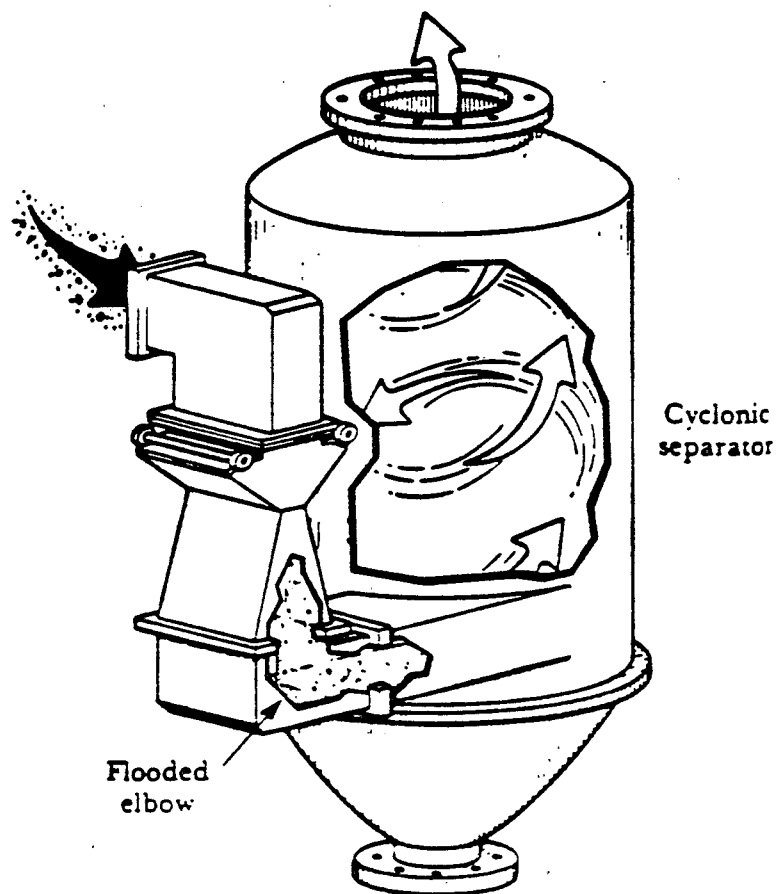


Figure 10. Venturi scrubber illustrating the flooded (wetted) elbow and exhaust gases passing to a cyclonic separator.³²

used for acid gas control where the entrained PM mixed with the scrubbing liquid is ultimately removed from the system with the scrubber liquid discharge (blowdown). (Packed-bed scrubbers are described in Section 3.1.3.) However, in those applications where a packed-bed scrubber is not used, the gas passes from the wetted elbow to the base of a cyclonic separator (see Figure 10). The gas is introduced tangentially to the cyclonic separator where the particles and moisture are thrown outward to the walls of the cylinder.³³ The droplets coalesce and drop down the walls to a central location carrying the PM with them.³³

The ID fan of a venturi scrubber system is located after the cyclonic separator (or packed-bed scrubber if so equipped) and pulls the exhaust gas through the system. Some installations utilize a variable-speed ID fan that can be tied to the control of the venturi throat insert and/or the MWI primary chamber draft so that the desired draft in the MWI primary chamber and a constant venturi throat pressure drop can be maintained. Other systems utilize a single speed ID fan equipped with a damper to control airflow.

The scrubber liquid recirculation system comprises a caustic solution tank, caustic addition equipment, recirculation pump, and piping. The liquid is recirculated through the system continuously. In many systems, a single recirculation pump is used (even on systems with packed-bed scrubbers) with a backup pump in parallel. A small blowdown stream is bled off to remove collected PM and a fresh water makeup stream is added to the system to replace the blowdown and any evaporative losses. Because the venturi scrubber liquid also absorbs a portion of the HCl in the exhaust gas, the pH of the scrubber liquid decreases. In most venturi scrubber applications, the scrubber liquid is a caustic solution used to neutralize acid gases and to prevent corrosion of equipment. A pH meter monitors changes in the scrubber liquid pH and a controller adds caustic solution to the system to maintain a pH of 7.0 or less.²²

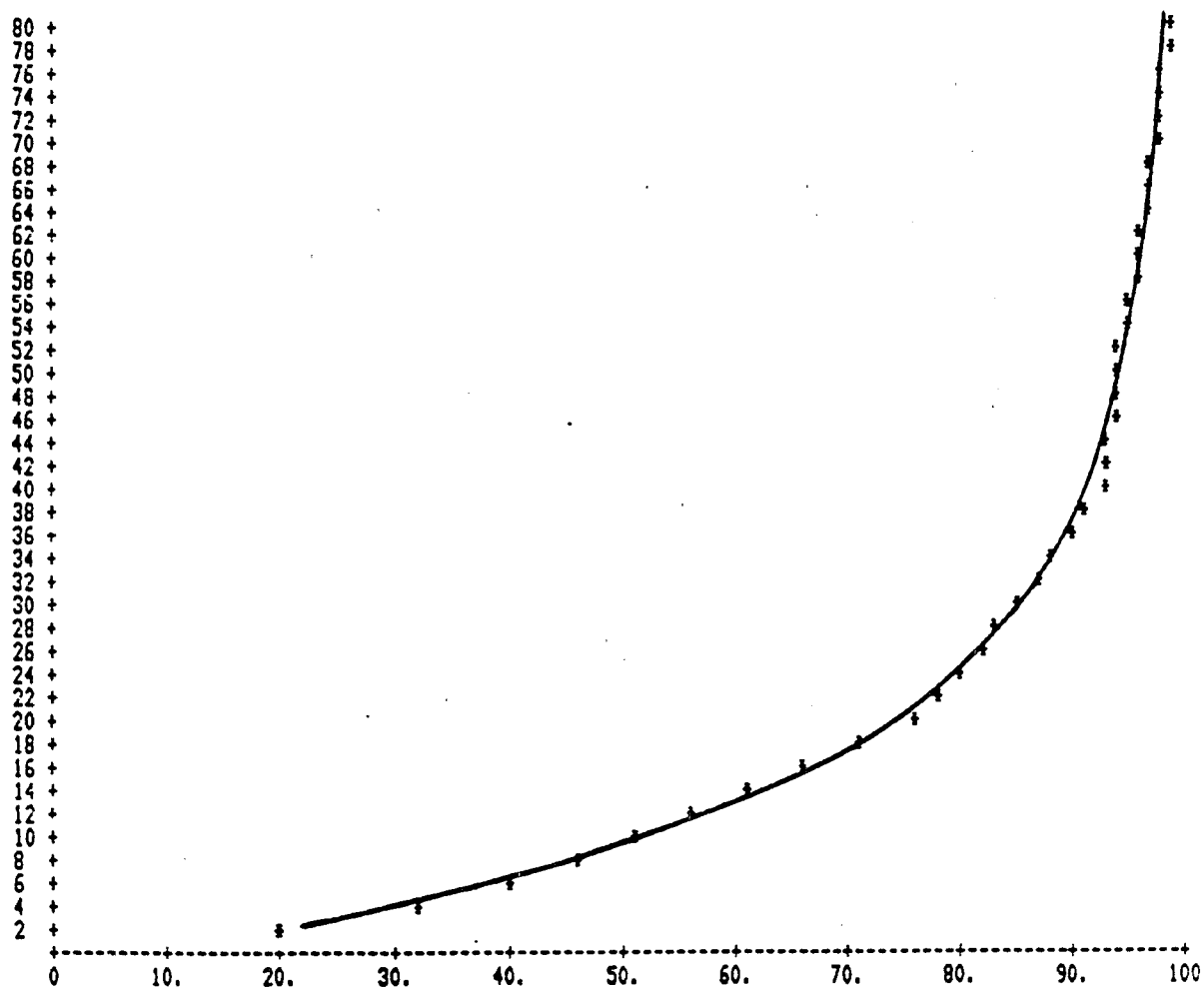
Venturi system controllers include those for the venturi throat insert, caustic feed, makeup water, and emergency water

quench for high-temperature excursions. The venturi throat insert is controlled either pneumatically or hydraulically to maintain constant throat velocity. The throat insert is moved upward or downward based on the pressure drop measured across the venturi throat. The rate at which caustic is added to the system is controlled in order to maintain a preset pH, typically 7.0 or slightly less.²² The rate at which makeup water is introduced to the scrubber typically is set at a rate necessary to replenish the liquid lost to blowdown and evaporation.

3.1.2.2 Factors Affecting Performance. The performance of the venturi scrubber relative to PM, acid gas, metals, and CDD/CDF emissions is affected by the venturi design and operating variables and also by key MWI operating variables. Key venturi scrubber design and operating variables are the pressure drop across the venturi throat, the liquid/gas (L/G) ratio, and the scrubber liquid pH, surface tension, and turbidity (i.e., solids content). Key process parameters that can affect venturi scrubber performance are the particle size distribution and the variations in temperature, flow rate, and pollutant concentrations that result from the heterogeneous nature of the MWI process.

Venturi scrubbers are used on MWI's primarily to control PM emissions. The PM collection efficiency in a venturi scrubber system increases as the pressure drop increases.³⁴ Figure 11 shows this relationship based on the particle size distribution in Figure 12. The static pressure drop is a measure of the total amount of energy used in the scrubber to accelerate the gas stream and to atomize the liquid droplets. In MWI applications, a common venturi scrubber pressure drop is 7.5×10^3 Pascals (Pa) (30 inches of water column [in. w.c.]) but can range from 3.7×10^3 to 1.5×10^4 Pa (15 to 60 in. w.c.). The pressure drop across the venturi is a function of the gas velocity and L/G ratio and in practice is a surrogate measure for gas velocity.³⁶

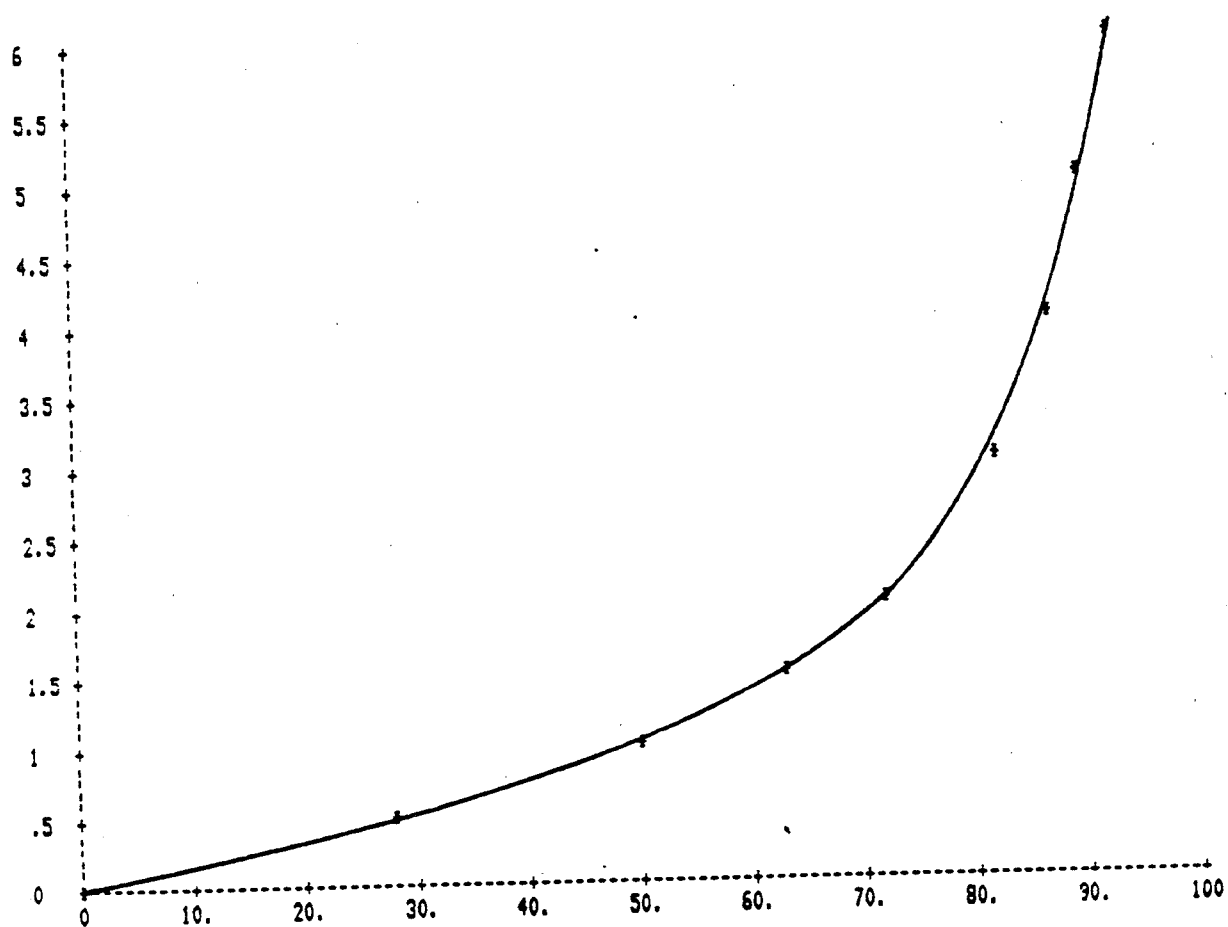
The Calvert equation can be used to predict the pressure drop for a given throat velocity. The Calvert equation is:



VERT AXIS: DIFFERENTIAL PRESSURE (INCHES W.G.)

HORIZ AXIS: % COLLECTION EFFICIENCY
: FROM 0 TO 100 IN STEPS OF 1

Figure 11. Venturi scrubber collection efficiency versus differential pressure.³⁵



VERT AXIS: AERODYNAMIC PARTICLE SIZE (MICRONS)
HORIZ AXIS: CUMULATIVE PERCENT LESS THAN STATED SIZE
: FROM 0 TO 100 IN STEPS OF 1

Figure 12. Typical medical waste incinerator exhaust gas particle size distribution.³⁵

$$\Delta P = (5 \times 10^{-5}) v^2 (L/G)$$

where

ΔP = pressure drop, in. w.c.

v = gas velocity in the venturi throat, feet/second, and

L/G = liquid-to-gas ratio, gallons/1,000 actual cubic feet (gal/Macf).

The equation implies that pressure drop is equal to the power required to accelerate the liquid to the gas velocity. The Calvert equation predicts pressure drop reasonably well for the range of L/G ratios from 668 to 1,604 liters/1,000 actual cubic meter ($L/Macm$) (5 to 12 gal/Macf). At L/G ratios above 1,604 $L/Macm$ (12 gal/Macf), measured pressure drops are normally about 80 percent of the value predicted by the Calvert equation. In practice it has been found that at L/G ratios less than 401 $L/Macm$ (3 gal/Macf), there is an inadequate liquid supply available to completely cover the venturi throat. Most venturi scrubbers are designed for liquid feed rates between 936 and 1,337 $L/Macm$ (7 and 10 gal/Macf), and there is virtually no change in performance over this range given that the pressure drop across the venturi throat remains constant.³⁷

The performance of a venturi scrubber in removing PM is strongly affected by the size distribution of the PM. For particles greater than 1 to 2 μm in diameter, impaction is so effective that penetration of particles in this size range through the venturi is quite low. However, penetration of smaller particles, such as the particles in the 0.1 to 0.5 μm range, can be high. Small particle size distribution, resulting from the condensation of partially combusted organic compounds and metallic vapors, is typical for combustion sources including MWI's.³⁸

To attain a high PM collection efficiency, venturi scrubbers need to achieve high gas velocities in the throat. At normal venturi pressure drops between 5×10^3 and 1.5×10^4 Pa (20 and 60 in. w.c.), the gas velocity in the throat section typically lies between 30 and 120 meter/second (100 and 400 feet/second).³⁴ These high gas velocities atomize the water droplets and create

the relative velocity differential between the gas and the droplets to effect particle-droplet collision.

The high exhaust gas velocities in the venturi result in a very short contact time between the liquid and gas phases, thereby limiting gas absorption into the scrubber liquid.³⁴ The limited residence time limits the amount of vaporous metallic and organic compounds that may be absorbed. However, because of the high solubility of HCl in water, a significant quantity of HCl may be absorbed even though the residence time is short. One vendor claimed an HCl removal efficiency of 90 percent across a venturi scrubber.³⁹

Other variables related to venturi scrubber performance are the liquid surface tension and liquid turbidity. If surface tension is too high, some small particles that impact on the water droplet will "bounce" off and not be captured. High surface tension also has an adverse effect on droplet formation. However, surface tension typically does not significantly impact scrubber performance. High liquid turbidity, i.e., high suspended solids content, will cause erosion and abrasion of the venturi section and ultimately lead to reduced performance of the system.⁴⁰ Therefore, the presence of a blowdown stream to remove suspended solids is important.

When hot MWI exhaust gases are quenched and saturated in the converging section of the venturi, an equilibrium temperature of between 66° and 85°C (150° and 185°F) typically is achieved.⁴¹ In this temperature range, volatile metals and unburned organics condense.⁴¹ As vaporous metals and organic constituents such as CDD/CDF cool, they condense, or agglomerate, on PM.⁴² The greater the cooling, the greater these condensation and agglomeration effects.⁴²

The variations inherent in the operation of MWI's translate to variations in gas stream characteristics including temperature, flow rate, and pollutant concentrations. In many MWI applications, a waste heat recovery boiler (WHB) is used both to recover heat for use at the facility and to cool the MWI exhaust gases prior to an APCS. The WHB tends to damp the

variations in the exhaust gas temperature with the result that the WHB outlet temperature fluctuates far less than the exhaust gas temperature. With a L/G ratio of up to 1,337 L/Macm (10 gal/Macf), this small fluctuation does not affect the performance of the venturi significantly.

On venturi scrubbers controlling MWI's without a WHB, the MWI exhaust gas temperature variation can range from 927° to 1260°C (1700° to 2300°F). Venturi scrubbers in these applications may be equipped with special quench sections ahead of the converging section to cool the gas stream. Emergency quench nozzles may be installed at the top of the converging section that rapidly provide the necessary quench water to cool the gases and to prevent damage to the system in upset conditions. If the gases are not cooled to the typical equilibrium temperature between 66° and 85°C (150° and 185°F), then the venturi will be less effective in condensing volatile metals and organics.

Variations in MWI exhaust gas flow rate are compensated for by a variable throat venturi. Variations in the MWI exhaust gas flow rate arise during waste charging and during combustion air modulation in the MWI. Venturi scrubbers perform optimally when they operate at conditions that approach steady state. The variable throat venturi adjusts the throat cross-sectional area to maintain constant velocity across the throat.

Variations in pollutant concentration in the MWI exhaust gas are dependent primarily on waste composition. For example, changes in the chlorine content of the waste directly affect the HCl concentration in the exhaust gas. The PM and volatile organics concentrations can also change as the combustion process changes. Because venturi scrubbers are designed to remove a certain percentage of the incoming PM based on the particle size distribution and inlet loading, any increase in the inlet loading is likely to cause an increase in the outlet PM loading because a similar percentage of PM would be removed. Therefore, the venturi scrubber system design must be based on the maximum gas flow rate, PM loading, and pressure drop considering the particle

size distribution. Similar effects would be likely on gaseous pollutants, i.e., increases in HCl, metals, and CDD/CDF inlet concentrations would cause increases in outlet concentrations of these pollutants.

3.1.3 Packed-Bed Scrubbers

This section provides a general description of a packed-bed scrubber system including equipment components, gas cleaning process, and key operating parameters followed by a discussion of the factors affecting the performance of the packed-bed.

3.1.3.1 General Description. A packed-bed scrubber system typically comprises the following components:

1. Scrubber vessel;
2. Packing media;
3. Mist eliminator;
4. ID fan;
5. Liquid recirculation system; and
6. System controllers.

These components are described in the following paragraphs along with the packed-bed gas cleaning process.

Packed-bed scrubbers are designed to remove acid gases (primarily HCl and sulfur dioxide [SO₂]) by absorption of the gases into the scrubbing liquid and subsequent neutralization. An alkaline solution typically is used to maintain a constant scrubber liquid pH to prevent corrosion of scrubber components. The scrubbing liquid typically used is caustic solution (NaOH) although sodium carbonate (Na₂CO₃) and calcium hydroxide (Ca[OH]₂) (slaked lime) also can be used. When the acid gases are absorbed into the scrubbing solution, they react with alkaline compounds to produce neutral chemical salts.²² The rate of absorption of the acid gases is dependent on the solubility of the acid gases in the scrubber liquid; HCl is absorbed rapidly while SO₂ is absorbed more slowly. The neutralization reactions are essentially stoichiometric, i.e., the stoichiometric ratio of alkaline compounds added to the system to that required for complete neutralization of the acid absorbed into the scrubber solution is essentially 1:1 in packed-bed scrubbers.²²

Packed-bed scrubber vessels used to control acid gases from MWI's typically are countercurrent, vertical columns where the gas flows upward through the scrubber vessel and the scrubbing liquid flows downward. Figure 13 illustrates a countercurrent, packed-bed absorber with packing media, liquid sprays, and a mist eliminator.

Scrubbing liquid is evenly distributed by the liquid sprays over the packing media and trickles down through the bed wetting the surface of the packing and, thereby, exposing the gas to a large, wetted surface area. The depth of the bed depends on many factors including the type of packing used, pollutant concentration and solubility, the desired removal efficiency of pollutants, type of scrubber liquid used, liquid and gas flow rates, and system temperature. However, a packing depth of 1.5m (5 ft) using Intalox® saddles has been reported.³⁵ Other vendors specify packing heights that range from 0.9m (3 ft) to 3m (10 ft) without specifying packing type.^{44,45} The exhaust gas is forced to make many changes in direction as it winds through the openings of the packing media, thereby causing the gas to mix with the liquid. The large surface area of liquid/gas interface, the packing depth, and the random packing provide the necessary contact area between liquid and gas, sufficient residence time, and good mixing, respectively, for effective absorption to occur.

After passing through the packing, the gases flow through a mist eliminator that removes entrained droplets of liquid that may contain alkaline salts, absorbed acid gases, and PM. In a combination venturi/packed-bed scrubber system, the venturi may remove 90 percent of the PM from the MWI exhaust gas, and the remaining particles can become entrained in droplets from the packing media in the form of alkaline salts and other ultrafine PM. Therefore, the appropriate mist eliminator must be selected for the packed-bed scrubber to minimize PM emissions from the overall combination system. Mesh-, chevron-, and diffusion-type mist eliminators are available. At least one vendor has stated that a venturi/packed-bed scrubber system equipped with mesh- and chevron-type mist eliminators can achieve outlet PM

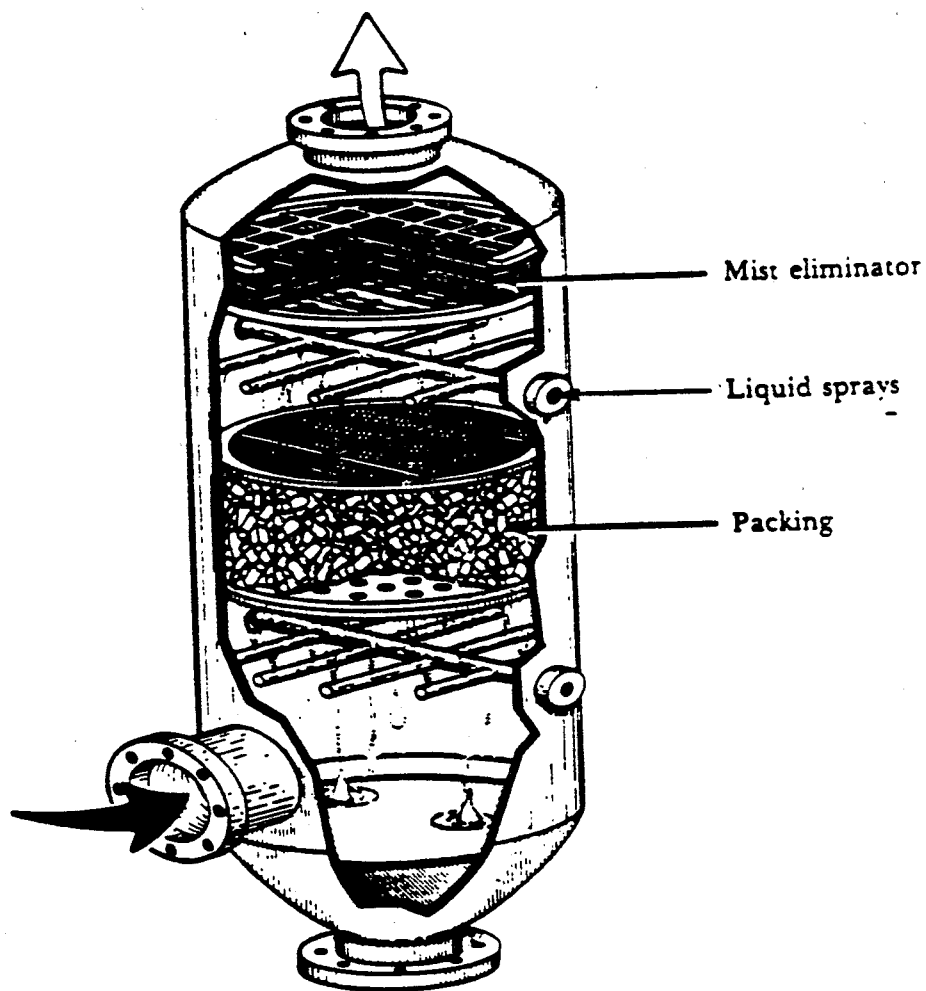


Figure 13. Schematic of countercurrent packed-bed scrubber.⁴³

concentrations of 0.03 grains/dry standard cubic foot (gr/dscf) while the diffusion-type mist eliminator can achieve concentrations less than 0.01 gr/dscf.^{35,46}

The ID fan, liquid recirculation system, and system controllers were discussed above in Section 3.1.2.1 on venturi scrubbers. With the exception of the variable throat and emergency water quench controllers, these discussions also apply to packed-bed scrubbers.

3.1.3.2 Factors Affecting Performance. The performance of the packed-bed scrubber relative to PM, acid gases, metals, and CDD/CDF emissions is affected by the packed-bed scrubber design and operating variables and also by key MWI operating variables. Key packed-bed scrubber design and operating variables are scrubbing medium, L/G ratio, packing height (liquid-to-gas contact time), suspended solids content, pH, and type of mist eliminator. Key MWI process parameters that can affect packed-bed scrubber performance are variations in exhaust gas stream temperature, flow rate, and pollutant concentrations that result from the heterogeneous nature of the MWI process.

The scrubbing medium or liquid used in packed-bed scrubbers to remove acid gases from MWI's typically is a caustic solution. This alkaline solution absorbs acid gases from the MWI exhaust gas stream and protects the scrubber components from corrosion by neutralizing the acid gases. The high solubility of HCl gas in this solution enhances the absorption of the HCl into the solution and thereby enhances the effectiveness of the packed-bed scrubber in removing HCl. When insoluble alkalis such as slaked lime are used as a scrubbing medium in packed-bed scrubbers, the suspended solids in the slurry deposit on the packing and cause plugging.²² Therefore, caustic solution absorbs and neutralizes acid gases, prevents corrosion, and eliminates plugging problems associated with insoluble alkalis.

The L/G ratio of a packed-bed scrubber is a design variable that is specified along with the packing height and packing media to achieve a specific control efficiency for a gaseous pollutant. A L/G ratio between 2,674 and 3,342 L/Macm (20 and 25 gal/Macf)

is typical for packed-bed scrubber applications on MWI's.^{35,44,45} The countercurrent packed-bed scrubber (typically used in MWI applications) does not operate effectively if there are large variations in the liquid or gas flow rates.⁴⁷ Generally, removal efficiency is increased by an increase in the liquid flow rate to the scrubber.⁴⁸ However, if either the liquid flow rate or gas flow rate is too high, a condition called flooding may occur.⁴⁷ Flooding is a condition where the liquid is "held" in the pockets, or void spaces, between the packing media and does not drain down through the packing.⁴⁷ The gas velocity at which flooding occurs is called the flooding velocity.⁴⁹ Flooding can be reduced by reducing the liquid flow rate.⁴⁸ In packed-bed applications to MWI's, a pump provides a constant liquid flow rate. The packed-bed diameter is sized so that the maximum gas velocity to be experienced by the packed-bed lies between 50 and 75 percent of the flooding velocity.⁴⁹

The performance of a packed-bed scrubber in removing acid gases from the gas stream depends on the effectiveness of the absorption process that takes place on the packing media. The packing media provides a large surface area for liquid-to-gas contact and promotes good mixing of the gas and liquid. The height of the packing determines the liquid-to-gas contact time; the greater the height, the greater the residence time. Packing heights of 1.5M (5 ft) using 7.6 cm (3 inch) Intalox® saddles have been reported.³⁵ Manufacturers guarantee HCl removal efficiencies from 99 to 99.9 percent and SO₂ removal efficiencies from 90 to 99 percent when a packed-bed scrubber is used in conjunction with a venturi scrubber.^{35,44,45} The effectiveness of the packed-bed scrubber in removing vaporous metals and condensible organics such as CDD/CDF from the gas stream is further enhanced as the gas stream is intimately contacted by the liquid film on the packing because vaporous metals and condensible organics may condense and be removed as PM.

The suspended and dissolved solids content and pH of the scrubber liquid are monitored to maintain scrubber performance. Solids accumulation at the entry to the packed bed and within the

bed is a problem that interferes with the absorption process by restricting liquid flow through the bed. To prevent solids accumulation, an adequate scrubber liquid blowdown rate must be maintained. Most manufacturers have designed their systems with a set blowdown rate that removes suspended and dissolved solids and that does not require shutdowns for solids removal.^{35,44,45} The pH typically is maintained at or slightly below 7.0 by monitoring pH and adding caustic solution as appropriate.²² Maintaining this pH level is important to prevent corrosion damage to scrubber components.

Selection of the appropriate mist eliminator is important to achieve low PM emissions. As described in Section 3.1.3.1, the mist eliminator removes entrained droplets of liquid that may contain alkaline salts, absorbed acid gases, and PM. A diffusion-type mist eliminator can achieve a three-fold reduction in PM emissions over the traditional chevron- and mesh-type mist eliminators.^{35,46}

The variations inherent in the operation of MWI's translate into variations in gas stream characteristics including temperature, flow rate, and pollutant concentrations. A packed-bed scrubber controlling emissions from an MWI typically is located after a PM control device such as a venturi scrubber or a fabric filter. In both of these cases, the MWI exhaust gas temperature is reduced before it reaches the packed-bed scrubber. In the case of the venturi scrubber, the MWI exhaust gases are cooled and saturated in the venturi and enter the packed-bed scrubber at a temperature between 60° and 85°C (140° and 185°F). In the case of the fabric filter, the MWI exhaust gases may be cooled initially by passing through a heat exchanger or WHB before passing through the fabric filter and a quench prior to the packed-bed scrubber. In either case, the temperature variations that occur in the exhaust gases leaving the MWI are damped and the gas stream temperature entering the packed-bed scrubber will be within a relatively narrow range. Gas stream temperatures in excess of 104°C (220°F) can damage or melt the

plastic packing media that typically is used in these scrubbers.⁵⁰

Variations in MWI exhaust gas flow rate are compensated for by the proper design and sizing of the packed-bed scrubber. As already described, the liquid flow rate to the packed-bed scrubber is set at a constant rate and the packed-bed scrubber diameter is sized such that the maximum gas velocity experienced by the system is 50 to 75 percent of the flooding velocity.⁴⁹ Therefore, as the gas flow rate varies in the MWI system, sufficient liquid is available for effective absorption without encountering flooding.

Variations in pollutant concentration in the MWI exhaust depend primarily on waste composition. Because HCl in the exhaust gas is highly soluble in the scrubbing solution, variations in HCl concentration are not expected to affect the performance of the packed-bed in removing HCl if the packed-bed has been properly designed for the maximum HCl concentration to be encountered. The effectiveness of the packed-bed scrubber in removing CDD/CDF and metals will depend in large part on the effectiveness of the system in condensing and subsequently collecting the resulting fine PM. The collection efficiency of a packed-bed scrubber in removing condensed metals and CDD/CDF is unknown.

3.1.4 Other Wet-Scrubbing Systems

Although venturi and packed-bed scrubbers are the systems that historically have been installed most frequently for MWI emissions control, other novel wet-scrubbing systems are beginning to penetrate the MWI market. Four types of systems that have been applied to various waste combustion processes are the Rotary Atomizing™ scrubber, the Ionizing Wet Scrubber™ (IWS™), the Calvert collision scrubber, and the Hydro-Sonic® scrubber. These systems have been used more frequently at municipal or hazardous waste incineration facilities, but they are being actively marketed to MWI facilities. Because the number of MWI installations of these systems is quite limited, very little information has been collected to date on the

performance of the systems or on the factors that affect performance. Consequently, the discussion below is limited to a brief description of each of the systems.

3.1.4.1 Rotary Atomizing™ Scrubbers.⁵¹⁻⁵³ Rotary Atomizing™ scrubbers are designed to remove PM primarily through impaction and acid gases primarily through absorption. Figure 14 illustrates a schematic of a rotary atomizing scrubber showing the major components listed above. The Rotary Atomizing™ scrubber comprises a quench vessel (on systems without a WHB), a prespray tower, a rotary atomizer, mist eliminators, and a liquid recirculation system. Because the liquid recirculation system is an integral part of the quench vessel, prespray tower, and rotary atomizer section of this scrubber and because it contains separate recirculation loops for each of these components, it is described first.

The liquid recirculation system on the rotary atomizer scrubber is unique in that there are three scrubber liquid recirculation loops. The liquid is staged in a countercurrent direction with respect to the gas flow. There are three separate scrubber liquid feed tanks that serve the rotary atomizer, the prespray tower, and the quench vessel. The fresh, clean scrubber liquid is fed to the rotary atomizer tank. Overflow from this tank flows to the prespray tower tank and a purge from the prespray tank then flows to the quench vessel. Blowdown from the quench vessel then flows to a sewer discharge.

On systems without a WHB, the combustion gases from the MWI are directed to the top of the quench vessel. The quench vessel serves two functions: (1) to cool the MWI exhaust gases and (2) to absorb a portion of the acid gases. The quench vessel evaporatively cools the MWI exhaust gases (982° to 1204°C [1800° to 2200°F]) to saturation (68° to 77°C [155° to 170°F]) through the introduction of the purge from the prespray section through spray nozzles located at the top of the vessel. The alkaline (NaOH) quench water converts a large portion of the HCl and SO₂ gases into sodium chloride and sodium sulfate salts. Once the total dissolved solids content has reached 15 percent in the

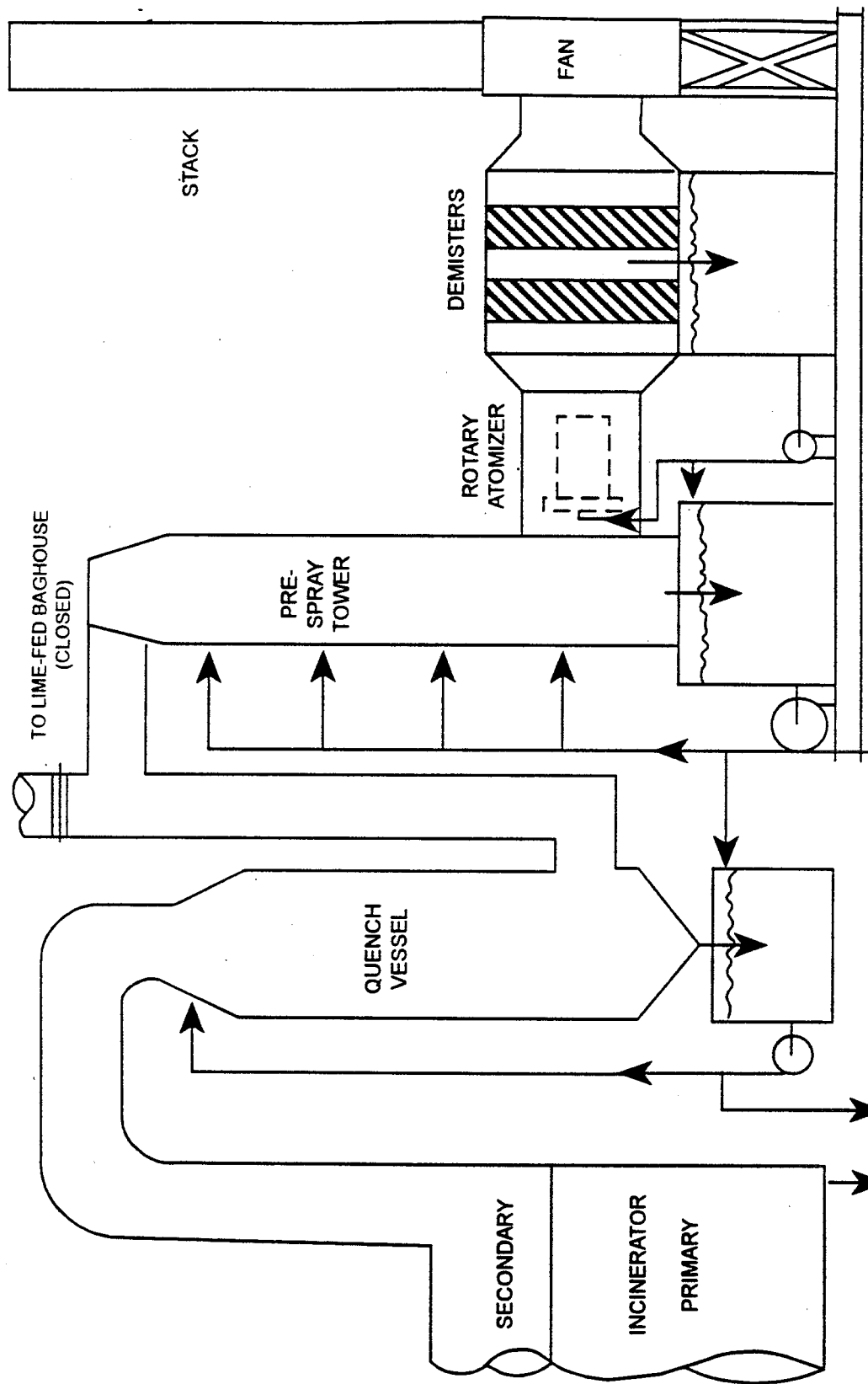


Figure 14. Schematic of Rotary Atomizing™ scrubber on a MWI. 52

quench tank feeding the quench vessel, a blowdown stream is activated that removes the dissolved and suspended solids from the system.

The saturated gases from the quench vessel (or from the WHB if so equipped) then enter the prespray tower where mid-size PM is removed by impaction on droplets produced by nozzles located at four different levels in the tower. Acid gases are further neutralized in the prespray tower. This tower operates at an L/G ratio of 8,020 L/Macm (60 gal/Macf) to completely saturate the gases prior to entering the rotary atomizer section. The tower is served by a prespray tank that uses the overflow from the rotary atomizer section as feed liquid. Liquid that exits the base of the tower unevaporated flows back into the tank and is recycled to the tower.

The saturated gases from the prespray tower subsequently pass to the rotary atomizer section of the system. Figure 15 illustrates the rotary atomizer. The rotary atomizer creates a constantly renewed high velocity water curtain equivalent to a 2.6×10^5 mmHg (5,000 pounds per square inch [psi]) spray nozzle. This water curtain is generated by means of a high speed rotating disc, that atomizes the water droplets and propels them toward the wall of the rotary atomizer housing. The droplets rebound off the wall creating a dense water curtain that acts as a filter pad. This dense spray of droplets removes PM through impaction, while gases are collected by absorption. The pressure drop across the rotary atomizing scrubber is about 7.5 mmHg (4 in. H_2O). Scrubbing solution also is recirculated through the rotary atomizer tank based on level control reward while fresh caustic reagent is added based on pH control demand.

The gas then passes from the rotary atomizer section through two Chevron-type mist eliminators that are used to collect and to separate the water droplets from the gas stream. The liquid collected by the mist eliminators is returned to the rotary atomizing section tank. The scrubber manufacturer claims that this 2-stage mist elimination system is rated at 99+ percent overall in removing droplets that are 2 microns or larger in size.

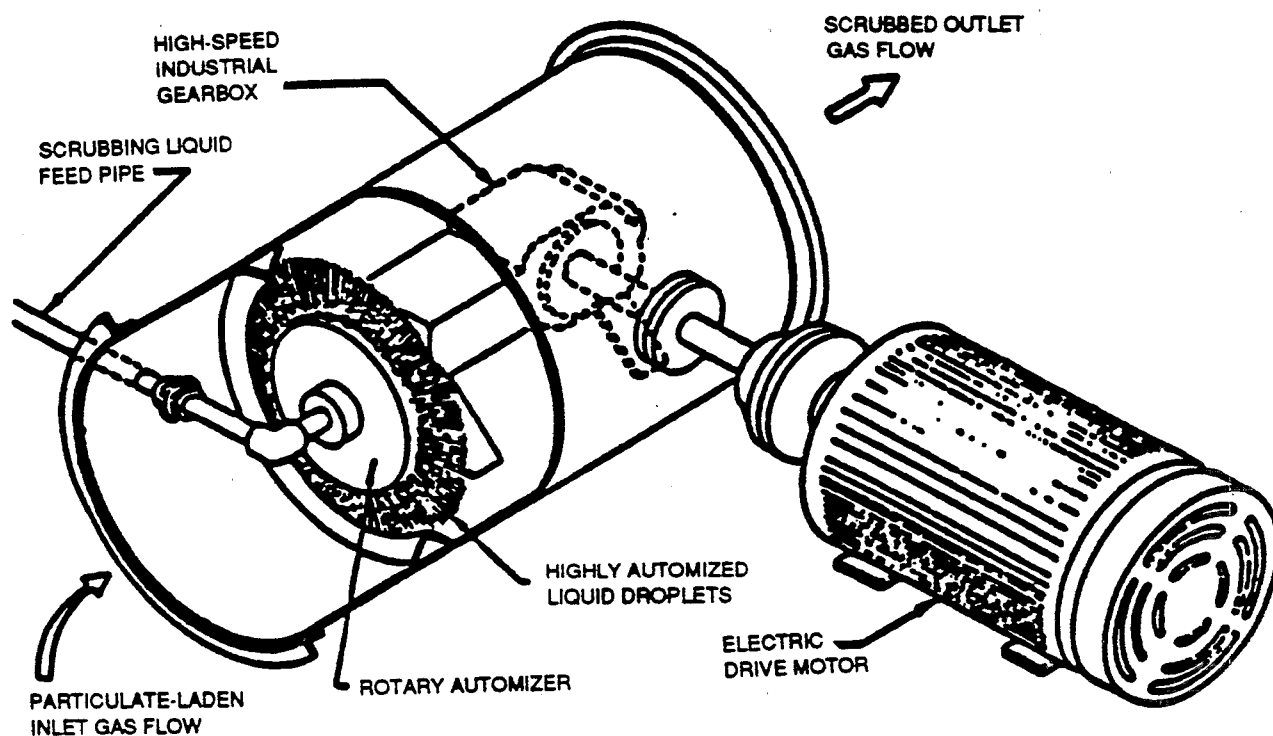


Figure 15. Schematic of rotary atomizer module.⁵²

3.1.4.2 Ionizing Wet Scrubber™.^{54,55} The IWS™ uses a combination of electrostatic forces and the common wet-scrubbing phenomena to provide both PM and acid-gas control. The typical system consists of a quench chamber to reduce gas temperature and one or more of the modular "units" shown in Figure 16 in series. Because each unit (or stage) acts to remove a nearly constant fraction of the acid gas and PM, the control efficiency is increased by staging these units.

Each unit in the system has two major sections. The gas stream passes through the entry plenum into the ionizing section of the unit. Here particles are charged as they pass between wires powered by a high-voltage DC power source and small grounded electrode "mini plates." The gas stream thus passes into the charged particle scrubber, which is a horizontal, cross-flow, packed-bed scrubber with a Tellerette® packing material. Acid gases are removed from the gas stream by absorption and particles are collected in the scrubber section by a combination of impaction and image force attraction, an electrostatic property that causes the charged particles to migrate to the neutral packing surfaces. Particles with diameters of 3 to 5 μm and larger are collected on packing surfaces by impaction. Smaller particles are collected by image force attraction. Particles are removed from these surfaces by a constant cross-flow of scrubbing liquor.

3.1.4.3 Calvert Collision Scrubber.⁵⁶ The Calvert collision scrubber is designed to achieve high collection of both PM and acid gases. The system comprises four major components in series: the quencher, the condenser/absorber, a collision scrubber, and an entrainment separator. A modified system without the condenser/absorber is available if only moderate control efficiencies are required. The major components of the system are described in the paragraphs below.

The hot gas from the MWI enters the dual flow quench chamber. The unit is called dual flow because two separate liquid streams are introduced to the gas stream at different

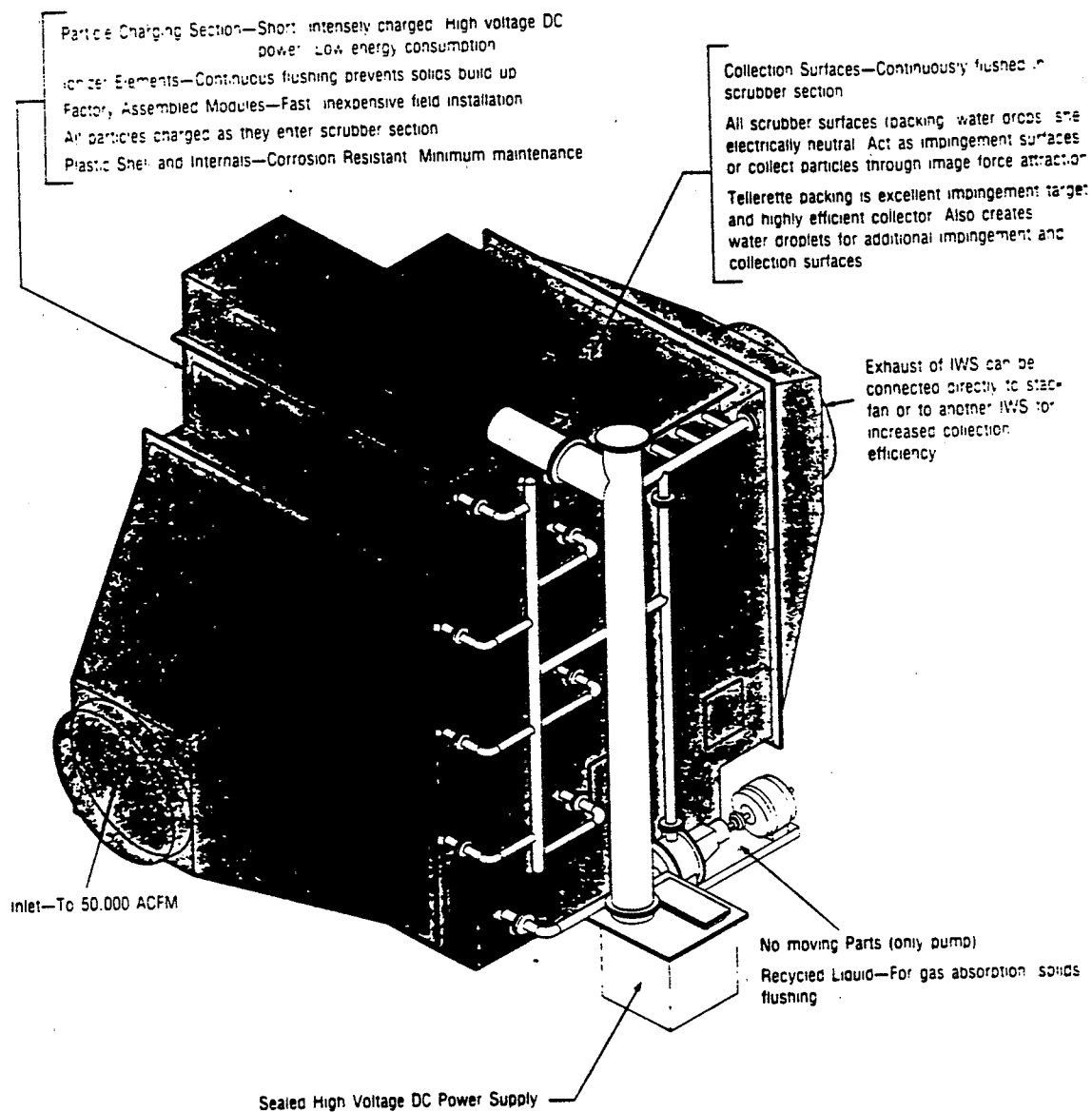


Figure 16. Schematic of an ionizing wet scrubber™.54

points. First, fresh makeup water is added to the inlet to provide a wetted approach. Just beyond the inlet, recycled scrubber water is added to the gas stream. These two liquid streams reduce the gas stream temperature to saturation levels, about 66° to 85°C (150° to 185°F), depending on inlet temperature and moisture content.

The saturated gas stream moves from the quencher into a horizontal, cross-flow or a vertical, counterflow packed-bed absorber. Generally, a caustic or lime scrubbing solution is used in the absorber. The HCl is removed from the gas stream and additional gas cooling reduces the temperature to 49° to 54°C (120° to 130°F). This temperature reduction results in condensation of moisture from the saturated stream. Small particles in the gas stream act as condensation nuclei. The moisture condensation on the surfaces of the particles effectively increases their aerodynamic diameter, thereby enhancing their collection downstream in the entrainment separator.

The gas stream moves from the condenser/absorber into the collision scrubber. There the gas stream is split into two equal streams, turned, and impacted head on. At the point of collision of the two streams, particles are collected on larger droplets via the impaction and interception phenomena described in Section 3.1.1. The particle-laden droplets in the gas stream then enter a multistage entrainment separator. There, the droplets are removed from the gas stream by impaction. Additional removal of HCl also is achieved in the collision scrubber and entrainment separator.

3.1.4.4 Hydro-Sonic® Scrubber.^{57,58} Hydro-Sonic® scrubbers comprise a family of wet scrubbers that have been used to control PM and HCl emissions on several waste incineration processes. The design most likely to be used on MWI systems is the fan drive, tandem nozzle shown in Figure 17. This design consists of two subsonic nozzles equipped with water sprays in series. As the water spray is injected into the high-velocity gas stream, very fine high-velocity water droplets are generated. Collisions

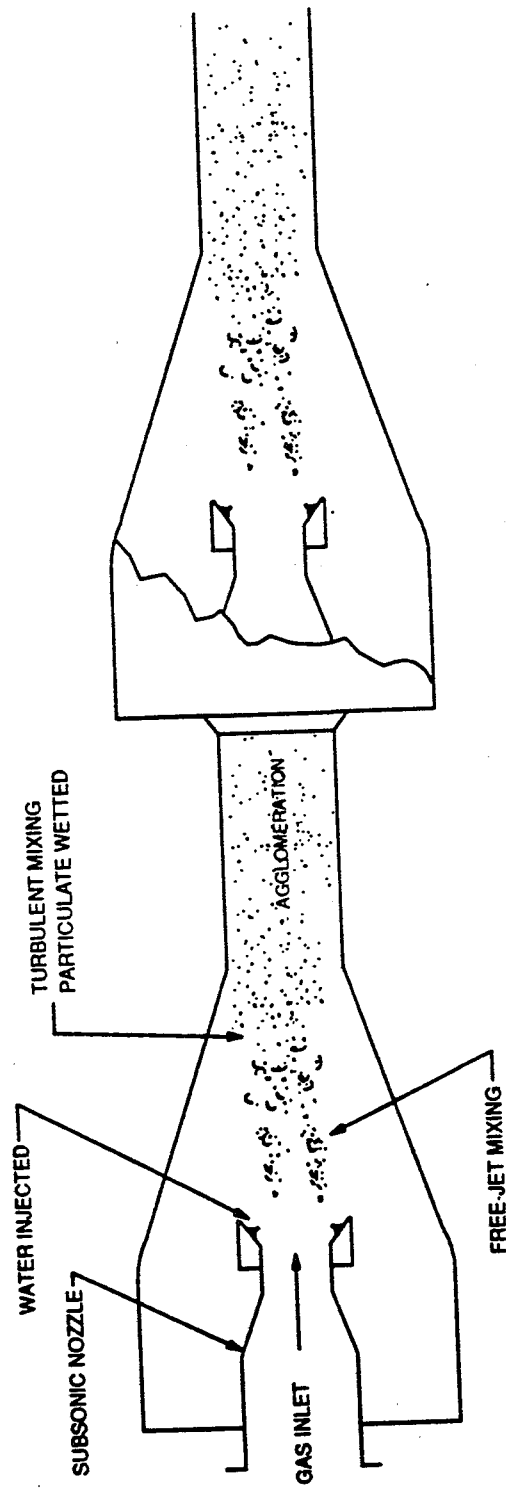


Figure 17. The Hydro-Sonic® family of wet scrubbers. 57

between the droplets and particles take place in the highly turbulent flow regimes in the mixing tubes, as does absorption of HCl into the droplets. Cyclonic mist eliminators are then used to remove the pollutant-laden droplets from the gas stream.

3.2 FABRIC FILTERS

Historically, fabric filters (or baghouses) have been used to control PM and nonvaporous metals emissions from combustion sources and other industrial processes. Fabric filters are often combined with other air pollution control techniques to achieve control of acid gas and organic pollutant emissions in addition to PM control. The two most common combinations are a fabric filter downstream from a sorbent-injection system (typically dry sorbent injection is used, but facilities can use spray dryers) and a fabric filter and packed-bed scrubber in series. Other components of these combined systems are discussed later in this report and will not be addressed in this section. The discussion below focuses on the fabric filter component of the systems with reference to later discussions as appropriate.

Fabric filters are typically classified with respect to their location relative to the fan and to their type of cleaning mechanism. All systems installed to date at MWI facilities have been negative-pressure systems (i.e., systems installed upstream from an induced-draft fan). Also, all of the systems use pulse-jet cleaning, although some vendors indicate that they would use a reverse-air system if a client so preferred.⁵⁹⁻⁶¹ Because pulse-jet systems dominate the industry, the discussion below focuses on these systems.

The remaining discussion is divided into three subsections. The first presents a brief overview of fabric filter PM collection principles. The second subsection presents a general description of the pulse-jet fabric filter. It describes components of the system and identifies key design and operating variables. The final subsection identifies primary control system and combustor design and operating variables that affect performance and discusses how these factors affect the performance relative to PM, HCl, metals, and CDD/CDF emissions.

3.2.1 Fabric Filter Collection Principles

Fabric filtration systems have been used for years to control PM emissions from a wide variety of industrial processes, to collect product materials from manufacturing processes, and to maintain dust loadings at acceptable levels in clean room environments. A substantial amount of research has been conducted on the performance of these PM and dust control systems. The results of this research have led to an understanding of the overall performance of fabric filter systems in removing particles from gas streams and of the specific collection mechanisms that apply. For MWI exhaust streams controlled by fabric filters in combination with dry sorbent injection, information collected to date suggests that the fabric filter also plays a role in controlling other pollutants. However, the mechanisms of control for other pollutants are not fully understood. This subsection describes those mechanisms that are generally accepted as the key mechanisms for fabric filtration of PM. It also briefly discusses the mechanisms that are postulated to affect the control of other pollutants.

A fabric filter is a collection of bags constructed of a fabric material (nylon, wool, or other) hung inside a housing. The combustion gases are drawn into the housing, pass through the bags, and exhaust from the housing through a stack to the atmosphere. When the exhaust from the incinerator is drawn through the fabric, particles are retained on the fabric material, while the cleaned gas passes through the material. The collected particles are then removed from the filter during the pulse-jet cleaning cycle. The dusty material cleaned from the bags falls to a collection hopper and is removed from the hopper for transfer to a storage area or disposal site.

With a new filter, the open areas in the fabric are of sufficient size that particles easily penetrate the bag. Over a short time, a cake builds on the bag surface; this cake acts as the primary particle collection medium. Particles are collected on a filter and cake by a combination of several mechanisms. The most important are impaction, direct interception, and diffusion.

As the exhaust gas flows through the cake and filter, it makes numerous turns around obstructions encountered in the cake or filter media and creates a flow pattern characterized by curved streamlines. In collection by impaction, the particles in the gas stream have too much inertia to follow the gas streamlines around the fiber or through pores in the cake. They leave the gas stream and deposit directly onto the fiber or the surface of the cake. In the case of direct interception, the particles have less inertia and barely follow the gas streamlines around the fiber. If the distance between the center of the particle and the outside of the fiber or pore is less than the particle radius, the particle surface will contact the surface of the fiber and be "intercepted." Impaction and direct interception mechanisms account for 99 percent of the collection of particles with an aerodynamic diameter greater than 1 μm in fabric filter systems.^{62,63}

For submicron particles, such as those generated by homogeneous condensation of volatile metals, diffusion acts as a key collection mechanism. Small particles that are affected by collisions on a molecular level behave individually through random motions. The particles do not necessarily follow the gas streamlines, but instead move randomly throughout the fluid, a phenomenon called Brownian motion. At some point in their random flow through the fluid, a fraction of these small particles come in contact with a surface of the filter medium and are collected.^{62,63}

3.2.2 Pulse-Jet Fabric Filter Description^{62,63}

A schematic of a pulse-jet fabric filter is shown in Figure 18. The primary components of the systems are the bags and auxiliary equipment, the housing that contains the bags, the inlet or dirty-side plenum that receives combustion gases and distributes them to the bags, the clean-air plenum that receives the cleaned combustion gas from the bags before it is discharged to the atmosphere, and the hopper and discharge system.

The bag compartment is separated from the clean-air plenum by a flat metal plate called a tube sheet. In larger systems,

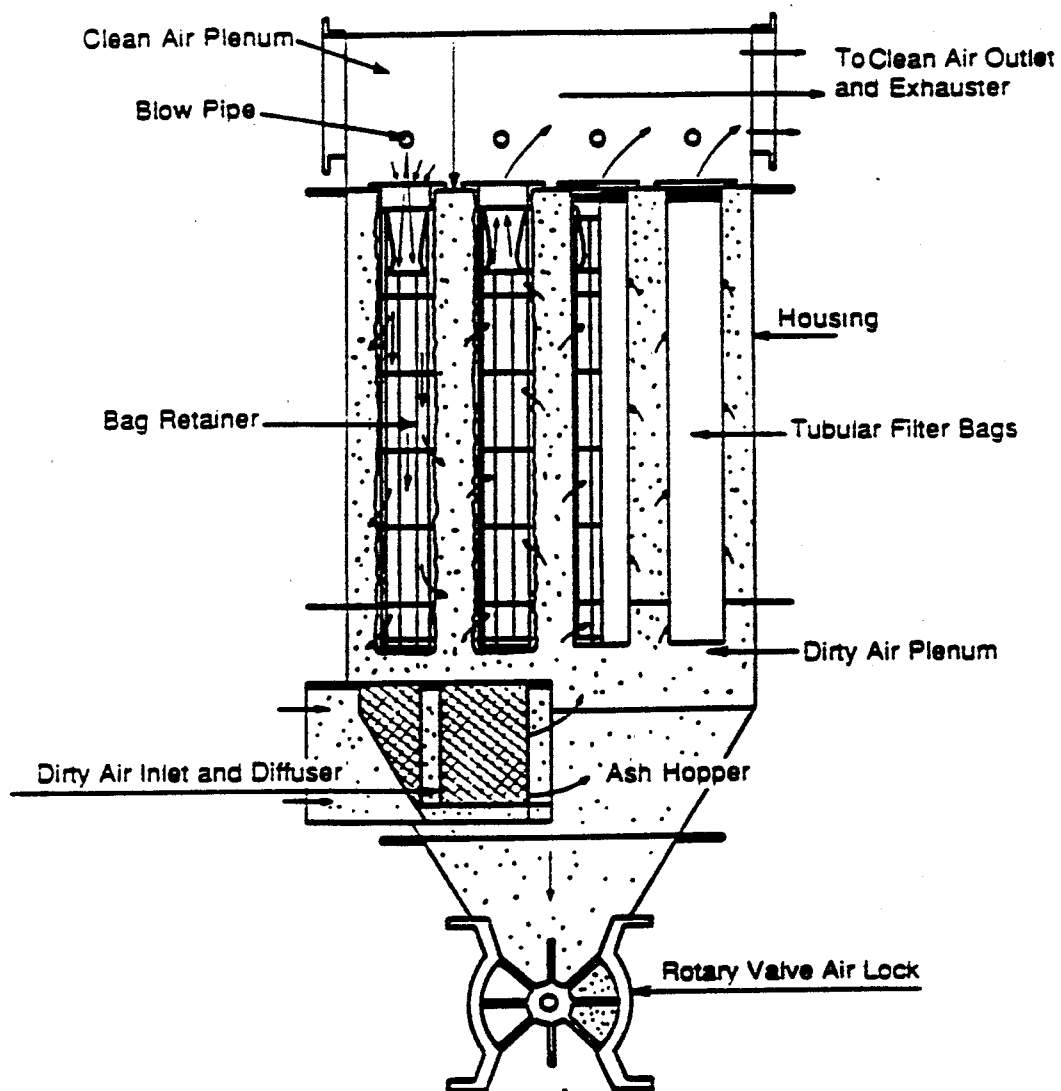


Figure 18. Schematic of a pulse-jet baghouse.⁶³

the bag compartment is frequently separated into multiple, smaller compartments. These compartments can be taken off-line individually for bag cleaning or maintenance. However, most smaller units, such as those used at MWI facilities, have a single compartment with bags arranged in a rectangular array. Within this compartment, bags are suspended from the tube sheet and supported internally by rings or cages. Bags are held firmly in place at the tube sheet by clasps and have an enclosed bottom (usually a metal cap). Dust-laden gas is filtered through the bag, depositing dust on the outside surface of the bag. All pulse-jet systems filter the gas from the outside to the inside of the bag.^{62,63}

The dust cake is removed from the bag by a blast of compressed air injected into the top of the bag tube. The blast of high-pressure air stops the normal flow of air through the filter. The air blast develops into a standing, or shock, wave that causes the bag to flex as the shock wave travels down the bag tube. As the bag flexes, the cake fractures, and deposited particles are discharged from the bag. The shock wave travels down and back up the tube in approximately 0.5 seconds.⁶²

The blast of compressed air must be strong enough for the shock wave to travel the length of the bag and shatter or crack the dust cake. Pulse-jet units use air supplies from a common header that feeds into a nozzle located above each bag. In most baghouse designs, a venturi sealed at the top of each bag is used to create a large enough pulse to travel down and up the bag. Alternatively, some baghouses operate with only the compressed air manifold above each bag. For either type system, the pressures involved are commonly between 414 and 689 kPa (60 and 100 psig).

As the shock wave moves down the bag, dust is released from the bag surface into the open area on the dirty side of the bag. A portion of the dust is immediately entrained in the incoming gas stream and deposited on the surface of the bag just cleaned, thereby maintaining a cake on the bag surface. The remainder

falls into the hopper at the base of the baghouse and is subsequently discharged.^{62,63}

Most pulse-jet filters at MWI facilities use bag tubes that are 10 to 15 cm (4 to 6 in.) in diameter and 1.8 to 5.8 m (6 to 19 ft) in length.^{59-62,64} The bags are usually arranged in rows and are cleaned one row at a time in sequence. The preferred method of cleaning initiation is based on pressure differential with a timer override to prevent extended operation without cleaning. Cleaning may alternately occur in a timed sequence.

3.2.3 Factors Affecting Performance

The performance of the fabric filter relative to PM, acid gas, metals, and CDD/CDF emissions is affected by the fabric filter design and operating parameters and also by key MWI operating parameters. Key pulse-jet filter design and operating parameters are the air-to-cloth ratio (or filtration velocity), bag material, operating temperature, pressure drop across the filter, and cleaning frequency. Key process parameters that can affect fabric filter performance, particularly long-term performance, are variations in temperature, flow rate, and pollutant concentrations that result from the heterogeneous nature of the MWI process. Process startup/shutdown procedures can also affect long-term performance.

The air-to-cloth (A/C) ratio is actually a measure of the superficial gas velocity through the filter medium. It is a ratio of the flow rate of gas through the fabric filter (at actual conditions) to the area of the bags and is usually measured in units of $\text{m}^3/\text{sec}/\text{m}^2$ (acfm/ft²). Data obtained from air pollution control device vendors indicate that pulse-jet fabric filters for MWI's typically are designed with an air-to-cloth ratio in the range of 0.008 to 0.02 $\text{m}^3/\text{sec}/\text{m}^2$ (1.6 to 4.3 acfm/ft²) of bag area.^{59-61,64} Fabric filter systems are designed to operate with as high an A/C ratio as feasible in order to limit size and cost. However, in general, the lower the A/C ratio, the lower the PM emission rate. Short-term exceedance of the design ratio is not likely to have a substantial effect on emissions. However, long-term exceedances will increase

particle-phase emissions from bleed-through and have the potential to cause bag failure through abrasive action. Under a failure condition (e.g., tears at the collar or multiple pinhole leaks), emissions of PM and materials such as metals and CDD/CDF attached to particles are likely to increase substantially. The fabric filter should be designed with an A/C ratio based on the maximum expected gas flow rate. Therefore, at lower gas flow rates, the operating A/C ratio will be lower and the PM collection performance would be expected to be the same or higher than that at the design A/C ratio.

Bags vary with respect to type of construction and material of construction. The three major types of construction are woven bags, felted bags, and membranes. A wide variety of materials have been used to construct bags. Usually both bag type and material are selected based on a vendor's experience with systems installed on comparable processes. Key factors that are considered in making the selection are the cleaning method, resistance of the material to abrasion and chemical attack, expected operating temperature, and costs. For MWI's, both fluctuating temperatures and resistance to acids are of concern. The choice of bag material and construction can affect the performance of the system in removing PM. Felted bags typically are recommended in pulse-jet fabric filters controlling emissions from MWI's. The relatively thick felt fabric provides maximum particle impingement and collects PM more efficiently than woven fabric at comparable gas velocities.⁶⁵ Gore-Tex® membrane bags can also be used to achieve low outlet PM loadings (i.e., 22.5 mg/dscm [0.01 gr/dscf]).⁶¹ If felted bags are used, synthetic materials that are temperature- and acid-resistant are recommended. Vendor recommendations include acrylic, P-84 (Raster® Scrim), and Rylon®.^{60,61}

The operating temperature of the fabric filter is critical to the long-term performance of the system. The system must be operated within a relatively narrow temperature range to prevent bag failure due to chemical attack or temperature-driven degradation. Because the exhaust gas from an MWI can contain

HCl, the unit should be operated at temperatures sufficiently high to ensure that no surface temperatures drop below the acid dewpoint. Otherwise, condensation of HCl will result in corrosion of the housing or bags. The boiling point of HCl (aqueous hydrochloric acid) is 110°C (230°F); gas temperatures should be maintained at or above 120°C (250°F) to ensure that no surfaces are cooled below the dewpoint. Each type of bag material has a specified maximum recommended operating temperature. If the system is operated at temperatures somewhat higher than the maximum recommended operating temperature, bags will degrade over time; operation at substantively higher temperatures can cause bags to fail completely. Gas temperatures should be within a temperature range bounded by the HCl dewpoint and the maximum recommended operating temperature for the specific material to prevent bag failures and the attendant increase in particle-phase emissions.

In addition to its importance in maintaining fabric filter integrity, temperature can also directly influence the control of acid gases, volatile metals, and CDD/CDF. All of the mechanisms described earlier related to these pollutants are temperature dependent. For all of the postulated mechanisms, improved control is achieved with lower temperatures in the baghouse. Consequently, the temperature should be maintained at as low a level as possible, given the acid gas constraints described above, to enhance control of these pollutants. Vendors suggest an optimal temperature range of 120° to 150°C (250° to 300°F) to achieve the best control in combined dry-injection/fabric filtration systems.^{59-61,64}

Pressure drop across fabric filters generally is maintained within a narrow range by controlling the cleaning cycle of the system. Pressure drops below the minimum indicate that either leaks have developed or excessive cleaning is removing the base cake from the bags. Either condition decrease performance immediately. Pressure drops greater than the maximum indicate that either bags are "blinding" or excessive cake is building on the bags because of insufficient cleaning. Over time, high

pressure drops lead to bag erosion and degradation and, subsequently, to decreased performance. The pressure drop on MWI systems generally is maintained in the range of 1.5 to 5 in. w.c. 59-61,64

As suggested by the above discussion, the fabric filter cleaning cycle can have a significant impact on fabric filter performance. Typically, one of two procedures is used to determine a cleaning cycle. For the simpler of the two, vendor engineers monitor facility operations carefully during equipment shakedown. The pressure drop pattern is observed, and a timed cleaning sequence is established to keep the pressure drop well within acceptable limits. This timed cycle is then incorporated into subsequent operating procedures. As an alternative, the system can be equipped with a pressure drop sensor, and a control loop can be used to initiate the cleaning cycle when the pressure drop reaches a specified upper level. Either system can work well, but a malfunction in either system or changes in the process create performance problems. Too frequent cleaning can cause the cake to deplete, resulting in an increase in emissions of PM. On the other hand, cleaning that is too infrequent will result in excessive cake buildup and an increased pressure drop through the system. This latter scenario creates two potential problems. If the pressure drop becomes too great, the system will lose draft to the primary chamber of the MWI, and fugitive emissions can be generated. The excessive cake buildup also results in substantial increases in local gas velocities at some points in the bags. These increased velocities can generate an immediate increase in emissions via particle seepage or bleed-through and can result in increased abrasion that deteriorates bag integrity.

The variations inherent in the operation of MWI's translate into variations in gas stream characteristics including temperature, flow rate, and pollutant concentrations. Of these three gas stream characteristics, temperature is most critical. All fabric filter control systems installed on MWI's incorporate some type of gas-cooling system upstream of the filter. For

those systems that do not have WHB's, the ability of these cooling systems to respond to rapid temperature changes in the combustor exhaust is a key to the long-term performance of the fabric filter. If these systems do not cool the gas stream properly, periodic temperature exceedances lead to bag degradation and reduced collection efficiency.

Variations in the MWI exhaust gas flow rate are compensated for by the proper design of the fabric filter system. The fabric filter system should be designed with an A/C ratio based on the maximum expected gas flow rate. Therefore, at lower gas flow rates, the A/C ratio will be lower and the PM collection performance would be expected to be the same or higher than that at the design A/C ratio.

The PM loading and particle size distribution must be considered during the design of a fabric filter and also during operation; however, within certain limitations (± 10 to 20 percent of design values), changes in these parameters do not seriously affect fabric filter efficiency.⁶⁵ Nevertheless, an increase in mass loading may require more frequent cleaning of the bags as a result of faster filter cake buildup.⁶⁵ A major advantage of a properly designed fabric filter system is its ability to perform well over the normal variation in MWI exhaust gas characteristics.

3.3 DRY SCRUBBERS

This section describes the application of dry scrubbers to MWI's. Dry scrubbing techniques that could be applied to MWI's can be grouped into two major categories: (1) dry sorbent injection, and (2) spray dryer absorber systems. During the past several years, many dry sorbent injection systems have been installed on MWI's. Many spray dryer absorber systems have been installed on municipal waste combustors (MWC's) but only one has been installed on an MWI to date.

Dry scrubbers use an alkaline sorbent to react with and to neutralize the acid gases in the MWI exhaust gas stream. Additionally, activated carbon can be injected to control mercury and CDD/CDF through adsorption. The reaction product is a dry

solid that is collected along with fly ash and any unreacted sorbent in a PM control device such as a fabric filter. In MWI applications, dry scrubbers are invariably followed by a fabric filter. The following paragraphs describe dry scrubbers and their operation. Section 3.3.1 describes dry scrubbing principles. Section 3.3.2 describes dry sorbent injection systems. Section 3.3.3 describes spray dryer absorber systems.

3.3.1 Dry Scrubbing Principles

Dry sorbent injection systems use adsorption to control acid gases while spray dryer absorbers use absorption and adsorption.⁶⁶ The addition of activated carbon also controls mercury and CDD/CDF emissions through adsorption. The principles of adsorption and absorption as applied to dry scrubbers are briefly described below.

3.3.1.1 Adsorption. During adsorption, one or more gaseous components are removed from an effluent gas stream by adhering to the surface of a solid.⁶⁷ The gas molecules being removed are referred to as the adsorbate, while the solid adsorbing medium is called the adsorbent.⁶⁷ In dry injection systems, the adsorbents or sorbents typically include a finely divided alkaline material such as calcium hydroxide (hydrated lime), magnesium oxide, or sodium bicarbonate. Activated carbon can be added for the control of mercury and CDD/CDF.

Adsorption occurs in a series of three steps as illustrated in Figure 19.⁶⁸ In the first step, the contaminant diffuses from the bulk area of the gas stream to the external surface of the adsorbent particle.⁶⁸ In the second step, the contaminant molecule migrates from the relatively small area of the external surface to the pores within each adsorbent particle.⁶⁸ In the third step, the contaminant molecule adheres to the surface of the pore.⁶⁸ In the dry sorbent injection system, the acid gas molecules adsorb onto the surface of and react with the sorbent particles (usually hydrated lime) to neutralize the acid gases by forming neutral chemical salts.

Effective adsorption of acid gases, mercury, and CDD/CDF in dry scrubber applications requires the following:

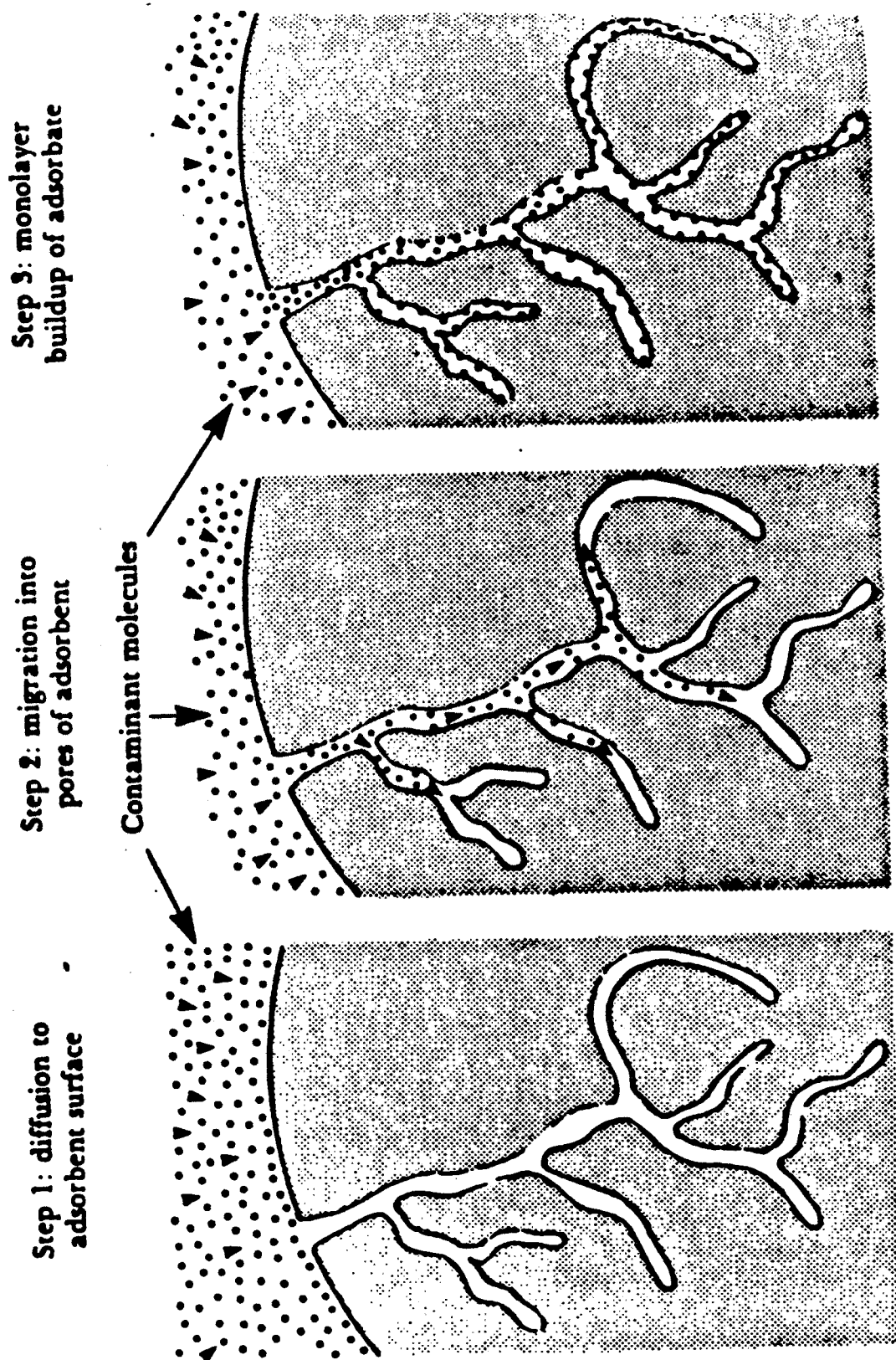


Figure 19. Mechanisms of adsorption. 68

1. A large interfacial surface area between the gas and the sorbent;
2. Good mixing of the gas and sorbent phases;
3. Sufficient residence, or contact, time between the phases for adsorption and subsequent neutralization to occur; and
4. Sufficient sorbent (type and amount) to adsorb and to neutralize the acid gases and to adsorb mercury and CDD/CDF.

Adsorption of vapor-phase organic and metallic compounds such as CDD/CDF and mercury also occurs in dry scrubber applications, especially when activated carbon is injected. The presence of a large interfacial contact area formed by the activated carbon and the fine particles of the alkaline sorbent provides numerous surface sites for condensation and/or adsorption of these vapor-state compounds to occur. Turbulence and adequate residence time also promote adsorption of these compounds. The temperature of the gas stream must be low enough to allow condensation of these compounds to occur but not so low as to allow condensation of HCl gas that causes corrosive conditions. Additionally, the adsorption process may be enhanced by the filter cake on the filter bags in a fabric filter.

3.3.1.2 Absorption. Section 3.1.1.2 described how gaseous pollutants are absorbed in wet scrubber applications. Many of the principles described there also apply to absorption in spray dryer applications. Effective absorption of acid gases in spray dryer applications requires the following:

1. A large interfacial contact area between the gas and slurry droplets;
2. Good mixing of the gas and slurry droplets (i.e., turbulence), and
3. Sufficient residence, or contact, time between the phases for absorption and subsequent neutralization to occur.

In the case of spray dryer absorber systems, the absorbing medium is the liquid slurry droplets as opposed to the scrubbing liquid used in packed-bed scrubbers. The acid gases are absorbed into the droplets where they are neutralized by the lime in the droplets. Subsequently, the liquid in the droplets is evaporated

so that the reaction products along with unreacted sorbents are dried for collection in a PM control device. After the sorbent has been dried, adsorption of unreacted acid gases and vaporous metals and organics onto sorbent particles may occur as the dry sorbent and exhaust gases pass to the PM collection device. This adsorption process may be enhanced by the filter cake on the filter bags in a fabric filter.

3.3.2 Dry Sorbent Injection

This section provides a general description of the dry sorbent injection system including equipment components and gas cleaning process followed by a discussion of the factors affecting the performance of the system including key operating and design parameters and gas stream characteristics.

3.3.2.1 General Description. A dry sorbent injection system typically is comprised of the following components:

1. Sorbent storage/feed hopper;
2. Sorbent transport system;
3. Venturi/injector;
4. Reaction/expansion chamber (optional); and
5. Recycle system (optional).

Figure 20 illustrates a schematic of a dry injection system showing the major components listed above with the exception of the venturi and the recycle system. The following paragraphs describe these components along with the dry injection system gas cleaning process.

The dry injection scrubber uses injection of a dry, finely divided alkaline sorbent such as calcium hydroxide (hydrated lime), magnesium oxide, or sodium bicarbonate for the adsorption of acid gases and powdered activated carbon for the adsorption of mercury and CDD/CDF. The alkaline sorbent typically is stored in a storage bin that also acts as a feed hopper for the system. This bin may have a cone shaped bottom to direct the sorbent to a rotary airlock, slide gate, or volumetric screw feeder that meters sorbent into the pneumatic line that feeds the MWI exhaust gas duct. The bin may also be equipped with a shaker mechanism and/or a screw auger that help prevent clumping of the sorbent.

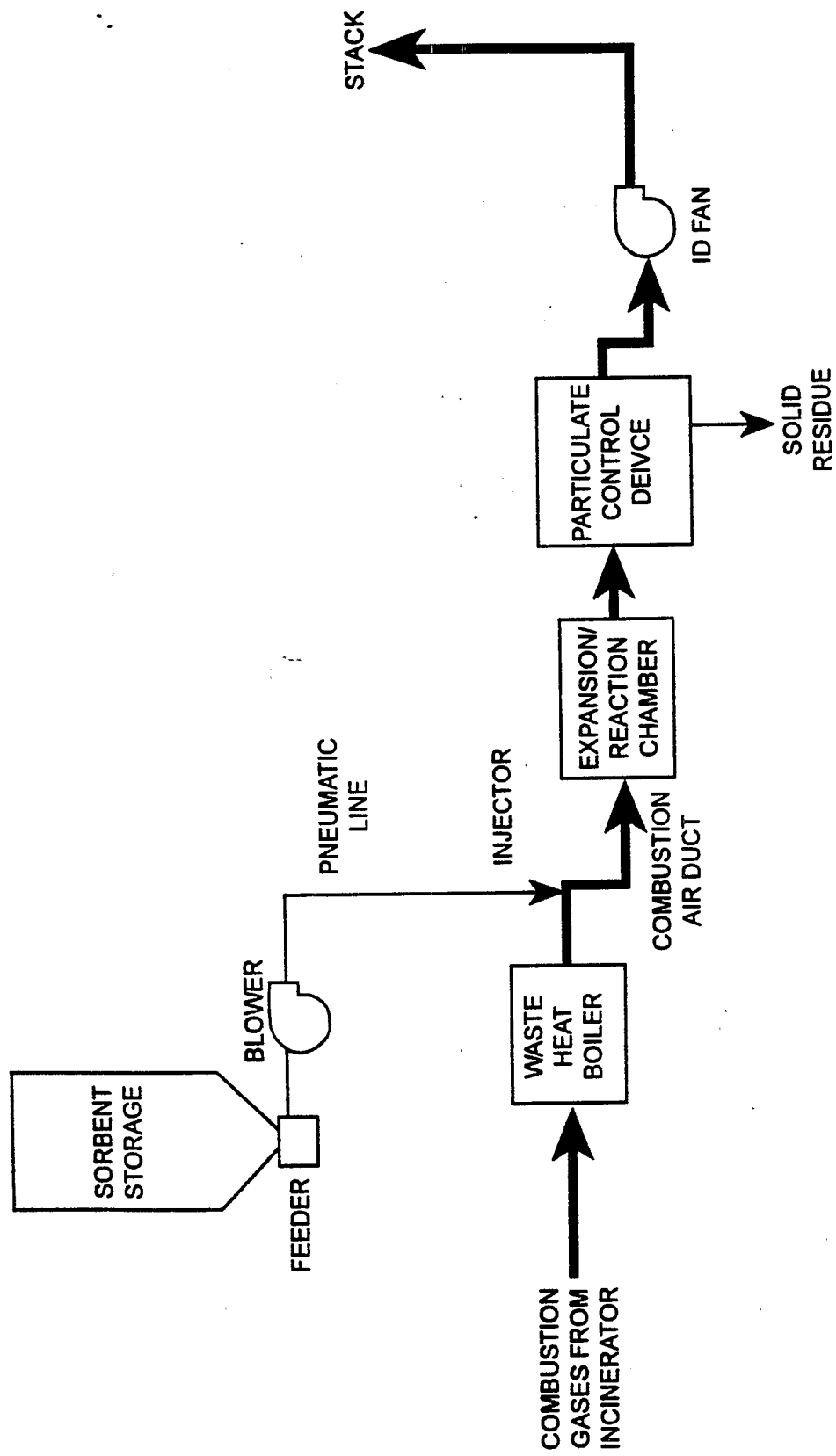


Figure 20. Schematic of dry sorbent injection system.⁶⁹

The feeding system typically is controlled by a microprocessor system that controls the operation of the rotary airlock, slide gate, or screw feeder in some systems, the sorbent injection rate is controlled by opening and closing the airlock. By controlling the length of time and the number of times in a given time period that the airlock or slide gate remains open, the sorbent injection rate can be closely controlled. Other systems simply feed sorbent on a continuous basis using a controller that controls the speed of the screw feeder.

Typically, the sorbent is transported to the MWI exhaust gas duct pneumatically. As the sorbent is metered into the pneumatic line, a blower propels the sorbent through the line to the duct. Additionally, the system's draft pulls the sorbent through the line. The action of the blower and the system draft provides the initial fluidization of the sorbent for transport to the duct. Other, simpler systems use a gravitational feed approach instead of a pneumatic system where the sorbent is fed through a vertical pipe from a feed hopper located above the duct.

In many systems, the sorbent is injected into the duct upstream of or at a venturi section of the duct. The purpose of the venturi is to introduce turbulence to the gas stream and sorbent, thereby providing good mixing and enhancing adsorption of the acid gases.^{70,71} Some systems have an adjustable venturi throat that compensates for the variations in the MWI exhaust gas flow rate.⁷⁰ As in a wet venturi system, adjusting the venturi maintains a constant gas velocity across the throat, thereby preventing the reagent from falling out in the duct.⁷⁰

In some dry injection systems, a reaction chamber (expansion chamber) is included that allows increased residence time for adsorption and neutralization to occur.⁷⁰ One vendor utilizes a specially designed heat exchanger that both cools the gases and provides increased residence time.⁶⁰ From the reaction chamber, the gas stream, containing the entrained sorbent particles and fly ash, is ducted to a fabric filter.

Some manufacturers include a sorbent recycle system that recycles a portion of the collected sorbent/fly ash back to the

sorbent injection system.⁷¹ The primary purpose of the recycle stream is to increase reagent utilization and thereby reduce overall sorbent costs.⁷¹ Recycle systems are installed on a case-by-case basis based on the economics of the installation.

The buildup of a cake on the filter bags in the fabric filter provides additional intimate contact between the gaseous pollutants and sorbent for adsorption to occur. Emission test data suggest that the fabric filter cake plays a role in collecting HCl, volatile metals, and organic pollutants such as CDD/CDF in combination dry sorbent injection/fabric filtration systems.^{71,72} Additionally, specific tests suggest that HCl control in such systems is related to cake build-up and depletion and that volatile mercury and CDD/CDF control is improved when activated carbon is used as a sorbent in the cake.⁷² Testing to investigate the effectiveness of injecting activated carbon (in addition to hydrated lime), in controlling both mercury and CDD/CDF emissions across a dry sorbent injection/fabric filter system, was conducted in September 1991. The results of this test along with the results of the entire test program are presented in Section 4.0 of this report.

3.3.2.2 Factors Affecting Performance. The performance of the dry sorbent injection system relative to acid gas, metals, and CDD/CDF emissions is affected by the dry injection system design and operating variables in promoting adsorption of these compounds and also by key MWI operating variables. Dry injection systems control primarily acid gases by adsorption; metals and CDD/CDF are also controlled by this mechanism but to a lesser extent. While PM is not controlled by dry injection, a PM control device located downstream of the dry injection system collects flyash from the MWI along with the dry, solid reaction product and any unreacted sorbent. The following paragraphs describe the key dry injection system design and operating variables that promote adsorption including sorbent fluidization and particle size, retention/reaction time, stoichiometric ratio, and gas stream moisture content and temperature. Additionally, key process parameters that can affect dry injection system

performance are discussed including variations in gas stream temperature, flow rate, and pollutant concentrations that result from the heterogeneous nature of the MWI process.

Maintaining proper sorbent particle size and fluidization is important in providing surface adsorption sites and in fully utilizing the injected sorbent. The sorbent (typically hydrated lime) has particle sizes that allow 90 percent by weight of the material to pass through No. 325 mesh screens.⁷¹ This particle size range is approximately the consistency of talcum powder.⁷¹ Sorbent particles in this size range provide sufficient total alkaline sorbent surface area for effective adsorption to occur.⁷¹ Larger particles have a smaller total surface area and would require larger fan capacity to fluidize the sorbent. The dry injection fluidization system (transport blower) capacity must be sufficient to fluidize the sorbent adequately. The sorbent must be fluidized uniformly across the duct so that all portions of the gas stream are contacted by sorbent particles.⁷² The use of a venturi constriction helps to provide the turbulent conditions necessary for intimate contact between the gaseous compounds and the surface of the particles.⁷¹ Insufficient fluidization allows sorbent to fall out of the gas stream unused and may ultimately lead to plugged lime feed pipes and/or MWI exhaust gas ducts.

Adequate retention/reaction time is necessary for effective adsorption of acid gases, metals, and CDD/CDF. Retention time in dry injection systems is prolonged through the use of specially designed reaction/retention chambers to provide intimate mixing between the gas stream and sorbent particles. One vendor supplies a specially designed heat exchanger both to extend the retention time and to cool the gases.⁶⁰ In some cases, an extended duct is used to prolong retention time while other systems compensate for a lack of retention time by operating the system at a higher stoichiometric ratio or extending the dirty-air side of the fabric filter.

The stoichiometric ratio is defined as the molar ratio of calcium in the lime fed to the dry sorbent injection system to

the theoretical amount of calcium required to completely react with the HCl and SO₂ in the MWI exhaust gas. Because of mass transfer limitations, incomplete mixing, differing rates of adsorption and reaction (SO₂ reacts more slowly than HCl), and the presence of other acid gases that react with the calcium in the lime (e.g, hydrogen fluoride, sulfur trioxide), stoichiometric ratios in excess of 1:1 are required. Vendors design dry injection systems with extended retention times to operate at stoichiometric ratios of sorbent (hydrated lime) to HCl that range from 1.3:1 to 2:1.^{59,61,64} At such stoichiometric ratios, these vendors guarantee HCl reductions that range from 90 to 99 percent.^{59,61,64} Higher removal efficiencies can be achieved by increasing the stoichiometric ratio.^{59,61,64}

The gas stream moisture content and temperature are important variables in achieving effective acid gas neutralization. Some vendors recommend using evaporative coolers both to humidify and to cool the gas stream.^{60,61,64} This process increases the reagent activity.⁶¹ These evaporative coolers may be used in conjunction with or without the use of a WHB but typically are used when no WHB is present.^{60,61,64} Other vendors use combinations of evaporative coolers and heat exchangers or heat exchangers alone.^{59,64} The optimum temperature for the neutralization of acid gases ranges from 121° to 177°C (250° to 350°F) according to vendors.^{59-61,64} The lower the temperature, the higher the HCl and SO₂ removal.⁵⁹ Additionally, one vendor reported that lower temperatures improve the removal efficiency of lead, mercury, and CDD.⁵⁹

The variations inherent in the operation of MWI's translate into variations in gas stream characteristics including temperature, flow rate, and pollutant concentrations. Because dry sorbent injection systems are located after gas cooling devices (WHB's, heat exchangers, or evaporative coolers) and because these devices are designed to achieve a setpoint outlet temperature, the effect of MWI exhaust gas temperature variation is minimized. The optimum temperature for gaseous pollutant removal in dry sorbent injection systems is approximately 121°C

(250°F). The boiling point of HCl (aqueous hydrochloric acid) is 110°C (230°F); gas temperatures maintained at 121°C (250°F) maximize gaseous pollutant removal and ensure that no surfaces are cooled below the dewpoint. However, condensation of HCl on cool surfaces (resulting in corrosion of metal components) can occur even when measured gas temperatures are greater than 121°C (250°F), particularly on systems without insulation. Insulation around ductwork and the dirty- and clean-air sides of the fabric filter will minimize the condensation of HCl on internal metal components by preventing cold spots. Corrosion caused by condensation of HCl can occur on the clean side (clean air plenum, outlet ductwork, and outlet stack) even though most of the HCl has been removed from the gas stream. Some combination of insulation and/or corrosion resistant materials can be used to reduce corrosion problems.

Variations in flow rate may cause problems with fluidization of sorbent in the duct. Flow rate variations may be compensated for by a variable speed fan that is tied to the incinerator draft. Some systems have adjustable venturi constrictions that maintain both a constant velocity across the venturi and turbulent mixing as the flow rate changes.⁷²

Variations in pollutant concentrations in the MWI exhaust gas are dependent primarily on waste composition. The stoichiometric ratio typically is specified based on the maximum expected HCl concentration through the system. Therefore, as the HCl concentration varies up to the maximum amount, the stoichiometric ratio of lime to the theoretical amount required will remain high enough for effective HCl removal. It is not clear how variations in the concentrations of metals and organics observed in MWI exhaust gas streams would impact the effectiveness of the dry sorbent injection system in removing these pollutants.

3.3.3 Spray Dryer Absorbers

This section provides a general description of a spray dryer absorber system including equipment components and gas cleaning process followed by a discussion of the factors affecting

performance of the system including key operating and design parameters and gas stream characteristics.

3.3.3.1 General Description. A spray dryer absorber system typically is comprised of the following components:

1. Sorbent preparation system;
 - storage
 - slaker
 - mixing tank
 - feed tank
2. Atomizers; and
3. Spray dryer absorber vessel.⁷³

The primary differences between a dry sorbent injection system and a spray dryer absorber system are: (1) the physical form of the alkaline sorbent and (2) the design of the system used for contacting the sorbent with the acid gas stream.⁷⁴ In a dry sorbent injection system, the sorbent is dry while in a spray dryer system, the sorbent is fed as an alkaline slurry. In a dry sorbent injection system, the dry sorbent is injected into a duct and may be followed by a reaction chamber while in a spray dryer system, the wet slurry is atomized in a spray dryer absorber vessel.

Figure 21 illustrates a spray dryer absorber. In this system, the alkaline reagent, usually pebble lime, is prepared as a slurry containing 5 to 20 percent by weight solids by slaking the lime.⁷³ Slaking is the addition of water to convert calcium oxide to calcium hydroxide.⁷⁶ Proper slaking conditions are important to ensure that the resulting calcium hydroxide slurry has the proper particle size distribution and that no coating of the particles has occurred due to the precipitation of contaminants in the slaking water.⁷⁶ From the slaker, the slurry passes to the mixing tank where the slurry is thoroughly mixed before passing to the slurry feed tank.

The prepared slurry is atomized into the gas stream in a large absorber vessel having a residence time of 6 to 20 seconds. Atomization of the slurry is achieved through the use of:

- (1) rotary atomizers or (2) air atomizing nozzles. Generally,

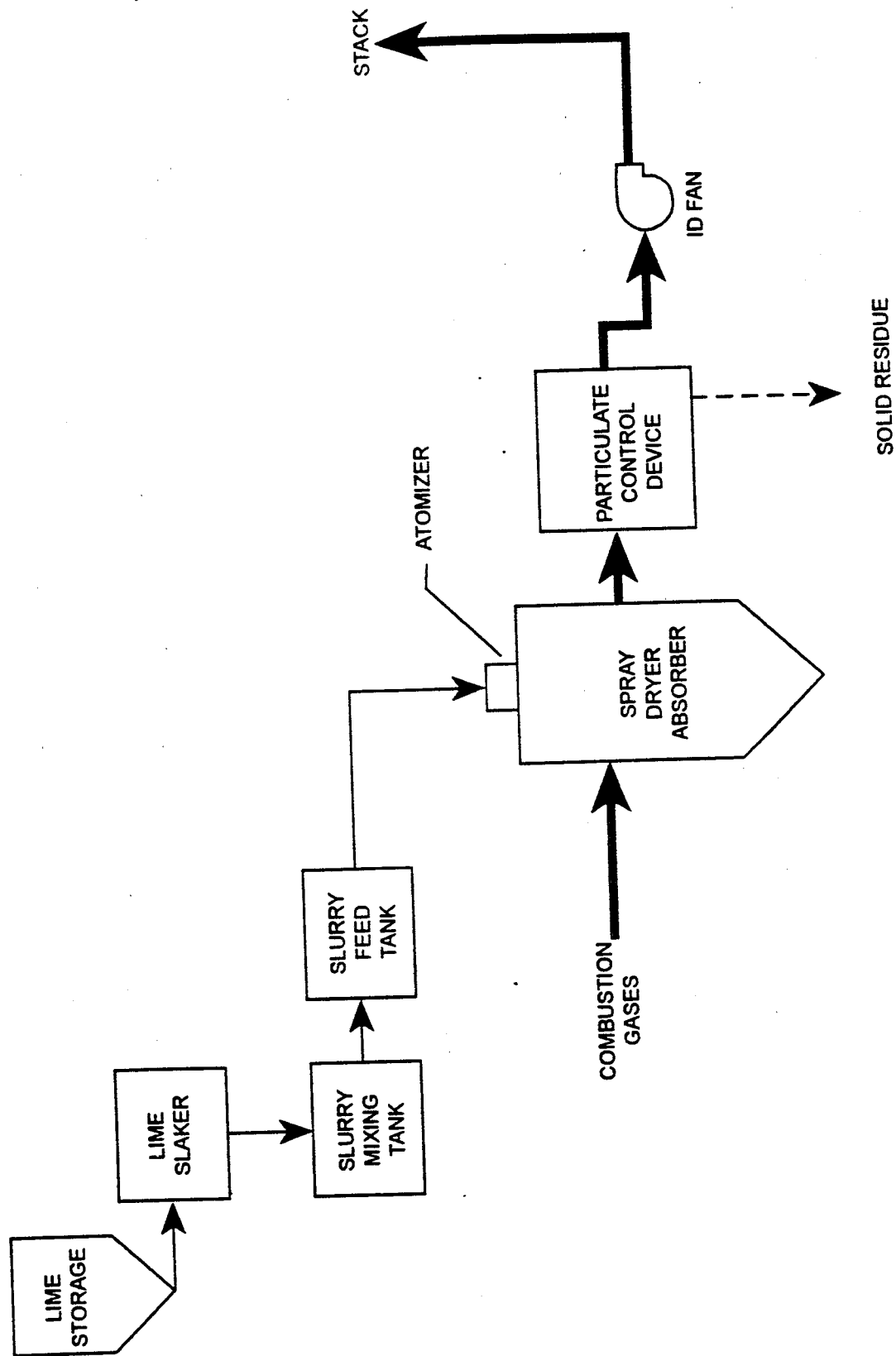


Figure 21. Schematic of spray dryer absorber system.⁷⁵

only one rotary atomizer is included in a spray dryer absorber. However, a few applications have as many as three rotary atomizers.⁷⁴

In rotary atomizers, a thin film of slurry is fed to the top of the atomizer disk as it rotates at speeds of 10,000 to 17,000 revolutions per minute. These atomizers generate very small slurry droplets having diameters in the range of 100 microns. The spray pattern is inherently broad due to the geometry of the disk.⁷⁷

High pressure air is used to provide the physical energy required for droplet formation in nozzle-type atomizers. The typical air pressures are 483 to 621 kPa (70 to 90 psig). Slurry droplets in the range of 70 to 200 microns are generated. This type of atomizer generally can operate over wider variations of the gas flow rate than can be used in a rotary atomizer. However, the nozzle atomizer does not have the slurry feed turndown capability of the rotary atomizer. For these reasons, different approaches must be taken when operating at varying system loads.⁷⁸

The shape of the scrubber vessel must be designed to take into account the differences in the slurry spray pattern and the time required for droplet evaporation for the two types of slurry atomizers. The length-to-diameter ratio of a spray dryer absorber vessel using rotary atomizers is much smaller than that for absorber vessels using air atomizing nozzles.⁷⁷

3.3.3.2 Factors Affecting Performance. The performance of the spray dryer system relative to acid gas, metals, and CDD/CDF emissions is affected by the spray dryer system design and operating variables in promoting absorption of these compounds and also by key MWI operating variables. Spray dryer systems control primarily acid gases by absorption; metals and CDD/CDF also are controlled by this mechanism but to a lesser extent. While PM is not controlled by a spray dryer, a PM control device collects fly ash from the MWI along with the dry, solid reaction product and any unreacted sorbent. The following paragraphs describe the key spray dryer system design and operating

variables that promote absorption including stoichiometric ratio, slurry droplet size, the approach-to-saturation and outlet gas temperature, and retention/reaction time. Additionally, key process parameters that can affect dry sorbent injection system performance are discussed including variations in temperature, flow rate, and pollutant concentrations that result from the heterogeneous nature of the MWI process.

The stoichiometric ratio is defined as the molar ratio of calcium in the lime slurry fed to the spray dryer to the theoretical amount of calcium required to completely react with the HCl and SO₂ in the flue gas at the inlet to the spray dryer.⁷⁹ However, because of mass transfer limitations, incomplete mixing, differing rates of reaction (SO₂ reacts more slowly than HCl), and the presence of other acid gases that react with calcium (e.g., hydrogen fluoride, sulfur trioxide), more than the theoretical amount of lime is generally fed to the spray dryer.⁷⁹ Stoichiometric ratios in the 1.2 to 1.3 range can reportedly achieve 90 to 95 percent removal of HCl and HF and 60 to 85 percent removal of SO₂.⁸⁰

The slurry droplet size would be expected to affect the performance of the spray dryer in removing acid gases, metals, and CDD/CDF. Smaller droplet size increases the surface area for adsorption and reaction between lime and acid gases and increases the rate of water evaporation.⁷⁹ Additionally, it is important that all of the slurry droplets evaporate to dryness prior to approaching the absorber vessel side walls and prior to exiting the absorber with the gas stream.⁷⁷ Accumulations of material on the side walls or at the bottom of the absorber would necessitate an outage since these deposits would further impede drying.⁷⁷ Proper drying of the slurry requires generation of small slurry droplets and adequate mixing with the hot flue gases.⁷⁷

Drying that is too rapid can reduce pollutant collection efficiency since the primary removal mechanism is absorption into the droplets.⁷⁷ There must be sufficient contact time for absorption to occur and for the slurry to evaporate to dryness.⁷⁷ For this reason, spray dryer absorbers controlling MWC's are

operated with an approach-to-saturation range of 32° to 82°C (90° to 180°F).⁷⁷ The approach-to-saturation is the difference between the wet bulb and dry bulb temperatures measured by wet and dry bulb monitors at the outlet of the spray dryer vessel.⁷⁷ An increase in the approach-to-saturation is sensed by the automatic control system that quickly reduces the slurry feed rate.⁸¹

The spray dryer outlet temperature is controlled by the amount of water in the slurry. More effective acid gas removal occurs at lower temperatures, but the temperature must be kept high enough to ensure that the slurry and reaction products are adequately dried prior to collection in the fabric filter. In addition, a minimum spray dryer absorber vessel outlet temperature of approximately 240°F is required to control agglomeration of PM.⁷⁹

In MWC applications, the amount of lime fed is generally controlled by one of two means. In one approach, the lime-slurry feed rate is controlled by an acid gas analyzer/controller (generally based on SO₂ or HCl emissions) at the stack. As the outlet acid gas concentration increases or decreases, the lime-slurry feed rate is accordingly raised or lowered, respectively, to maintain a specified outlet, acid gas concentration. The second approach uses a constant lime-slurry feed rate that is sufficient to react with peak expected acid gas concentrations.⁷⁹

For effective absorption of gaseous pollutants to occur, adequate retention/reaction time is required. The retention time in spray dryers is determined by the size of the spray dryer absorber vessel. Retention times in spray dryers controlling emissions from MWC's range from 10 to 15 seconds.⁸⁰

The variations inherent in the operation of MWI's translate into variations in gas stream characteristics including temperature, flow rate, and pollutant concentrations. For those systems equipped with a WHB or heat exchanger, the variation in the MWI exhaust gas temperature is damped. The spray dryer outlet flue gas temperature is controlled at levels well above its saturation value by controlling the amount of water in the

slurry. This control precludes any sorbent from contacting downstream surfaces as a wet powder leading to solids buildup. It also assures operation well above the dew points of any acid gases. Because of the presence of calcium chloride (a very hygroscopic, difficult-to-dry solid), temperatures are typically controlled at 110° to 160°C (230° to 320°F) by limiting the amount of water injected.⁸²

Flow rate variations may be compensated for by a variable speed ID fan that is tied to the incinerator draft.

Variations in pollutant concentrations in the MWI exhaust gas are dependent primarily on waste composition. A second control loop can be provided based on the pollutant emission levels in stack gases to regulate the addition of reagent to the system. In many cases, the sorbent rate is fixed at a conservatively high rate to ensure low stack emissions, but waste disposal plus sorbent operating costs are increased.⁸²

4.0 PERFORMANCE OF EMISSION CONTROL MEASURES

One component of the background information development for MWI's was a comprehensive emission test program. The program generated emission test data on a wide variety of pollutants including all of those for which emission limits are to be established (PM, CO, HCl, SO₂, NO_x, CDD/CDF, Cd, Pb, and Hg). These test data provide information on the effects of combustion system operating parameters on emissions and on the performance capabilities of add-on APCS's. This section summarizes the results of the test program. Section 4.1 briefly describes the test program and facilities tested and presents a summary of the test data. Section 4.2 presents a discussion of the test results including a comparison of the emission results obtained when incinerating different waste types, a discussion of the effects of combustion control parameters on emissions, and a discussion of the performance of four APCS's--a combination dry injection fabric filter (DI/FF), a combination venturi scrubber/packed-bed scrubber (VS/PB), a fabric filter in series with a packed-bed scrubber (FF/PB), and a spray dryer/fabric filter combination (SD/FF)--with respect to PM, HCl, CDD/CDF, and metals emissions.

Note that tests on the DI/FF and SD/FF systems were performed with and without activated carbon injection. Section 4.3 presents demonstrated emission control levels (i.e., emission limits) associated with each of the emission control techniques described above.

4.1 TEST PROGRAM SUMMARY

4.1.1 Facility and Test Condition Descriptions

The emissions test program generally consisted of triplicate test runs under multiple sets of operating conditions at seven MWI facilities, which are denoted herein by the letters A, B, J, K, M, S, and W. At the four facilities equipped with add-on APCS's (A, B, J, and M), simultaneous measurements were made at the APCS inlet and outlet for PM, HCl, SO₂, CDD/CDF, and metals. Operating parameters that were varied to achieve different operating conditions included waste feed type, waste feed charging mode, and secondary chamber temperatures. Table 1 provides a summary of the test conditions and the test program conducted at each facility, including the test condition numbers, the waste type charged, the target waste charge rates, and the target secondary/tertiary chamber temperatures.

Summary tables for the incinerator and APCS operating data collected from the test program are included in Appendix A. Table A-1 presents pertinent incinerator operating data for each of the 25 test conditions (77 test runs) that were conducted as a part of this program, and Tables A-2 through A-5 present pertinent APCS operating data for those facilities with add-on APCS's. The paragraphs below briefly describe the systems at each of the seven facilities tested and the general structure of the test program at each site; more detailed descriptions of the facilities are included in the individual test reports.⁸³⁻⁹⁰

4.1.1.1 Facility A. The incineration unit at Facility A is a Cleaver-Brooks Model 780-A/31 intermittent-duty MWI with three combustion chambers. The primary chamber operates at starved-air levels, while the secondary and tertiary chambers operate with excess air. The nameplate charging capacity of the unit is 295 kg/hr (650 lb/hr) at an assumed waste heating value of

TABLE 1. MATRIX OF TEST CONDITIONS FOR TESTS CONDUCTED
AT EACH FACILITY

Facility	Test condition	Waste type ^a	Target waste charge rate, lb/hr	Target tertiary/secondary chamber temp., °F
A	1	G500	520	1800
A	2	G500	455	1600
A	3	G500	600	2000
A	4	G100	600	1800
A	5	RB	420	1600
A	6	RB	455	1800
A	7	RB	520	2000
A	1A	G500	560	1800
A	8	G500	560	1800
A	9	G500	560	1800
B	1	General	800	1800
J	1	General	750 ^b	1800
J	2	General	-- ^c	--
K	1	General	200	1900
K	2	General	300	1900
K	3	General	300 ^d	1600
M	1	General	780	1800
M	2	General	780	1800
S	1	Pathological	100	1900
S	2	Pathological	160	1600
S	3	General	160	1600
W	1	General	200	1900
W	2	General	300	1900
W	3	General	300 ^d	1600

^aG500 - general medical waste generated at a 500-bed hospital

G100 - general medical waste generated at a 100-bed hospital

RB - red bag waste

General - general medical waste

Pathological - pathological waste

^bAt facility J, the target charge rate was 750 lb/batch.

^cAt facility J, test condition 2 refers to testing during the burn-down phase of the batch where test condition 1 was conducted during the burn phase.

^dSame hourly charge rate as test condition 2 but larger charges were charged less frequently.

19,800 kJ/kg (8,500 Btu/lb). The facility is equipped with a WHB for energy recovery and a DI/FF APCS.

Two separate test sequences were conducted at Facility A. During the first sequence, emissions were measured simultaneously at the DI/FF inlet and outlet under seven sets of test conditions based on waste feed type and tertiary chamber operating temperature. The target operating characteristics for these test conditions were: Condition 1--general medical waste from a 500 bed hospital (G500) at a tertiary chamber temperature of 980°C (1800°F); Condition 2--G500 waste at 870°C (1600°F); Condition 3--G500 waste at 1090°C (2000°F); Condition 4--general medical waste from a 100 bed hospital (G100) at 980°C (1800°F); Condition 5--red bag waste from a 500 bed hospital (RB) at 870°C (1600°F); Condition 6--RB waste at 980°C (1800°F); and Condition 7--RB waste at 1090°C (2000°F).

The second test sequence was designed to evaluate the effect of activated carbon injection on DI/FF performance. During the second test sequence, emissions were measured simultaneously at the DI/FF inlet and outlet. The incinerator operating target was identical to Condition 1 above and the DI/FF system was operated at three carbon levels--none (Condition 1A), 0.45 kg/hr (1 lb/hr) (Condition 8), and 1.14 kg/hr (2.5 lb/hr) (Condition 9). The actual incinerator operating parameters for all test runs within both test sequences are presented in Table A-1 while the actual DI/FF operating parameters are presented in Table A-2.

4.1.1.2 Facility B. The incinerator at Facility B is a Basic Environmental Engineering, Inc., Model 1500 continuous-duty MWI with both secondary and tertiary chambers and a WHB. The primary chamber of this unit operates at near stoichiometric conditions, while the secondary and tertiary chambers operate at excess-air conditions. The nameplate charging capacity of this MWI is approximately 680 kg/hr (1,500 lb/hr) of medical waste with an assumed heating value of 19,800 kJ/kg (8,500 Btu/lb). This MWI is equipped with an Andersen 2000, Inc., venturi scrubber followed by two packed-bed scrubbers in series. The two packed-bed scrubbers were installed in series because space

limitations prevented the installation of a single packed-bed scrubber of suitable size. Emissions were measured at the inlet and outlet of the APCS at one test condition: burning general medical waste from the hospital at a nominal secondary chamber temperature of 980°C (1800°F). The actual Facility B operating parameter values for each test are included in Table A-1, and the APCS operating parameter values for each test are presented in Table A-3.

4.1.1.3 Facility J. The incinerator at Facility J is a Simonds Model 2151B batch-duty MWI with two combustion chambers. This unit has a nominal capacity of 340 kg/batch (750 lb/batch) at an assumed heating value of 22,400 kJ/kg (9,600 Btu/lb). After a batch is charged to the primary chamber, the unit is sealed and completes an operating cycle with three components--a low-air phase (burn phase), a high-air phase (burndown phase), and a cooldown phase. The unit is equipped with an APCS comprising an air-to-air heat exchanger, and a FF/PB. Emissions measurements were obtained during each of the first two components of the operating cycle. Simultaneous measurements were made upstream from the heat exchanger and downstream from the FF/PB under one set of test conditions considered to represent normal operating conditions for the facility. Separate tests were conducted during two components of the operating cycle--the low-air phase (Condition 1) and the high-air phase (Condition 2). Limited CEM data were also collected during the cooldown phase of the process. The values for the incinerator operating parameters for the six test runs are included in Table A-1, and APCS operating data for facility J are presented in Table A-4. The incinerator was charged with general medical wastes for these tests. Note that although only one test condition was used at Facility J, the manual test data are separated into two conditions that represent the low-air and high-air components of the process cycle, respectively.

4.1.1.4 Facility K. The incineration unit at Facility K is an Environmental Control Products (now Joy Energy Systems) Model 480-E intermittent-duty, dual-chamber MWI. The unit nominally

operates at starved-air conditions in the primary chamber and excess-air conditions in the secondary chamber. It has a charging capacity of 145 kg/hr (320 lb/hr) at an assumed heating value of 19,800 kJ/kg (8,500 Btu/lb). The unit is not equipped with an APCS.

The emission test program at Facility K included a total of eight test runs under three different test conditions defined by charging characteristics and secondary chamber temperatures. Condition 1 consisted of frequent charges at less than design feed rates. For Condition 1, waste was charged approximately every 6 minutes at 9.1 kg (20 lb) per charge for an average feed rate of 91 kg/hr (200 lb/hr). Condition 2 represents the unit's design feed rate with frequent charges. For Condition 2, the nominal charging conditions were to charge 14 kg (30 lb) of waste every 6 minutes for a total charging rate of 140 kg/hr (300 lb/hr). Condition 3 represents the unit's design feed rate with infrequent charges. For Condition 3, plans called for charging 140 kg/hr (300 lb/hr) waste in 23 kg (50 lb) batches every 10 minutes. During all three conditions, general medical waste was charged to the unit. The target secondary chamber temperatures were 1040°C (1900°F) during Conditions 1 and 2 and 870°C (1600°F) during Condition 3.

4.1.1.5 Facility M. The incineration system at Facility M was custom designed and sized by ThermAll, Inc. The primary components of the system are a rotary kiln, which is also called the primary combustion chamber, followed by a fixed secondary combustion chamber. The system is equipped with a WHB. The system is designed with a heat input rate of 10.5×10^6 kJ/hr (10×10^6 Btu/hr), which corresponds to a feed capacity of 454 kg/hr (1,000 lb/hr) at an assumed waste feed heating value of 21,000 kJ/kg (10,000 Btu/lb). Currently, the system is limited to a feed rate of 354 kg/hr (780 lb/hr) (permit limit) and at that level, the rotary kiln is designed to operate at stoichiometric conditions. The APCS at Facility M comprises a spray dryer followed by a pulse-jet fabric filter (SD/FF).

The test program at Facility M comprised three runs at each of two sets of test conditions. The incinerator operating conditions were identical for both conditions with the charge rate maintained at about 354 kg/hr (780 lb/hr) and a secondary chamber set point maintained at 982°C (1800°F). The exhaust gas temperature from the rotary kiln or primary chamber was typically about 780°C (1450°F). During both conditions, general medical waste was charged to the unit. The primary difference between the two conditions was that, during the second condition, approximately 1.1 kg/hr (2.5 lb/hr) activated carbon was added to the lime slurry to treat the exhaust gas.

4.1.1.6 Facility S. The incinerator at Facility S is a Consumat Model C-75P intermittent-duty, dual-chamber MWI. This unit is designed to fire either general medical waste or 100 percent pathological waste. When general waste is fired, the unit is designed to operate at starved-air conditions in the primary chamber and excess-air conditions in the secondary chamber. The unit operates with excess-air conditions in both chambers when pathological waste is being fired. The nominal charge capacity is 80 kg/hr (175 lb/hr) for pathological waste and 110 kg/hr (250 lb/hr) for general medical waste. These charge capacities are based on a heating value of 2,300 kJ/kg (1,000 BTU/lb) for pathological waste and a heating value of 19,800 kJ/kg (8,500 Btu/lb) for general medical waste. This facility has no APCS.

Emissions were measured at the Facility S secondary chamber exhaust under three test conditions defined by waste type, waste charging rate, and secondary chamber temperature. Plans for Condition 1 called for 45 kg/hr (100 lb/hr) pathological waste, which is below design capacity, to be charged in equal charges at 15-minute intervals. During Condition 2, pathological waste was to be charged at 73 kg/hr (160 lb/hr) in equal charges at 15-minute intervals. For Condition 3, general medical waste was to be charged at 73 kg/hr (160 lb/hr) in equal charges at 15-minute intervals. Target secondary chamber temperatures were 870°C (1600°F) for Conditions 2 and 3 and 1040°C (1900°F) for

Condition 1. Note that for all runs actual secondary chamber temperatures are substantially below target values. The relatively high primary chamber temperatures suggest that substantial waste combustion occurred there, and under such conditions, the secondary burner appeared to have insufficient capacity to maintain the target temperatures.

4.1.1.7 Facility W. The Facility W incinerator is an Environmental Control Products (now Joy Energy Systems) Model-480 E/SR-12H intermittent-duty, dual-chamber MWI. It is designed to operate at starved-air levels in the primary chamber and excess-air levels in the secondary chamber. The unit has a charge rating of 175 kg/hr (385 lb/hr) at an assumed heating value of 19,800 kJ/kg (8,500 Btu/lb). This facility has no APCs.

The test program at Facility W involved three sets of test conditions defined by charging practices and secondary chamber temperature. Measurements were made at the secondary chamber exhaust while general medical waste was charged to the unit. The planned levels for Condition 1, which represents below design feed rates with frequent charges and high secondary chamber temperatures, were a charge rate of 90 kg/hr (200 lb/hr) with equal charges at 6-min intervals and a secondary chamber temperature of 1040°C (1900°F). For Condition 2, which represents design feed rate with frequent charges and high secondary chamber temperatures, the charge rate was increased to 136 kg/hr (300 lb/hr) with the same charging frequency and secondary chamber temperature as Condition 1. For Condition 3, which represents design feed rate with infrequent charges and low secondary chamber temperatures, the average charging rate was maintained at 136 kg/hr (300 lb/hr), but the frequency was changed to 10-min intervals and the secondary chamber temperature was decreased to 870°C (1600°F). For all conditions, general medical waste was charged to the unit.

4.1.2 Test Data Summary

The emission test program generated data on a wide variety of pollutants for 25 test conditions (77 separate test runs) at the seven sites. As described above, emissions measurements were

made downstream from the secondary chamber and/or WHB ("post-combustion" emissions) at all sites; measurements also were made downstream of an APCS ("post-APCS" emissions) at four sites. Table 2 presents average post-combustion and post-APCS emission concentrations by facility and test condition. For those pollutants expected to be affected by add-on APCS's, Table 2 also presents removal efficiencies based on mass emission rates. Tables B-1 and B-2 in Appendix B present post-combustion emission data in concentration units corrected to a uniform excess air level (7 percent O_2) for each test run conducted at the seven sites. Table B-1 presents data on PM, CO, HCl, SO_2 , and NO_x emissions, while Table B-2 presents data on CDD/CDF, Cd, Pb, and Hg emissions. These data are presented with a mixture of English and SI units in accordance with most common usage.

Graphical summaries of post-combustion emissions concentrations are presented in Appendix C for PM (Figure C-1), CO (Figure C-2), HCl (Figure C-3), SO_2 (Figure C-4), NO_x (Figure C-5), CDD/CDF (Figure C-6), Cd (Figure C-7), Pb (Figure C-8), and Hg (Figure C-9). Each of the graphs displays a substantial amount of information about the distribution of emission concentrations separately for each test condition. The concentration levels for each individual test run are indicated by the symbol '*' on each graph. In each graph and for each test condition, the range of emissions is shown along with a small bar in the range that denotes the average emission concentration.

Post-APCS emission concentrations corrected to a uniform excess air level (7 percent O_2) for PM, HCl, CDD/CDF, Cd, Pb, and Hg for each test run are presented in Table B-3. Table B-3 also presents APCS removal efficiencies based on mass emission rates for those runs for which data were sufficient to permit calculations. Appendix D provides graphical summaries for the post-APCS emissions concentrations for those pollutants that are expected to be affected by the add-on APCS's. These graphs, which are analogous to those presented in Appendix C for post-combustion pollutant concentrations are presented for PM (Figure D-1), HCl (Figure D-2), SO_2 (Figure D-3), CDD/CDF

TABLE 2. MEAN POLLUTANT EMISSION CONCENTRATIONS AND REMOVAL EFFICIENCIES FOR EACH TEST CONDITION^a

Facility	Test condition	Waste type	Post-combustion PM, gr/dscf	Post-APCS PM, gr/dscf	PM removal efficiency, %	Post-combustion CO, ppmv	Post-combustion HCl, ppmv	Post-APCS HCl, ppmv	HCl removal efficiency, %	Post-combustion SO ₂ , ppmv	Post-APCS SO ₂ , ppmv	Post-combustion NO _x , ppmv
A	1	G500	0.074 ^b	0.0242	84.9	16.5	1,770	47.9	97.6	7.31	6.38	210
	2	G500	0.074 ^b	0.0242	c	19.0	1,370	40.5	97.0	13.5	8.05	190
	3	G500	0.0627	0.0020	97.0	16.7	1,740	82.4	95.5	6.15	5.91	164
	4	G100	0.1204	b	c	20.5	1,050	18.7	98.3	20.9	10.3	188
	5	RB	0.0989	0.0720	46.0	1.9	1,600	108	93.6	6.47	13.2	178
	6	RB	0.1235	0.0022	97.9	10.3	1,770	72.8	96.1	2.04	9.13	181
	7	RB	0.0866	0.0079	80.1	18.2	2,450	67.2	97.2	3.46	13.6	162
A	1A	General	0.0771	0.0027	96.1	13.3	1,670	69.5	95.7	6.0	9.0	143
	8	General	0.0740	0.0023	97.6	7.2	2,230	34.4	98.5	4.6	19.0	140
	9	General	0.0780	0.0025	96.3	8.5	1,940	40.8	97.5	8.3	15.6	153
B	1	General	0.1003	0.0463	59.6	26.0	1,160 ^d	1.38 ^d	99.9 ^d	1.46	0.73	72.2
J	1	General	0.0039	0.0011	>74.8 ^e	5.7	112	18.3	90.0	8.44	2.12	85.5
	2	General	0.0267	0.0021	95.7	14.5	284	70.4	82.6	25.4	11.5	85.0
	3 ^d	General				6,620 ^d				22.0 ^d	1.03 ^d	169 ^d
K	1	General	0.1359	e	e	75.6	992	e	e	7.55	e	79.2
	2	General	0.1488	e	e	110	1,430	e	e	11.7	e	82.0
	3	General	0.4521	e	e	1,400	1,830	e	e	18.4	e	97.8
M	1	General	0.493	0.0038	99.2	14.5	724	5.97	99.4	10.5	9.2	84.9
	2	General	0.488	0.0011	99.8	8.9	1,070	26.1	99.4	17.8	3.9	82.6
S	1	Path	0.0427	e	e	79.2	123	e	e	100	e	310
	2	Path	0.0490	e	e	133	111	e	e	124	e	390
	3	General	0.4517	e	e	1,200	1,540	e	e	42.3	e	180
W	1	General	0.0830	e	e	97.0	1,080	e	e	17.5	e	73.2
	2	General	0.1900	e	e	435	1,320	e	e	28.4	e	84.3
	3	General	0.1967	e	e	359	1,530	e	e	23.3	e	92.9

^aAll concentrations corrected to 7 percent O₂. Pollutant removal efficiencies based on mass emission rates, except condition 4 at Facility A, which is based on concentrations.

^bData not measured.

^cEfficiency not calculated because either data not measured or data measured did not meet quality control standards.

^dValues shown based on CEM data.

^eNo APCS at this facility.

^fOutlet values higher than inlet values; negative efficiencies were not calculated.

^gOne or more outlet values below detection.

^hAverages based on at least one value below detection (see Tables B-1 through B-3).

TABLE 2. (continued)

Facility	Test condition	Post-combustion total CDD/CDF, ng/dscm	Post-APCS total CDD/CDF, ng/dscm	CDD/CDF removal efficiency, %	Post-combustion Cd, µg/dscm	Post-APCS Cd, µg/dscm	Cd removal efficiency, %	Post-combustion Pb, µg/dscm	Post-APCS Pb, µg/dscm	Pb removal efficiency, %	Post-combustion Hg, µg/dscm	Post-APCS Hg, µg/dscm	Hg removal efficiency, %
A	1	489	648	6.1	335	1.6 ^g	h	3,300	23.1	99.3	11,900	6,570	34.6
	2	421	348	17.5	h	h	c	3,410	h	c	h	h	c
	3	351	319	14.1	558	2.9 ^g	h	2,350	25.0	99.3	16,300	10,700	42.8
	4	271	h	c	282	h	c	5,360	h	c	203	h	c
	5	b	h	c	145	1.7 ^g	h	6,760	16.7	99.7	1,220	2,300	f
	6	520	270	46.4	266	2.9 ^g	h	5,200	20.0	99.6	3,940	2,140	10.7
	7	459	544	f	210	1.9 ^g	h	1,500	33.6	99.4	1,300	4,980	f
A	1A	237	131	38.0	402	1.15	99.6	1,500	4.24	99.7	6,880	7,410	f
	8	411	16.0	96.0	1,930	2.24	99.9	2,110	4.87	99.7	7,380	904	86.5
	9	416	6.27	98.2	714	10.4	98.4	1,500	6.93	99.5	9,500	389	95.1
B	1	1,450	407	69.4	385	220	40.8	3,320	1,760	43.7	366	301	18.7
J	1	33	6,820	f	29.7	4.0	92.8	805	15.3	98.8	1,260	464	78.3
	2	1,210	3,070	f	207	4.9	98.6	5,540	78.3	99.2	3,390	1,184	69.6
	3 ^d												
K	1	5,570	e	e	168	e	e	4,280	e	e	142	e	e
	2	7,260	e	e	214	e	e	1,870	e	e	139	e	e
	3	35,500	e	e	370	e	e	2,670	e	e	2,060	e	e
M	1	192	32.2	84.0	471	1.77	99.7	3,590	5.7	99.9	2,590	1,980	29.6
	2	199	3.3	98.3	492	0.84	99.8	4,410	2.5	99.9	2,630	284	90.0
S	1	914	e	e	174	e	e	442	e	e	40.5 ^g	e	e
	2	576	e	e	20.5	e	e	307	e	e	61.2 ^g	e	e
	3	24,700	e	e	55.0	e	e	1,880	e	e	5.5 ^g	e	e
W	1	2,400	e	e	280	e	e	4,660	e	e	184	e	e
	2	5,950	e	e	385	e	e	6,250	e	e	510	e	e
	3	5,030	e	e	584	e	e	5,340	e	e	2,640	e	e

(Figure D-4), Cd (Figure D-5), Pb (Figure D-6), and Hg (Figure D-7).

4.2 DISCUSSION OF THE TEST RESULTS

This section summarizes general findings based on an examination of the MWI and APCS operating parameters and emission test data. Substantial insight about the performance of the combustion systems and add-on APCS's tested can be gained by a careful examination of the information presented in Table 2 and Appendices B through D.

Table 2 presents emission concentrations for PM, CO, HCl, SO₂, NO_x, CDD/CDF, and three metals. With the exception of CO and NO_x, emissions of each of these pollutants can be affected substantially by waste characteristics. Emissions of four of the pollutants--PM, CO, CDD/CDF, and to a lesser extent, NO_x--are likely to be affected by the combustion system characteristics. Section 4.2.1 discusses the effects of waste types on post-combustion emissions. In particular, emissions measured for test conditions burning red bag waste and general medical waste are compared and emissions measured for test conditions burning pathological waste and general medical waste are compared. Section 4.2.2 discusses the effects of variations in combustion parameters on measured emissions. First, the relationships of CDD/CDF emissions to CO and PM emissions are discussed. Second, the relationships between emissions of CDD/CDF, CO, and PM and combustion process parameters are discussed. In Section 4.2.3, the variations in CO and THC emissions during the burndown/cooldown phases of the batch and the intermittent MWI operating cycles are described. In Section 4.2.4, the operating cycle of batch MWI's is discussed. In Section 4.2.5, the effect of combustion parameters on metals partitioning is described. Finally, Section 4.2.6 presents a discussion of the performance of the four APCS's: DI/FF, SD/FF, VS/PB, and FF/PB.

4.2.1 Effects of Waste Types on Emissions

The test programs conducted at Facilities A and S were designed to evaluate the effect of different waste types on emissions. The test program at Facility A was designed to

characterize emissions during combustion of two general medical wastes, (general waste from a 500-bed hospital [G500] and general waste from a 100-bed hospital [G100]), and red bag infectious wastes. The test program at Facility S was designed to compare emissions from the combustion of pathological waste and general waste.

4.2.1.1 Emissions from Combustion of General Medical Waste Versus Red Bag Waste. In general, emission concentrations at Facility A showed substantial overlap between general waste runs and red bag runs. Neither waste type produced substantially greater emissions for the pollutants measured. Additionally, for the pollutants most likely to be affected only by waste characteristics and not combustion conditions (HCl, SO₂, and metals), the concentrations associated with red bag waste generally are within the ranges obtained when general waste was fired at Facility A and the other four intermittent-duty units. The results of this test program indicate that uncontrolled emissions from the combustion of red bag and general medical waste are comparable.

While the emissions from red bag and general waste combustion are generally comparable, two additional observations (one related to Hg and one related to HCl) on the red bag/general waste comparison at Facility A are noted below. The principal difference in emissions resulting from burning red bag and general waste at Facility A is in the Hg emissions. Figure 22 shows the effects of waste type on emissions of Hg at Facility A. As indicated in Figure 22, Hg emissions from burning G100 (waste obtained from another hospital) are one to two orders of magnitude lower than Hg emissions measured while burning G500 and red bag wastes. Also, with the exception of the first run of test condition 6 (RB at 1800°F), the Hg concentrations associated with burning G500 waste are higher than those from burning red bag waste. Figure 23 compares the Hg concentrations measured at Facility A with the Hg concentrations measured at other facilities. The Hg concentrations found during the G500 (general medical waste) runs at Facility A are substantially higher than

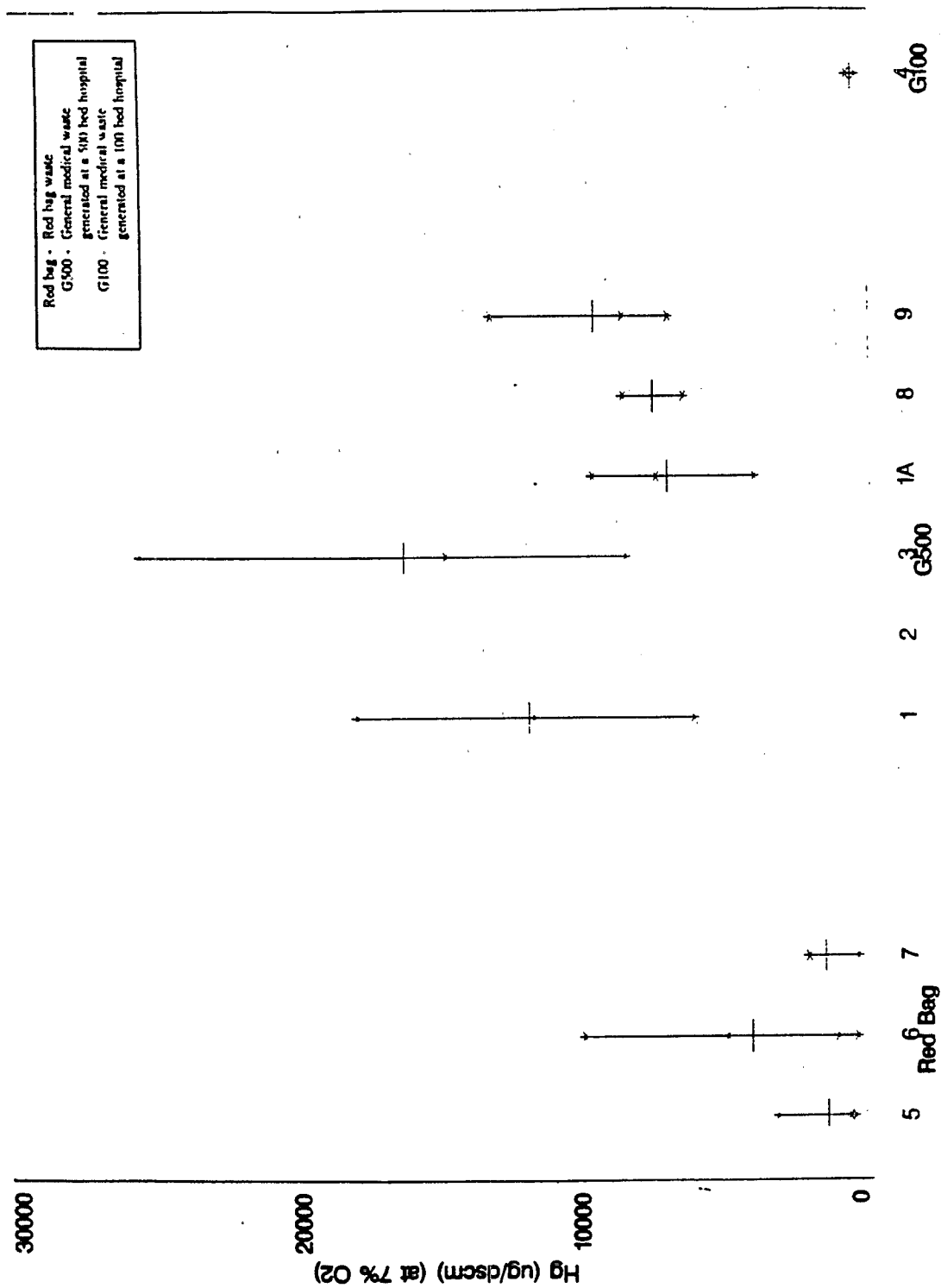


Figure 22. Effect of waste type at Facility A on post-combustion Hg emissions.

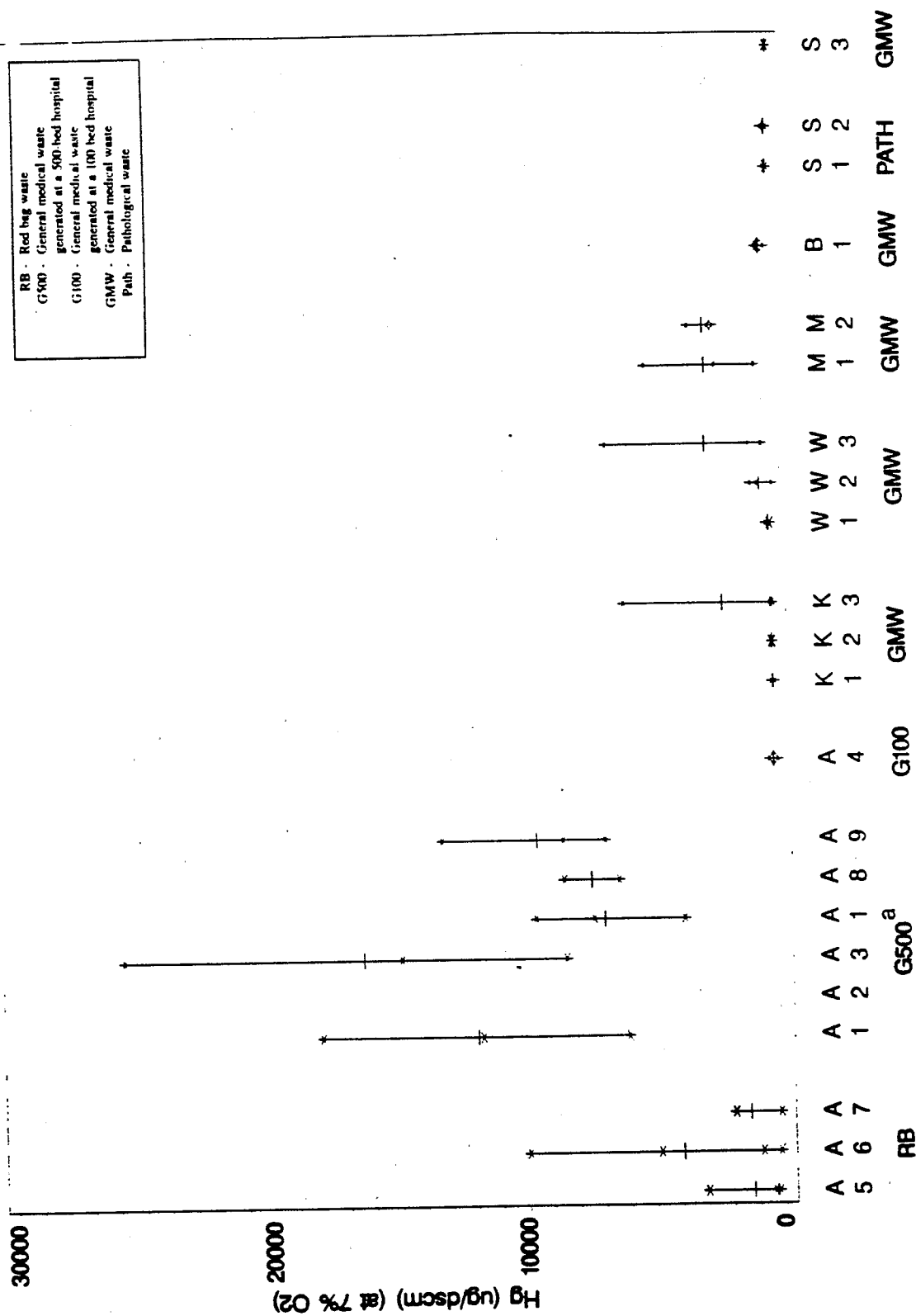


Figure 23. Effect on waste type on Hg emissions for all intermittent/continuous MWI's.

those typically found at other facilities burning general medical waste. Although the source of the Hg in the Facility A waste has not been identified, the data indicate that the general waste stream at Facility A has an Hg source that differs from those at the other facilities tested. Overall, these data indicate that Hg emissions may vary substantially from facility to facility and between waste types, with neither RB nor general medical waste consistently having higher Hg emissions.

Figure 24 shows the effects of waste type on emissions of HCl at Facility A. It is clear from Figure 24 that HCl concentrations measured during two of the three test condition 7 runs (RB at 2000°F) were substantially higher than those during the other red bag runs. These higher concentrations are the result of spiking hexachlorobenzene as a cytotoxic surrogate during these runs and are not attributed to the red bag wastes. Additionally, two general waste runs (test condition 3, run number 2 and test condition 8, run number 1) had HCl concentrations somewhat higher than the other general waste runs. However, no differences in waste feed conditions were noted during these runs, and the increased HCl concentrations for these runs are assumed to be attributable to normal waste variability.

4.2.1.2 Emissions from Combustion of General Medical Waste Versus Pathological Waste. Table 3 presents the post-combustion emissions measured at Facility S during the combustion of general and pathological wastes. At Facility S, for the majority of pollutants (PM, CO, HCl, CDD/CDF, and Pb), the emissions from the pathological waste runs were substantially less (often as much as an order of magnitude less) than those from general waste combustion. The emission characteristics for the other pollutants were more varied as described below.

The concentrations of Cd emissions were generally lower for pathological runs than for general waste runs. The lone exception was test condition 1, run no. 3, which had a Cd concentration (504 $\mu\text{g}/\text{dscm}$ at 7 percent O_2) that was more than an order of magnitude higher than the next highest concentration (26 $\mu\text{g}/\text{dscm}$ at 7 percent O_2) from the pathological runs. A

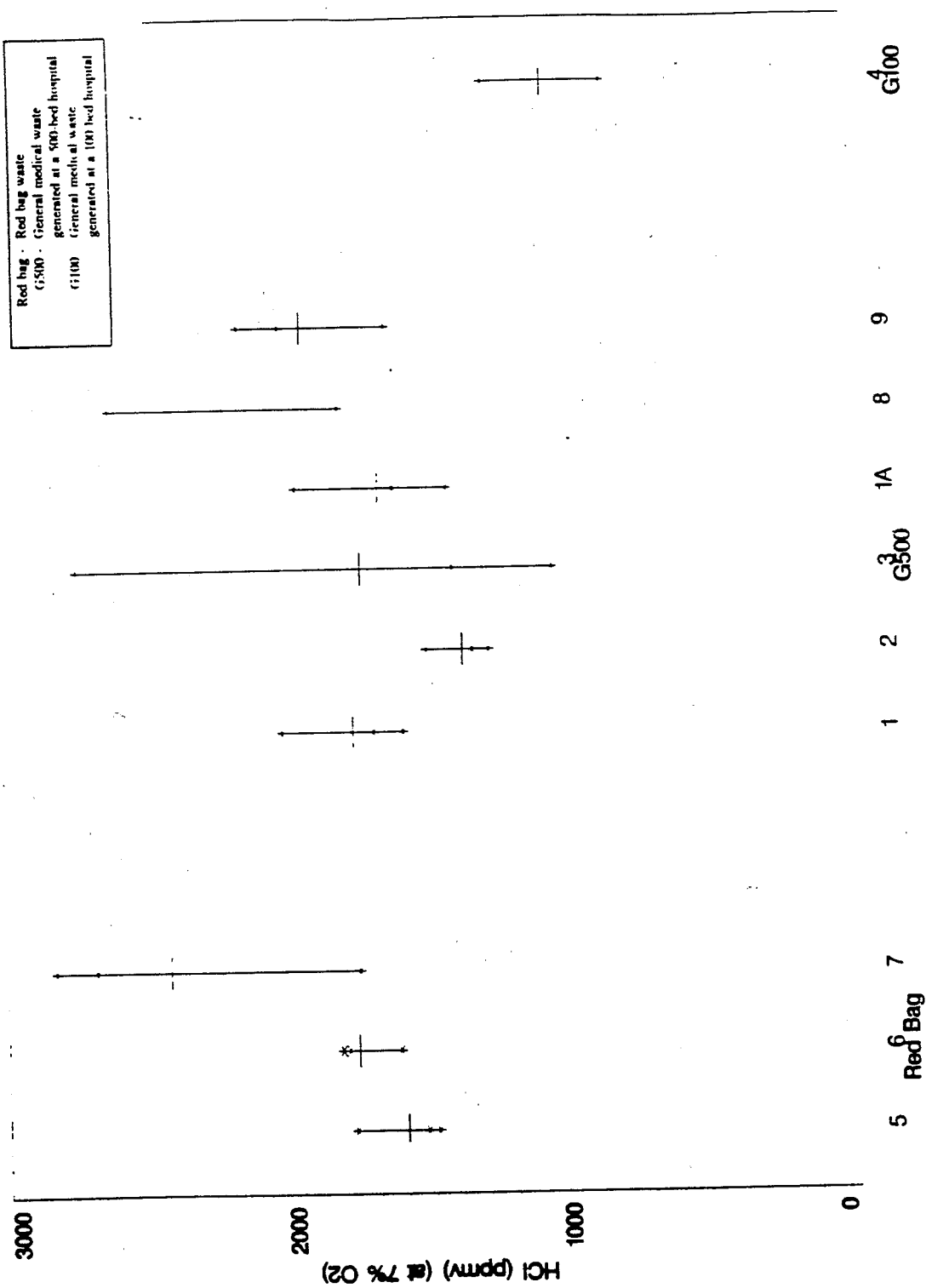


Figure 24. Effect of waste type at Facility A on post-combustion HCl emissions.

TABLE 3. POST-COMBUSTION EMISSIONS MEASURED AT FACILITY S
FROM COMBUSTION OF GENERAL MEDICAL WASTE AND PATHOLOGICAL WASTE. ^a

Test condition ^b	Waste type	Run No	PM, gr/dscf	CO, ppmv	HCl, ppmv	SO ₂ , ppmv	NO _x , ppmv	CCD/CDF, ng/dscf	Cd, µg/dscf	Pb, µg/dscf	Hg, µg/dscf
1	Pathological	1	0.042	117	84	105	335	279	16	512	4.3
1	Pathological	3	0.044	40.0	185	117	285	1,990	504	814	<0.9
1	Pathological	10	0.042	80.3	99	79.6	309	468	<1	0	116
2	Pathological	5	0.038	102	100	132	378	427	13	329	183
2	Pathological	6	0.061	193	81	134	398	157	26	202	<0.7
2	Pathological	9	0.048	105	153	107	393	1,140	22	389	<0.5
3	General medical	2	0.181	400	1,280	36.7	205	12,700	55	2,380	10.7
3	General medical	4	0.931	2,750	1,580	43.8	142	41,000	42	1,210	5.2
3	General medical	8	0.243	445	1,750	46.4	194	20,500	67	2,050	<0.7

^a All concentrations corrected to 7 percent O₂.

^b Test condition 1: Pathological waste charged at a rate of 100 lb/hr at 1900°F

Test condition 2: Pathological waste charged at a rate of 160 lb/hr at 1600°F

Test condition 3: General medical waste charged at a rate of 160 lb/hr at 1600°F

review of the charging records provided no indication that the wastes used for this run were different from those used for the other pathological runs.

The Hg concentrations from three pathological runs and one general waste run at Facility S were below the detection limit. The other two general waste runs had concentrations of 10 $\mu\text{g}/\text{dscm}$ at 7 percent O_2 or less. However, two of the pathological runs (10 and 5) had Hg concentrations of 116 and 182 $\mu\text{g}/\text{dscm}$ at 7 percent O_2 , respectively. Review of test records provided no additional information that could explain the higher levels. Consequently, they are assumed to be within the normal range of Hg emissions from combustion of pathological waste. Mercury emissions from the combustion of pathological waste are low in comparison to test runs conducted at other facilities where general medical waste and red bag waste were combusted. Additionally, Hg emissions from the combustion of general medical waste at Facility S were significantly lower than the Hg emissions measured at other facilities. Overall, Hg emissions from Facility S during combustion of pathological waste and general medical waste fall into the low end of the range of Hg emissions measured from all facilities during this test program.

The two pollutants that showed consistently higher concentrations when pathological wastes were burned than when general wastes were burned at Facility S are NO_x and SO_2 . A significant amount of heat input to the primary chamber from auxiliary fuel is required during the combustion of pathological waste. Because pathological waste combustion requires the use of substantially more natural gas than the combustion of general waste, the higher NO_x concentrations are not unexpected. Initially, the higher SO_2 levels were somewhat surprising. However, a review of the biological literature suggest that the sulfur level in pathological tissue is high enough to explain the SO_2 concentrations found at Facility S.⁹¹ Consequently, both the NO_x and SO_2 concentrations found at Facility S are assumed to be reasonable uncontrolled levels for pathological waste combustion. Overall, the waste-related pollutant emissions from pathological

wastes are significantly lower than from general medical wastes. The figures in Appendix C provide a comparison of Facility S data with data from all of the other tests.

4.2.2 Effects of Combustion Controls

A wide variety of combustion control measures were described in Section 2.2. As a part of the test program, two of those parameters--waste feed rate and secondary chamber temperature--were varied intentionally between different test conditions. Additionally, facilities with different design secondary chamber residence times were selected for testing. Variations in primary chamber temperature and combustion air rates as indicated by excess air levels were monitored during each test run. The post-combustion emission data were analyzed to assess the effects of variation in these combustion parameters on PM, CO, and CDD/CDF emissions. These pollutants were selected because they are the pollutants most likely to be affected by combustion controls.

The subsections below summarize the results of these analyses. First, the interrelationships among CO, PM, and CDD/CDF emissions are described. Then, the relationships among emissions of each of these three pollutants and combustion process parameters are discussed.

Initial examination of the data in Table 2 suggest that the batch unit at Facility J operates quite differently than the other units tested and that emissions for the Facility S pathological waste combustion were different than those for the Facility S general waste condition. Because of these differences, analyses of combustion controls and PM, CO, and CDD/CDF emissions were conducted using only the data from continuous and intermittent units firing general waste.

4.2.2.1 Relationship of CDD/CDF to PM and CO Emissions.

One of the goals of the data analysis was to determine whether relationships between emissions of CDD/CDF and CO and between emissions of CDD/CDF and PM could be established. If strong relationships between these pollutants exist, then CO and/or PM could be used as surrogates for CDD/CDF emissions. The results show that, overall, the relationship between CDD/CDF and CO is

strong over the full range of data and that large (order of magnitude) changes in CO are indicative of changes in CDD/CDF emissions. However, small changes in CO at low CO levels are not related to changes in CDD/CDF emissions. These results are described in more detail below.

Examination of the complete set of test data from continuous and intermittent units showed CDD/CDF emissions to be strongly related to both CO and PM emissions. Figures 25 and 26 show plots on a log-log scale of CDD/CDF versus CO and PM, respectively. Note that these plots suggest a nearly linear relationship on a log-log scale between CDD/CDF emissions and both PM and CO emissions over the full range of the test data. This visual observation is confirmed by the estimated correlations among the data which yield correlation coefficients of 0.74 between the logs of CDD/CDF and PM and 0.85 between the logs of CDD/CDF and CO.

While these results suggest reasonably strong relationships, further insight into the relationships can be obtained by looking at several subsets of the data. First, the data are divided into two groups--those from newer facilities with better overall combustion control measures (A, B, and W) and those from older facilities (S and K). The results for the two groups are quite different. For the newer facilities a strong correlation (0.90) between the logs of CDD/CDF and CO still exists, but the correlation between the logs of CDD/CDF and PM is substantially weaker (0.55). However, for older facilities both correlations remain strong (0.90 for PM and 0.93 for CO).

On balance, these data show a strong relationship between CDD/CDF and CO over a wide range of emissions represented by the test data as a whole. However, the results should be interpreted cautiously for any smaller range of data. Examination of the relationship between the logs of CDD/CDF and CO at Facility A, which has emissions at the low end of the emission ranges, showed essentially no relationship between CO concentrations and CDD/CDF emissions.

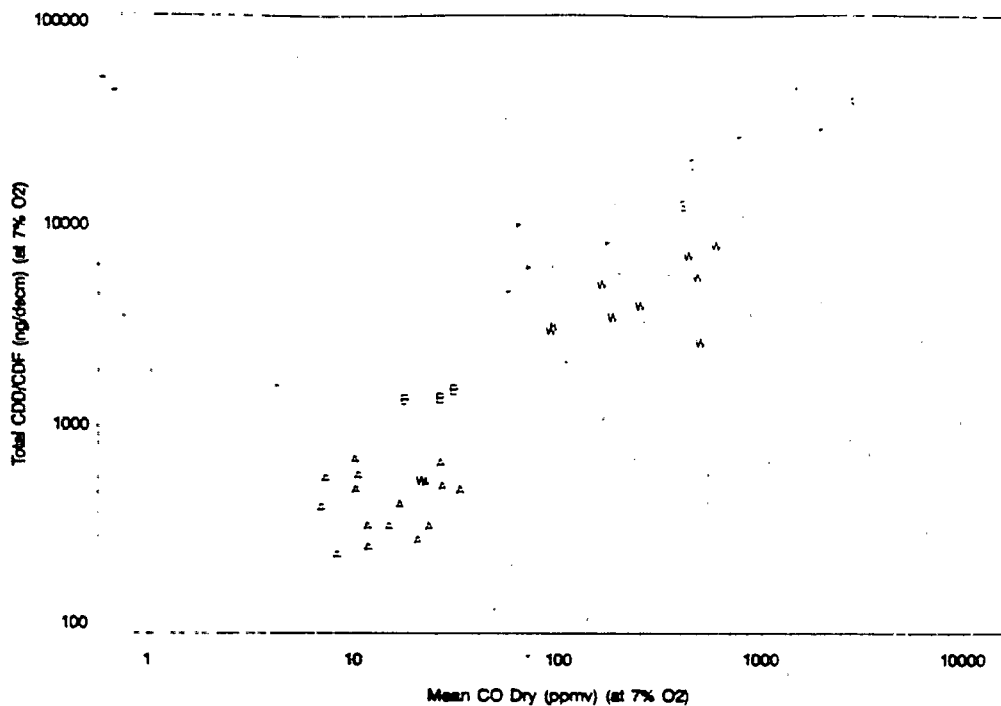


Figure 25. Relationship between CDD/CDF and CO emissions.

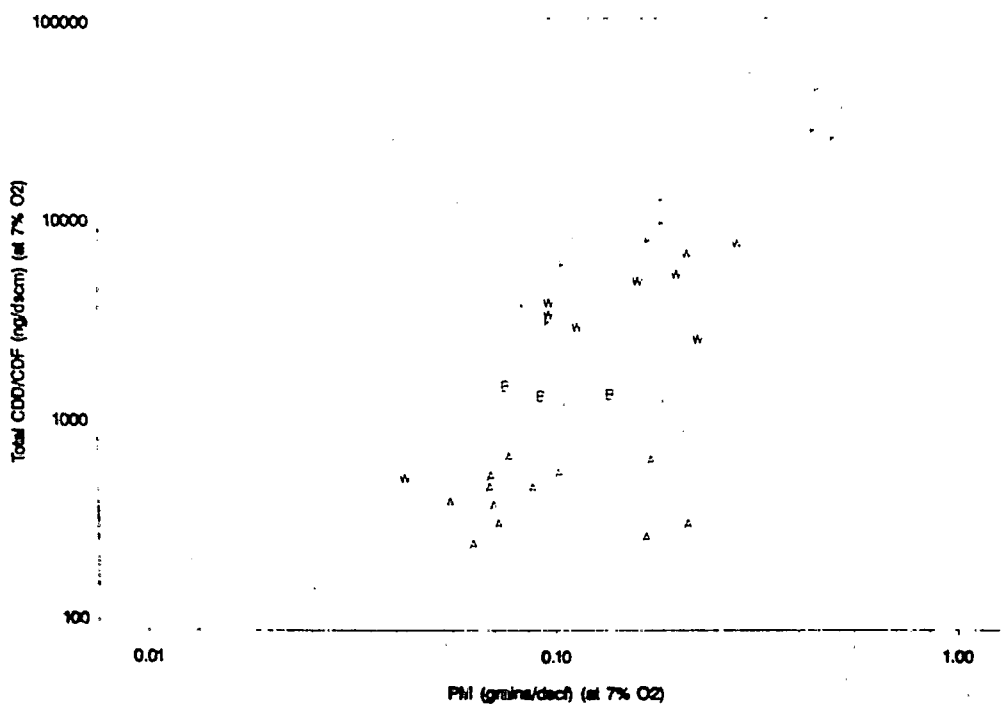


Figure 26. Relationship between CDD/CDF and PM emissions.

Taken together, the data suggest quite different interpretations, depending on the magnitude of changes in CO levels. Large (order of magnitude) changes in CO concentrations appear to be indicative of changes in CDD/CDF emissions. However, because small changes in CO concentrations at low levels such as those found at Facility A are not related to changes in CDD/CDF emissions, CO does not provide a good surrogate for CDD/CDF emissions at low concentrations.

4.2.2.2 Effect of Combustion Parameters on PM, CO, and CDD/CDF Emissions. The three pollutants that are most affected by combustion control parameters are PM, CO, and CDD/CDF. In developing the matrix of test conditions for this test program, several combustion control parameters were considered potentially to have an impact on emissions of PM, CO, and CDD/CDF. These parameters include secondary/tertiary chamber residence time, secondary/tertiary chamber temperature, primary chamber temperature, and waste charge rate. One of the goals of the test program was to measure the impact of as many of these parameters as possible on emissions by selecting MWI facilities and test conditions that would allow the appropriate comparisons of emission results to be made. The evaluation of the effect of combustion parameters on measured emissions are presented in two sections. The effects of variations in the secondary/tertiary combustion chamber control parameters--secondary/tertiary chamber temperature and secondary/tertiary chamber gas residence time--on emissions are discussed in Section 4.2.2.2.1. The effects of variations in the primary combustion chamber control parameters--primary chamber temperature and waste charging procedures--on emissions are discussed in Section 4.2.2.2.2.

4.2.2.2.1. Secondary/tertiary chamber combustion control parameters. In the secondary/tertiary chambers of MWI's, combustion gases from the primary chamber containing volatiles are further combusted under excess-air conditions. Effective combustion in the secondary/tertiary chambers is accomplished when sufficiently high temperatures are attained, turbulent conditions are achieved in the presence of sufficient oxygen

(good mixing of combustion air with volatiles), and sufficient residence time at high temperature is allowed. Because all MWI's are designed to operate the secondary/tertiary chambers in an excess-air mode and because all MWI's incorporate secondary chamber designs that introduce some degree of turbulent mixing between combustion air and primary chamber exhaust gases, the focus of the test program was to select MWI facilities with specific features, to operate them at specified conditions, and to measure post-combustion emissions to determine the impact of secondary/tertiary chamber temperature and residence time on emissions. This section first summarizes the variations in secondary/tertiary combustion control parameters integrated into the test program design and subsequently presents an evaluation of the emission results with respect to these combustion control parameters.

Testing conducted at Facilities A, W, and K included test conditions where general medical waste was charged to the MWI and target secondary/tertiary chamber temperatures were 870°C (1600°F) and 980° to 1040°C (1800° to 1900°F). (Facility A also included a test condition where general medical waste was charged and the target secondary/tertiary chamber temperature was 1090°C [2000°F].) At Facilities B and M, testing comprised charging general medical waste with a target secondary/tertiary chamber temperature of 980°C (1800°F). Testing at Facility S included one test condition where general medical waste was charged and the target secondary/tertiary chamber temperature was 870°C (1600°F). These MWI facilities were selected for testing in part because they had different design secondary/tertiary chamber residence times. Facility A has a design secondary/tertiary chamber residence time of 1.34 seconds at 1800°F. The design secondary chamber residence time at Facility W is 1.0 second; Facility K is 0.33 second; Facility B is 1.75 seconds; and Facility M is 2.1 seconds. In designing the test program in this manner, the effect of secondary/tertiary chamber temperature and residence time on the emissions of CDD/CDF, CO, and PM could be evaluated. Figures 27, 28, and 29 present the data from these

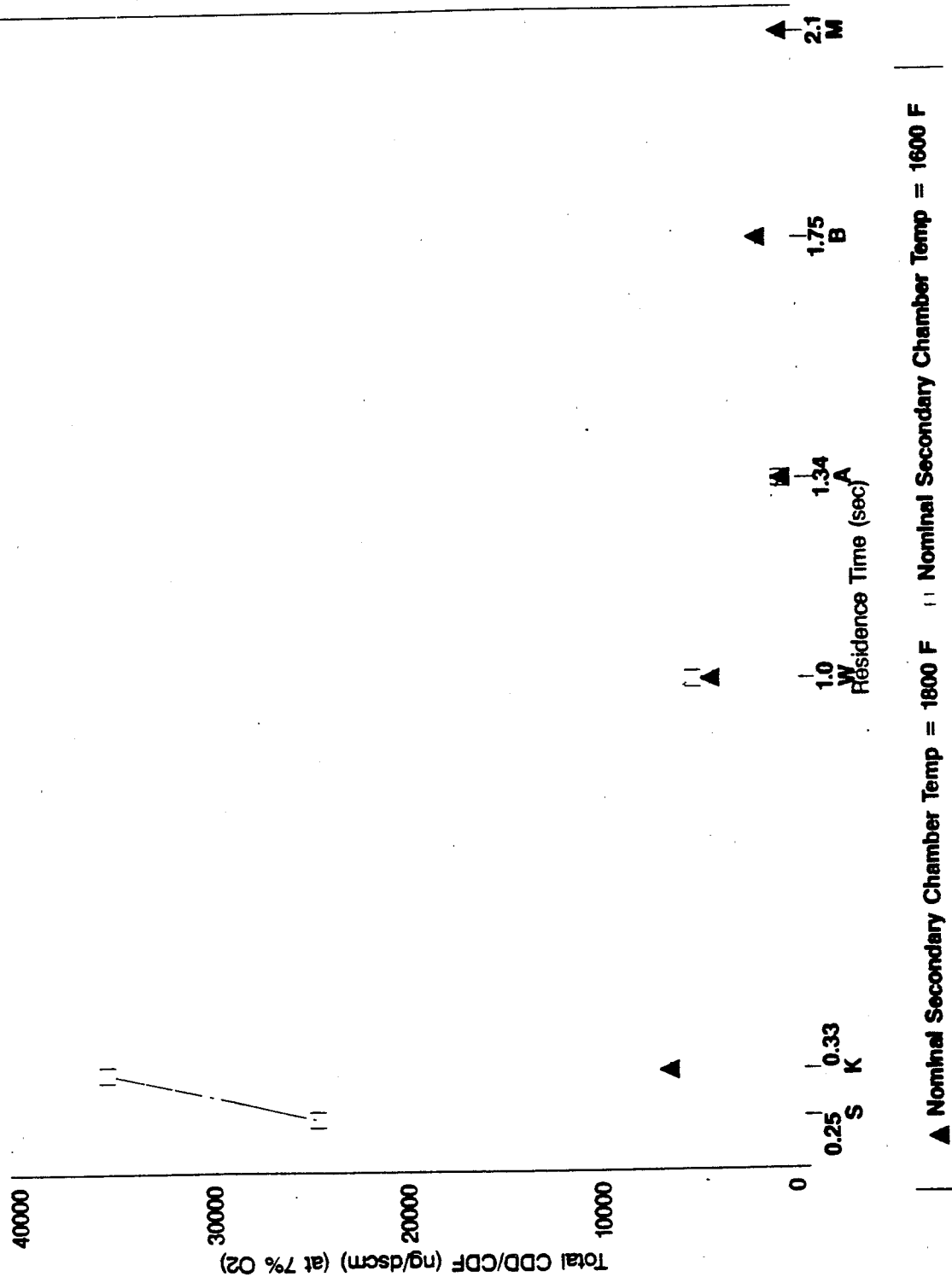


Figure 27. Effect of secondary/tertiary chamber temperature and residence time on CDD/CDF emissions.

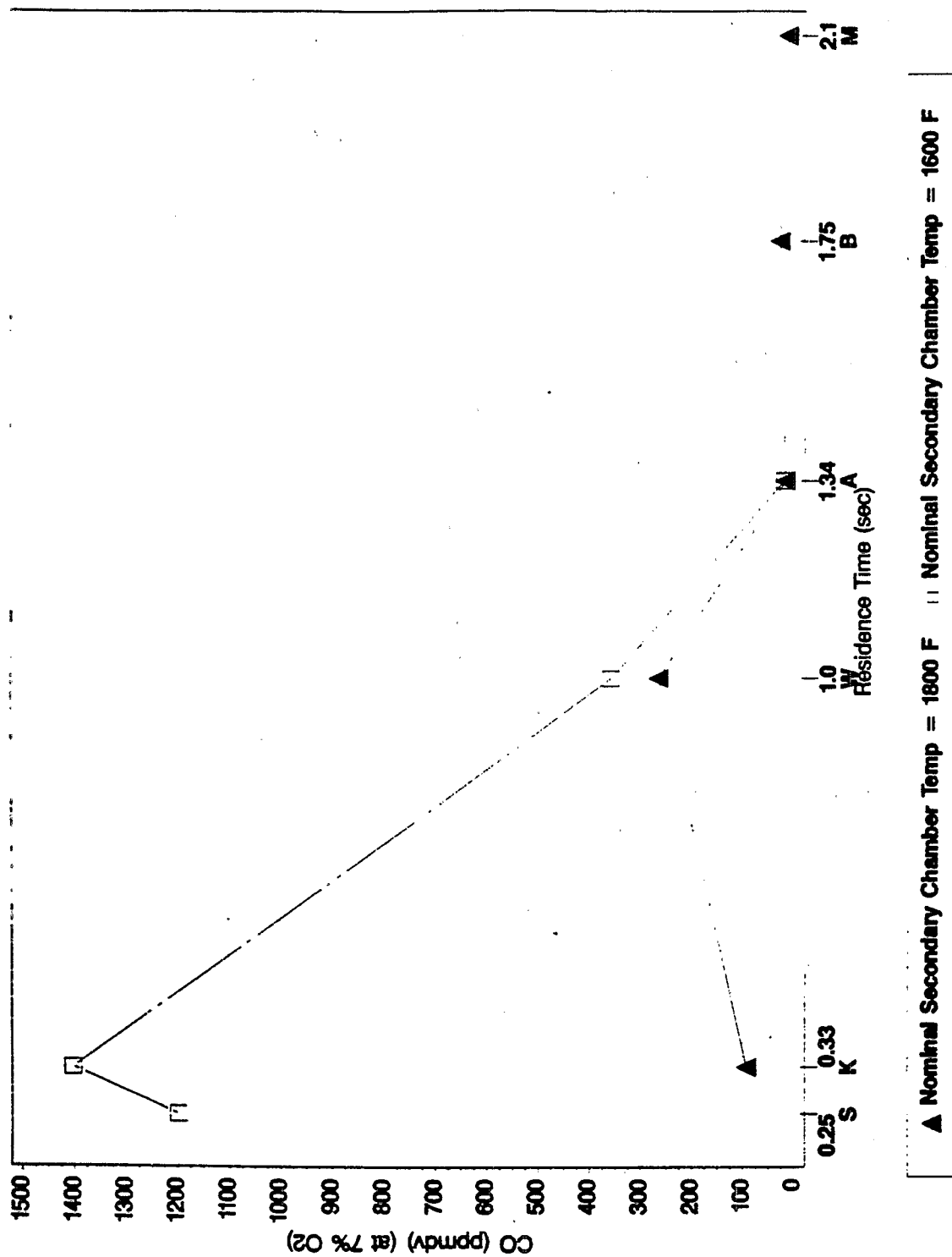


Figure 28. Effect of secondary/tertiary chamber temperature and residence time on CO emissions.

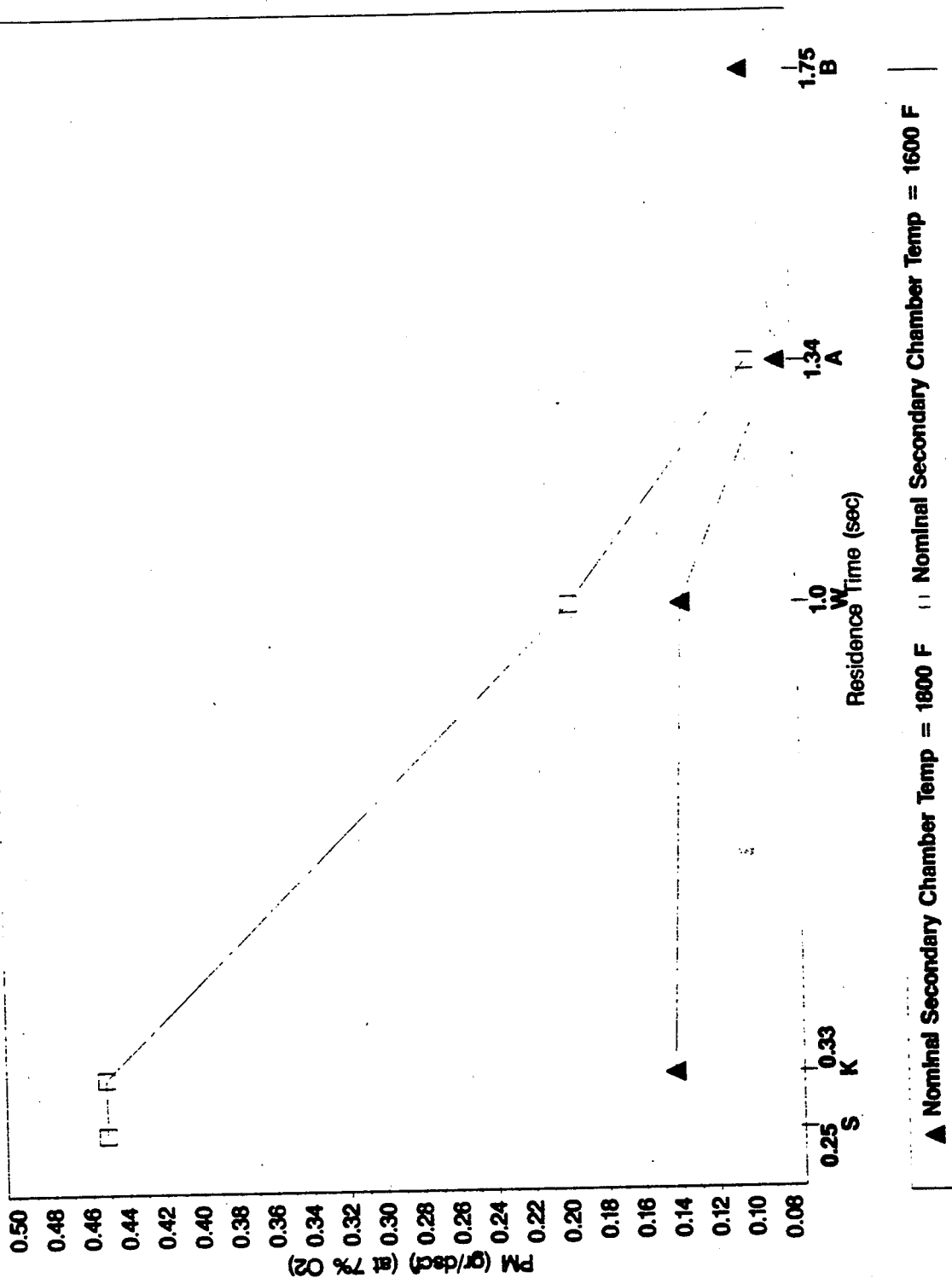


Figure 29. Effect of secondary/tertiary chamber temperature and residence time on PM emissions.

tests for CDD/CDF, CO, and PM, respectively, as a function of both secondary/tertiary chamber temperature and residence time. The data presented in these figures are the averages of the three test runs conducted at each test condition. The data for each facility are plotted in order of increasing residence time (x-axis). The data for the 980°C (1800°F) test conditions conducted at five of the six facilities are represented by solid triangles. The data for the 870°C (1600°F) test conditions conducted at three of the six facilities are represented by open squares. For each figure, to highlight the general trend of the results, separate lines have been added to connect the 980°C (1800°F) data points and the 870°C (1600°F) data points. Note that although CO and CDD/CDF emissions were measured during the 870°C (1600°F) general medical waste test condition at Facility A, PM emissions were not measured. Therefore, the PM results from the 870°C (1600°F) RB test condition are shown because, as discussed earlier, there is little difference in the general medical and RB emission rates. Also, note that the PM emissions are not shown for Facility M. The results of the PM test at Facility M showed that, as expected, a rotary kiln MWI has a higher post-combustion PM emission rate than other MWI's because of the increased turbulence of the ash bed in rotary kilns. Therefore, the PM data from Facility M were not comparable to the data from fixed hearth MWI's. In reviewing the test data, the following general observations can be made:

1. An increase in the secondary/tertiary chamber temperature from 870°C (1600°F) to 980°C (1800°F) decreases the emissions of PM, CO, and CDD/CDF for the tests conducted on units with residence times of less than or equal to 1 second. As the secondary chamber residence time increases, the effect on emissions of increasing the secondary chamber temperature decreases. Secondary chamber temperature has much less effect on emissions for the facilities which had longer residence times and better combustion air control. At Facility A (with a design secondary chamber residence time of 1.34 seconds), there is

essentially no decrease in emissions as a result of increasing the secondary chamber temperature;

2. As indicated by the downward trend in the lines connecting the 870°C (1600°F) data and the 980°C (1800°F) data, as the secondary/tertiary chamber residence time increases, the emissions of CDD/CDF, CO and PM decrease;

3. The emissions measured at Facilities A, B, and M at a nominal secondary/tertiary chamber temperature of 980°C (1800°F) and a secondary/tertiary chamber residence time of at least 1.34 seconds are significantly lower than the emissions measured under operating conditions with 870°C (1600°F) secondary chamber temperatures and shorter residence times.

4.2.2.2.2. Primary chamber combustion control parameters.

In the primary chamber of most MWI's, waste is combusted under substoichiometric air conditions. The purpose of maintaining a substoichiometric air condition in the primary chamber is to maintain control of the waste combustion rate. The objective is to completely combust the waste in the primary chamber at a rate that does not generate more combustible gases than the secondary/tertiary combustion chambers can efficiently and completely combust. The rate at which combustion proceeds in the primary chamber can be controlled in several ways. These primary chamber combustion control methods were described in Section 2 and include: (1) proper waste charging procedures; (2) control of combustion airflow to the primary chamber; and (3) use of a water spray. Proper waste charging procedures are operational practices that include charging waste in charges of similar weight at regular intervals. The other two methods incorporate MWI combustion control system designs that use primary chamber temperature as an indicator of the rate of combustion in the primary chamber. In these designs, when primary chamber temperature exceeds a specified setpoint temperature, a control loop is triggered that either decreases the combustion airflow into the primary chamber or activates a water spray system to help reduce temperatures below the setpoint.

All MWI's control combustion in the primary chamber through proper waste charging procedures. The combustion air rate and distribution to the primary and secondary combustion chambers also are controlled to some degree for all MWI's; however, sophistication of the design of the air control system varies and the level and degree of air control achieved varies widely. Some MWI systems have combustion control designs that allow the combustion air rate and distribution to be varied very little, if at all, from predetermined settings during the combustion process. As a result, these MWI's must rely solely on proper charging procedures to maintain operation of the unit within the limits of the preset conditions to achieve proper combustion.

Combustion control at Facility A is achieved through use of a combination of techniques. First, the primary air combustion rate is set at a level which will maintain the primary chamber at a substoichiometric condition when the unit is charged at or near the design rate. Second, a water spray system is provided in the primary chamber to help quench the primary chamber combustion if the temperature begins to exceed the desired level; the water spray system is activated at a setpoint temperature of 730°C (1350°F). Third, the waste charge amount and frequency is carefully monitored and controlled. Secondary combustion air is provided via a separate system which is independently controlled; the secondary combustion air is fully modulated.

At Facilities K and W, a single combustion air blower provides the air for the primary and secondary combustion chambers. Combustion control is accomplished through the use of a modulating damper that controls the distribution of the combustion air to the primary and secondary chambers. The control system at Facility W is fully modulated whereas at Facility K, the modulating damper does not move very much about a preset position.

One of the objectives of this test program was to determine the impact on emissions of alternative waste charging practices. At Facilities K and W, (MWI's with the same capacities but different secondary chamber residence times), the following waste

charging practices were employed: test condition 1 comprised undercharging waste, i.e., charging at a rate (200 lb/hr) less than design capacity at 6-minute intervals; test condition 2 comprised charging waste at the MWI capacity charge rate (300 lb/hr) at 6-minute intervals; and test condition 3 was comprised of charging waste at the MWI capacity charge rate (300 lb/hr) at 10-minute intervals (larger, less-frequent charges).

Table 4 presents the average emission rates of PM, CO, and CDD/CDF for the test conditions conducted at Facilities K and W. It is clear that at Facility K, emissions of PM, CO, and CDD/CDF increase from test condition 1 to test condition 2 to test condition 3. The differences in emissions between test conditions 1 and 2 are relatively small. The differences in emissions between test conditions 2 and 3 are dramatic with a four-fold increase in PM emissions, an order of magnitude increase in CO emissions, and a five-fold increase in CDD/CDF emissions. Note also, that the average primary chamber temperature for test conditions 2 and 3 conducted at the design capacity charge conditions (1820°F and 1835°F, respectively) also were significantly higher than for test condition 1 (1620°F). These data indicate that at Facility K, infrequent waste charging (large charges every 10 minutes as opposed to smaller charges every 6 minutes) coupled with poor combustion control in the primary chamber (as indicated by higher primary chamber temperatures), and a lower secondary chamber temperature, results in a significant increase in emissions.

The data obtained at Facility W also show an increase in emissions of PM, CO, and CDD/CDF from test condition 1 to test condition 2. The average primary chamber temperature for test condition 2 was also higher than for test condition 1. However, when the size and frequency of the charges were changed (larger, less frequent charges--test condition 3) no increase in emissions was noted. For test condition 3, the primary chamber temperature was actually lower than for condition 2, indicating that

TABLE 4. AVERAGE POST-COMBUSTION EMISSIONS OF PM, CO, AND CDD/CDF FOR DIFFERENT WASTE CHARGING PROCEDURES AT FACILITIES K AND W

Test condition	Charging procedure		Average primary chamber temp., °F	Average secondary chamber temp., °F	PM, gr/dscf	CO, ppmv	CDD/CDF, ng/dscm
	Rate, lb/hr	Frequency, minutes					
K1	200	6	1620	1680	0.1359 ^a	75.6	5,570 ^a
K2	300	6	1820	1790	0.1488	110	7,260
K3	300	10	1830	1660	0.4521	1,400	35,500
W1	200	6	1690	1890	0.0830	97.0	2,400
W2	300	6	1810	2030	0.1900	435	5,950
W3	300	10	1660	1660	0.1967	359	5,030

^a Average of two test runs; all other data presented are average of three test runs.

Facility W incorporates more effective primary chamber combustion controls than Facility K.

At Facility A, the primary combustion chamber temperature was controlled and maintained at a temperature of less than 730°C (1350°F) for all runs, indicating good combustion control in the primary chamber. Proper waste charging procedures were followed for all test conditions. Charge rates were adjusted based on the target secondary/tertiary chamber temperature (i.e., lower charge rates were used for the 870°C [1600°F] secondary chamber test condition than for the 980°C [1800°F] test condition). The emission results obtained during the test at Facility A indicate that proper waste charging procedures coupled with good control of primary chamber temperatures, a longer residence time (than Facilities K and W), and good control of secondary/tertiary chamber temperature produce the lowest emissions of PM, CO, and CDD/CDF between Facilities A, W, and K.

4.2.3 Emissions During Burndown and Cooldown Phases

Manual emission test data were collected at the seven facilities during only the normal combustion component of the operating cycle. However, CEM data were collected during the burndown/cooldown phase at Facility A and during the cooldown phase at Facility J. Figures 30 and 31 show example plots of CO and THC concentrations for one 24-hour period at Facilities A and J, respectively. Corresponding plots of the primary and secondary chamber temperature profiles over the same 24-hour periods are shown in Figures 32 and 33. The data from the other test runs are comparable to those shown in the example plots.

These 24-hour CEM data indicate that at the two facilities tested, CO and THC emissions during the cooldown period are substantially higher than those during "normal" operations. Also, given the very high levels of CO emissions measured (always over 1,000 ppmv and sometimes as high as 50,000 ppmv) and the strong relationship between CO emissions and CDD/CDF found at these high CO levels, CDD/CDF emissions during cooldown could be substantial.

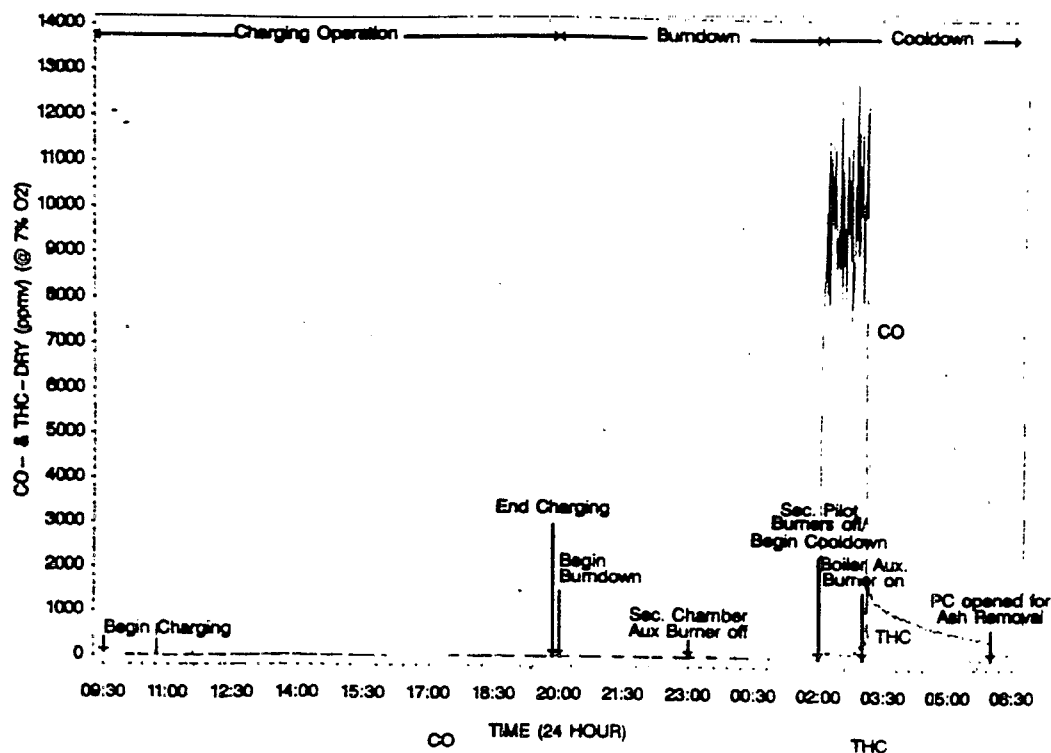


Figure 30. 24-hour real time CO and THC concentrations--Facility A, test condition 2, run number 2.

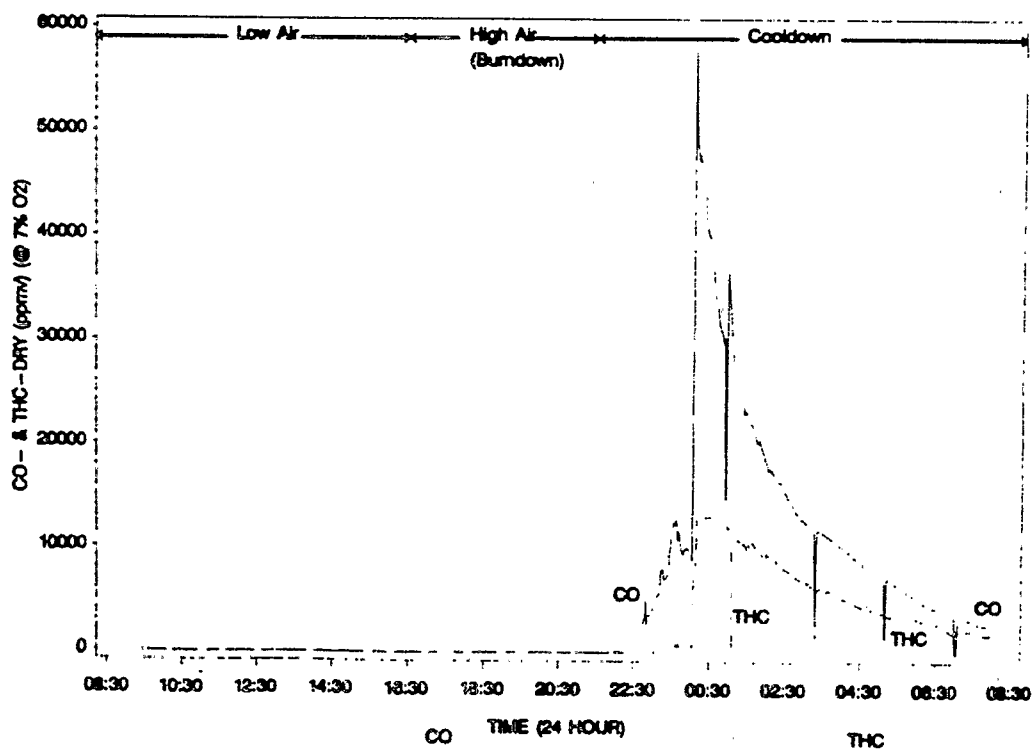


Figure 31. 24-hour real time CO and THC concentrations--Facility J, run numbers 5 and 6.

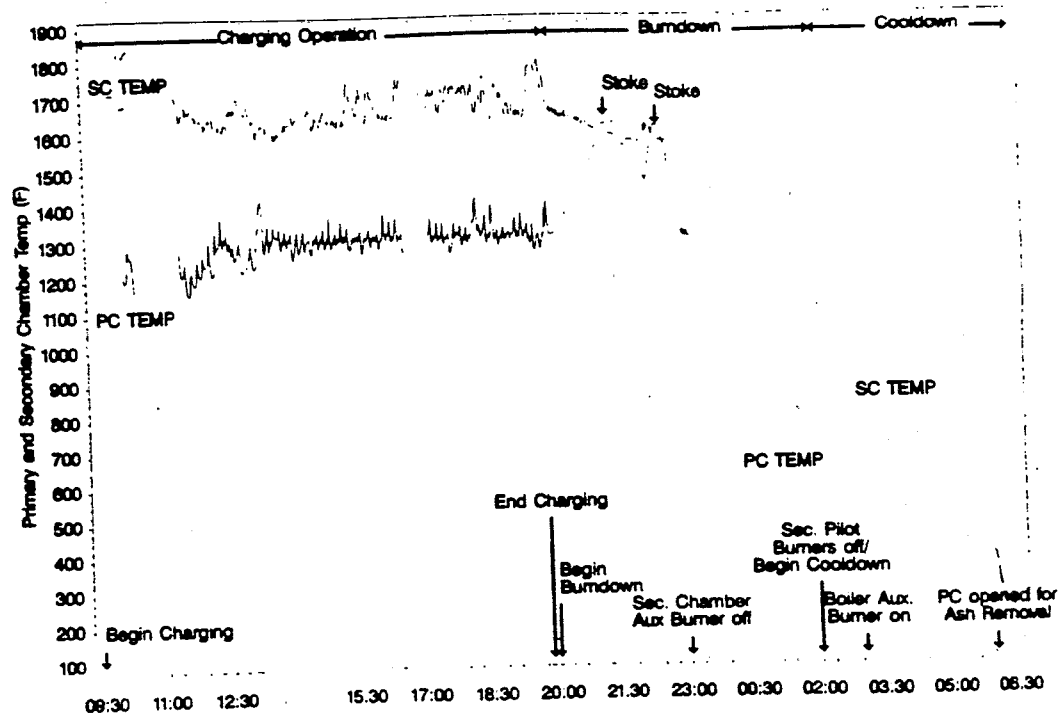


Figure 32. 24-hour temperature plot--Facility A, test condition 2, run number 2.

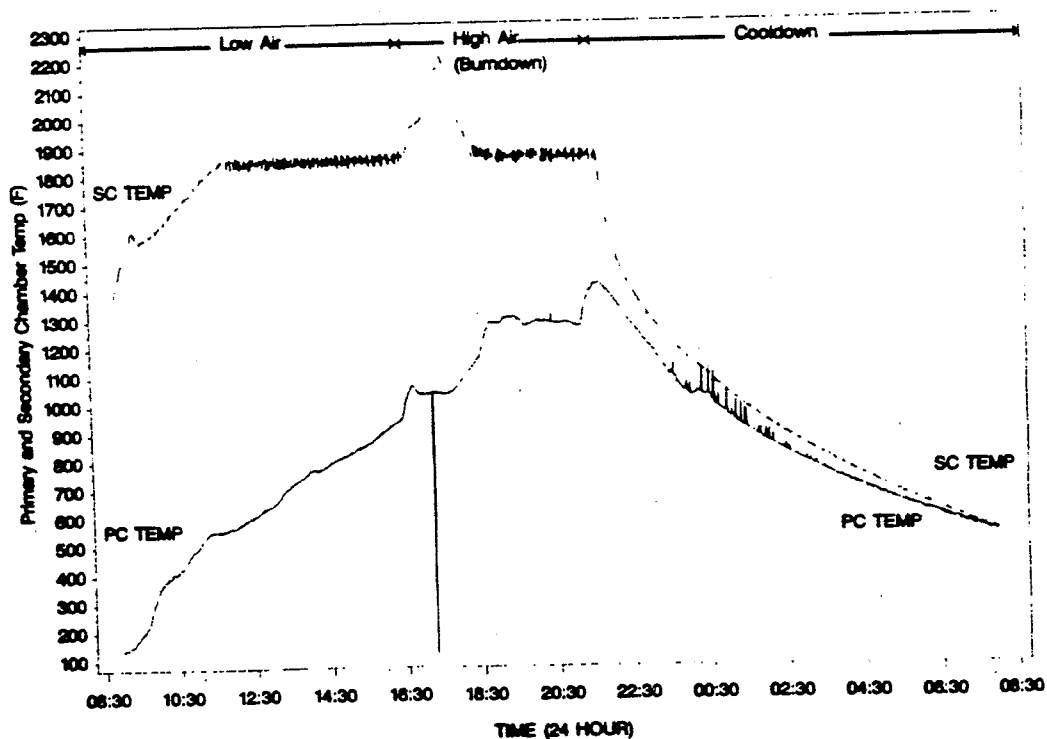


Figure 33. 24-hour temperature plot--Facility J, run numbers 5 and 6.

Further examination of the CEM data for the cooldown period provides insight into potential control options. Figures 34 and 35 provide an expanded view of the cooldown period for the data presented earlier. These figures overlay the CO concentration curve and the temperature plots. Note that at both facilities, primary chamber temperatures remain elevated for some period after the cooldown period starts. (In fact, for some runs not shown at Facility J, the primary chamber temperature actually increased during cooldown). These elevated temperatures indicate that waste burnout at these facilities has not been completed before the start of the cooldown period. Consequently, unburned organic material may still be released to the secondary chamber. However, during the cooldown period the auxiliary fuel combustion in the secondary chamber is substantially reduced or completely shutdown, thereby accounting for the reductions in secondary chamber temperature shown in the graphs. This secondary chamber temperature decrease is accompanied by increases in CO concentrations.

The available CEM data suggest that primary chamber temperatures may be indicative of complete burndown. Generally, CO concentrations appear to remain at high levels until primary chamber temperatures fall to the 120° to 150°C (250° to 350°F) range. These data suggest, therefore, that the significant emissions during the cooldown period may be controlled by maintaining the secondary chamber temperature at normal operating levels until burndown is complete, as indicated by primary chamber temperature.

4.2.4 Operating Cycle of a Batch MWI

Batch MWI's operate on a different cycle than intermittent and continuous MWI's. In batch MWI's, all of the waste to be burned during a complete batch cycle is loaded into the primary chamber prior to operation with no additional waste charging during operation. The batch operating cycle normally takes 1 to 2 days depending on the size of the MWI and the amount of waste charged. In intermittent and continuous MWI's, waste is charged

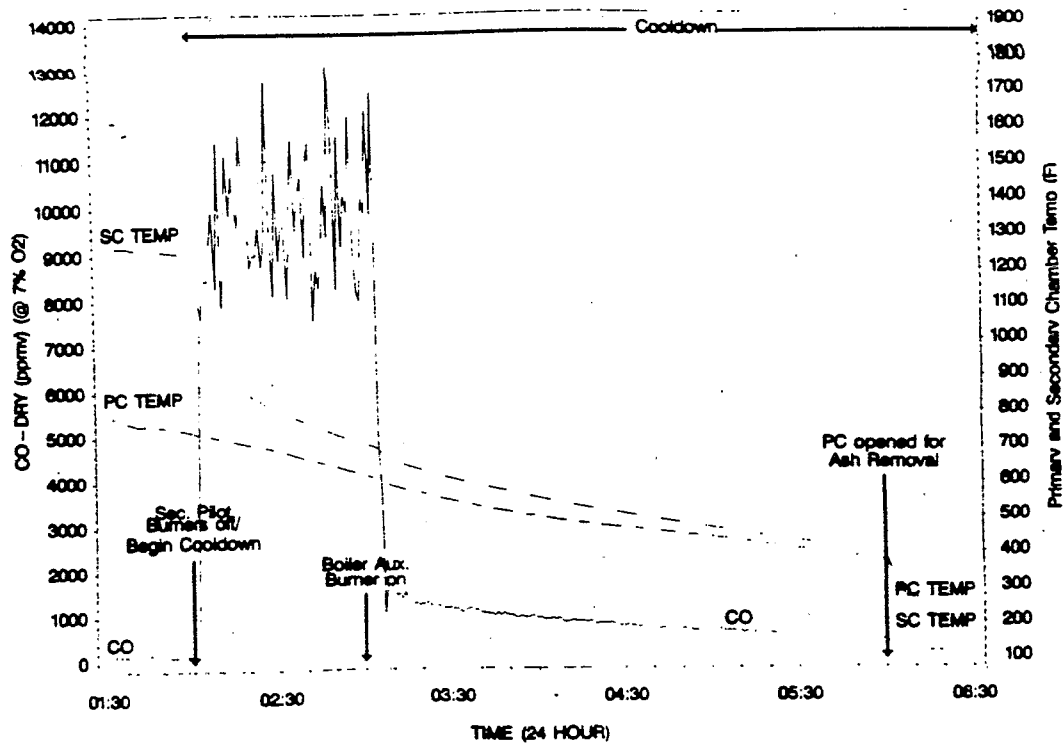


Figure 34. Cooldown period--Facility A, test condition 2, run number 2.

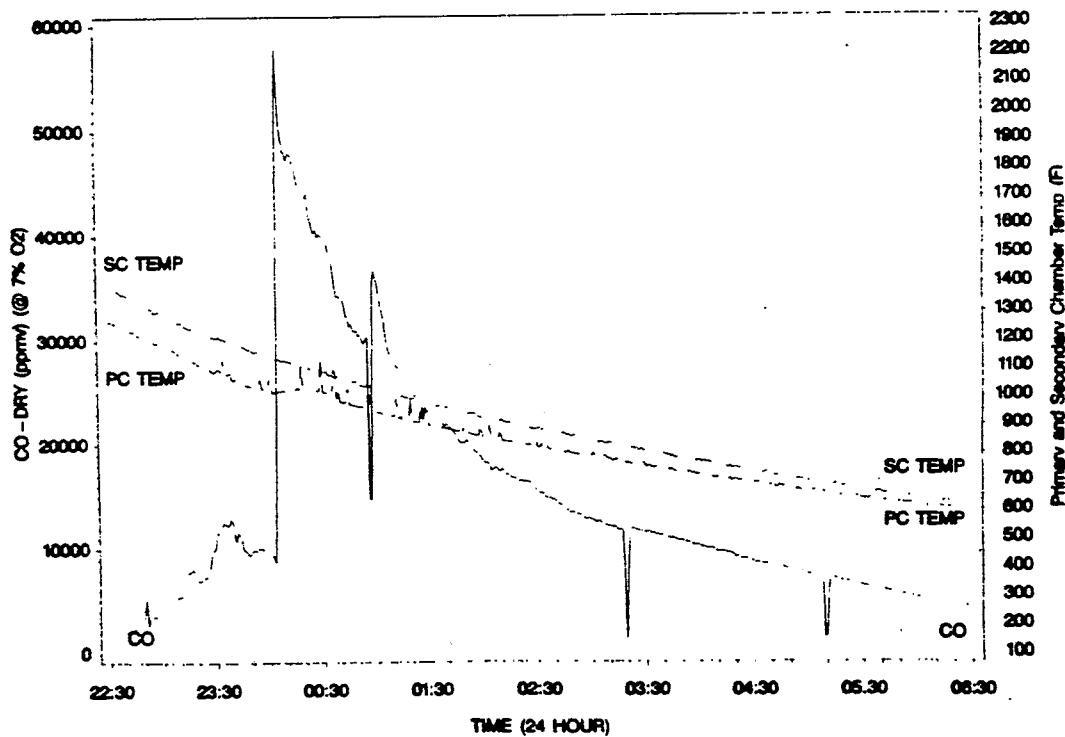


Figure 35. Cooldown period--Facility J, run numbers 5 and 6.

in small charges on a regular basis throughout much of the operating cycle.

In addition to the waste charging differences, the burn cycle of a batch MWI proceeds differently than that of a continuous or intermittent MWI. The burn cycle of a batch MWI comprises three distinct phases--a low-air phase, a high-air phase, and a cooldown phase. During the low-air phase, combustion of the waste proceeds very slowly and primary chamber temperature increases gradually over several hours. Combustion proceeds more rapidly during the high-air phase and the primary chamber reaches and maintains maximum operating temperatures. Continuous and intermittent MWI's do not incorporate a low-air phase and, therefore, reach maximum operating temperatures in only a fraction of the time required for a batch unit.

Table 5 presents the average post-combustion emission concentrations for test conditions conducted at the batch MWI at Facility J during the low-air phase (test condition 1) and the high-air phase (test condition 2). Additionally, Table 5 presents post-combustion emission concentrations for the test conditions indicated for Facilities A, B, M, and W where the target secondary/tertiary chamber temperatures were the same or similar to the tests conducted at Facility J. In comparing the emission concentrations for the low-air phase at Facility J with the emission concentrations at the other facilities, the post-combustion emission levels for all pollutants except Hg are significantly lower for the batch MWI than for the intermittent and continuous MWI's. The emission concentrations for the high-air phase at Facility J, however, are comparable to the concentrations from the other facilities. These comparisons suggest that during the high-air phase of operation, batch MWI's achieve a somewhat steady-state operating level that is equivalent to the steady-state levels of continuous and intermittent units.

TABLE 5. COMPARISON OF POST-COMBUSTION EMISSIONS FROM BATCH AND
CONTINUOUS/INTERMITTENT MWI's^a

Facility	Test condition	PM, gr/dscf	CO, ppmdv	HCl, ppmdv	CDD/CDF, ng/dscm	Pb, µg/dscm	Cd, µg/dscm	Hg, µg/dscm
J	1 ^b	0.0039	5.7	112	33	805	29.7	1,260
J	2 ^c	0.0267	14.5	284	1,210	5,540	207	3,390
A	1	0.0983	16.5	1,770	489	3,300	335	11,900
A	1A	0.0771	13.3	1,670	237	1,500	402	6,880
B	1	0.1003	26.0	1,160 ^d	1,450	3,320	385	366
M	1	0.493	14.5	724	192	3,590	471	2,590
W	2	0.1900	435	1,320	5,950	6,250	385	510

^aAll concentrations corrected to 7 percent O₂.

^bTest condition 1 at Facility J is the low-air phase.

^cTest condition 2 at Facility J is the high-air phase.

^dBased on HCl CEM data.

4.2.5 Metals Partitioning

In general, combustion control measures are not used to limit metals emissions from MWI's. However, some combustion parameters, particularly primary chamber temperature and combustion air controls in the primary chamber, can affect the partitioning of metals among the different incinerator exhaust streams. The data from the EPA test program were examined to determine whether the relative fractions of Cd, Pb, and Hg that were partitioned to the bottom ash and exhaust gas varied substantially across test runs, and if so, whether the differences could be related to process operating conditions.

Data from the emission tests were sufficient to estimate relative fractions of metals distributed to the bottom ash and stack gas for a total of 15 test conditions at 4 facilities. Table 6 summarizes the average fraction of Pb, Cd, and Hg partitioned to each of the two streams by facility and test condition. Note that for Facility A, the ash samples collected for each run were composited across the different runs by test condition prior to metals analysis. Consequently, only one sample was obtained per test condition and this one sample was compared to average stack gas emissions over the runs that constituted the test conditions. For other facilities, the values in Table 6 are based on distinct ash and stack gas samples for each of three runs per test condition.

With the exception of the data from Facility S, the partitioning data are relatively consistent and follow expected patterns. Generally, almost no Hg remains in the bottom ash, with the percentage ranging from less than 1 percent at Facilities A and W to about 6 percent at Facility K. Cadmium partitions primarily to the stack gas with the percentage in the bottom ash ranging from about 14 percent at Facility W to about 37 percent at Facility A. Finally, Pb partitions approximately equally in the bottom ash and stack gas with the percentage in the bottom ash ranging from 44 percent at Facility K to 59 percent at Facility A. Among these three facilities, the

TABLE 6. SUMMARY OF BOTTOM ASH AND STACK GAS METALS DISTRIBUTION

Facility	Test condition	Cadmium		Lead		Mercury	
		B-Ash fraction, mean	Stack fraction, mean	B-Ash fraction, mean	Stack fraction, mean	B-Ash fraction, mean	Stack fraction, mean
A	1	0.245	0.755	0.559	0.441	0.000	1.000
	3	0.140	0.860	0.489	0.511	0.000	1.000
	4	0.258	0.742	0.671	0.329	0.003	0.997
	5	0.297	0.703	0.584	0.416	0.000	1.000
	6	0.235	0.765	0.541	0.459	0.000	1.000
	7	0.389	0.611	0.700	0.300	0.001	0.999
K	1	0.366	0.634	0.331	0.669	0.065	0.935
	2	0.378	0.622	0.430	0.570	0.063	0.937
	3	0.355	0.645	0.523	0.477	0.063	0.937
M	1	0.150	0.850	0.301	0.699	a	a
	2	0.104	0.896	0.324	0.676	a	a
S	1	0.793	0.207	a	a	a	a
	2	a	a	a	a	a	a
	3	0.722	0.278	0.937	0.063	0.663	0.337
W	1	0.163	0.837	0.416	0.584	0.003	0.997
	2	0.156	0.844	0.898	0.102	0.024	0.976
	3	0.109	0.891	0.431	0.569	0.000	1.000

^aAll B-ash values at detection limit. Fraction could not be determined.

B-ash: Bottom ash

Stack: Incinerator exhaust gas

distribution showed some variation, but the variation could not be related to waste type or primary chamber temperature.

The distribution at Facility S differed substantially from those at the other facilities with significantly greater fractions of metals remaining in the bottom ash. The percentages of metals in the bottom ash were Cd--75 percent and Pb--90 percent. The results appeared to be consistent across waste types. In general, primary chamber operating data appeared to be reasonably consistent across facilities, and no explanation was found for the difference between Facility S and the other facilities. However, the data from Facility S should be interpreted cautiously in that ash levels were near detection limits.

4.2.6 APCS Performance

The emission test program generated performance data for four APCS's--a DI/FF system at Facility A, a VS/PB system at Facility B, a FF/PB system at Facility J, and a SD/FF system at Facility M. At Facilities B and J, performance data were collected for only a single test condition at each facility; consequently parametric analyses of APCS performance at these facilities were not feasible. However, data were collected for a range of operating conditions at Facility A, making detailed analysis of the DI/FF system performance possible.

The performance of these four APCS's is described in three subsections below. The first briefly summarizes the performance of VS/PB system and FF/PB system found at Facilities B and J, respectively. The second presents the results of the evaluation of the effect of system operating parameters on the DI/FF performance at Facility A including the effect of activated carbon injection. The third subsection describes the performance of the SD/FF system at Facility M and the effect of activated carbon injection on system performance.

4.2.6.1 Performance of the VS/PB and FF/PB Systems.

Pollutant specific removal efficiencies for PM, HCl, CDD/CDF, and three metals (Cd, Pb, and Hg) are shown for each run at Facilities B and J in Table 7. Note that for Facility J, the test runs represent different components of the operating cycle. Those test runs designated by BR are from the low-air component of the cycle, while those designated as BD are from the high-air component of the cycle.

The data from Facility B indicate that the VS/PB system performs very well with respect to HCl emissions with a consistent removal efficiency of 99.8 percent or greater and reasonably well with respect to CDD/CDF (approximately 70 percent removal). Given the moderately high VS pressure drop (30 in. water gauge), the PM removal efficiency was quite low, about 60 percent on the average. The particle size data collected at the inlet to the VS/PB suggest that the particles at this facility are relatively fine (about 60 percent of PM in the

TABLE 7. PERFORMANCE OF THE VS/PB AND FF/PB AIR POLLUTION CONTROL SYSTEMS

Facility	APCD	Test	Removal efficiency, percent					
			PM	HCl	CDD/CDF	Cd	Pb	Hg
B	VS/PB	MM1-1	48.3	100	66.3	34.9	40.6	62.5
		MM1-3	21.2	100	69.4	34.2	44.7	a
		MM1-4	72.4	99.8	77.8	54.9	50.1	44.0
J	FF/PB	J1-BR	>94.2	92.4	b	93.6	99.3	65.3
		J2-BD	97.6	82.7	b	98.9	99.3	59.7
		J3-BR	73.7	90.4	b	92.0	98.2	81.9
		J4-BD	94.4	69.1	b	98.9	99.4	79.7
		J5-BR	56.8	89.1	b	92.4	98.9	87.6
		J6-BD	95.0	97.1	64.1	98.1	99.0	69.5

^aOutlet Hg emissions measurements were higher than inlet Hg emissions measurements.

^bOutlet emissions were higher than inlet emissions measurements by factors of 5 to 2,500.

submicron range), which may in part explain the low efficiencies. Due in part to a low average inlet loading of 0.1 gr/dscf at 7 percent O₂, Facility B did achieve moderately low outlet PM concentrations with the outlet concentration averaging 0.046 gr/dscf at 7 percent O₂. The VS/PB system provided some removal of Cd (41 percent) and Pb (42 percent), but the performance relative to Hg varied widely (no control up to 62.3 percent removal) suggesting that on the average, little Hg control is achieved by the system.

The FF/PB at Facility J generally performed quite well with respect to PM and metals emissions. The PM removal efficiencies were generally 94 percent or higher with the exception of two low-air component (74 and 57 percent) runs that had low inlet PM loadings (0.004 gr/dscf for both runs). For all six runs, the outlet PM loadings were less than 0.004 gr/dscf at 7 percent O₂ with an average outlet loading for the six runs of 0.0018 gr/dscf at 7 percent O₂. When metals inlet concentrations were at "typical" levels such as those achieved during the high-air component of the cycle, Cd removal efficiencies exceeded 98 percent while Pb removal efficiencies exceeded 99 percent. For Hg, which showed no real variation between the two operating cycle components, the overall removal efficiency was about

73 percent with no apparent relationship between removal efficiency and inlet loading. The HCl removal efficiencies at Facility J ranged from 69 to 97 percent with an average of 87 percent. The variation in efficiency had no apparent relationship to inlet HCl concentrations, and no apparent process differences were found to account for the one extremely low efficiency (69 percent on Test J4) or the generally poor performance of the system. Subsequent to the test program, a representative of the engineering firm that designed the facility visited the facility to examine the APCS. He found that approximately 2 months after the test, six of the eight scrubber spray nozzles were plugged with material commonly encountered during start-up.⁹² Although there had been a 2-month interval since the test, the nature of the plugging material convinced the engineering firm representative that it had probably been there during the test and prevented adequate scrubbing liquor from entering the scrubber and may have contributed to the low HCl removal efficiencies.⁹²

For all but one test run at Facility J, the levels of CDD/CDF were substantially higher at the APCD outlet than at the heat exchanger inlet. An understanding of the system configuration at Facility J helps in interpreting these results. The exhaust from the incinerator first passes through an indirect air-to-air heat exchanger into the fabric filter before passing through the packed bed scrubber and out the stack. The post-combustion sample location was upstream of the heat exchanger and the post-APCS sample location was downstream from the packed bed. The temperature drops from over 590°C (1100°F) at the inlet of the heat exchanger to 85°C (185°F) at the outlet of the packed bed scrubber. Although the exact amount of time required to accomplish the drop in temperature is unknown, this range spans temperatures over which de novo synthesis of CDD/CDF is known to occur. Consequently, CDD/CDF formation potentially occurred in the heat exchanger, and/or fabric filter, and is not unexpected. These data indicate that the CDD/CDF that is formed in the system is not retained in the fabric filter or packed bed scrubber.

4.2.6.2 Performance of the DI/FF Control System. As outlined in Section 4.1.1.1, two test sequences were performed on the DI/FF system at Facility A. During 1990, tests were conducted under 7 different operating conditions. Generally, these different conditions were related to the incinerator operation and were not expected to affect the APCS performance. However, lime rates were varied during those tests and factors such as baghouse inlet temperatures and inlet gas moisture content, which could affect the DI/FF performance, were monitored during all tests. Subsequently, during 1991, additional tests were conducted under three test conditions to assess the effects of carbon injection on APCS performance. The paragraphs below describe the performance of the DI/FF relative to PM, HCl, CDD/CDF, and metals emissions and summarize the results of the evaluation of the effects of operating parameters on performance.

The data on PM concentrations at the outlet of the DI/FF system at Facility A that were presented in Table B-3 indicate that the system typically achieves outlet PM levels corrected to 7 percent O₂ of 0.004 gr/dscf or less. The four exceptions to these low readings were test condition 1, run 1 (0.068 gr/dscf), test condition 5, run 2 (0.056 gr/dscf), test condition 5, run 3 (0.088 gr/dscf), and test condition 7, run 1 (0.020 gr/dscf), all of which were obtained during the first series of tests. Such large variations in outlet concentrations are unusual for fabric filter systems, and examination of plant operating data showed no readily apparent differences in operating conditions during the runs with high PM loadings. Also, the data showed no deterioration in metals performance during those runs. Between the 1990 and 1991 test series, all of the filter bags and the entire outlet plenum were replaced. During the 1991 test series, PM concentrations were consistently low with all runs measuring 0.004 gr/dscf or less @ 7 percent O₂. The inconsistent results obtained during the first test series indicate that the fabric filter system might have been in need of repair at that time. Consequently, the high PM levels found during a few runs at the

first series of tests are not considered representative of FF performance.

Two measures of HCl performance were considered for Facility A, mass emission rate-based removal efficiency and concentration-based removal. Because the two measures were highly correlated ($r = 0.99$) and concentration-based measures were available for more test runs than were mass emission rate-based measures, concentration-based efficiencies were used in the analyses. Table 8 presents average removal efficiencies and inlet and outlet concentrations for each of the nine test conditions. The average removal efficiencies range from 93.2 percent for Condition 5 to 98.6 percent for Condition 8. The average for Condition 5 was strongly influenced by a low efficiency of 88 percent on one of the three runs. This efficiency was substantially below the next lowest value of 92 percent.

TABLE 8. FACILITY A HCl PERFORMANCE SUMMARY

Test condition	Inlet HCl (ppmdv) (@ 7% O ₂), mean	Outlet HCl (ppmdv) (@ 7% O ₂), mean	Efficiency concentration- based, mean
1	1,770	47.9	97.5
2	1,370	40.5	97.1
3	1,740	82.4	95.3
4	1,050	18.7	98.3
5	1,600	108	93.2
6	1,770	72.8	95.4
7	2,450	67.2	97.0
1A	1,670	69.5	96.0
8	2,230	34.4	98.6
9	1,940	40.8	97.9

The HCl performance data were examined further graphically and with a combination of correlation and regression analyses to

assess the affects of carbon injection, stoichiometric ratio, gas temperature, and gas moisture on HCl performance. No relationship was found between performance and either gas moisture or gas temperature. However, HCl performance of this system appears to be related strongly to stoichiometric ratio and may be related to carbon injection, although the evidence related to carbon injection is much weaker than that related to stoichiometric ratio. These relationships are depicted graphically in Figure 36, which shows a plot of HCl removal efficiency as a function of stoichiometric ratio with the carbon injection runs circled. The HCl efficiency has a strong nonlinear relationship to stoichiometric ratio. For all runs having a stoichiometric ratio of 6 or more, efficiencies of at least 97 percent are achieved, while efficiencies for runs with stoichiometric ratios of less than 6 range between 88 and 99 percent. Note that in the lower regime, the carbon runs showed much higher efficiencies on average than did the noncarbon runs. However, because performance did not appear to improve with increased carbon usage, the effect of carbon usage on HCl performance is considered to be inconclusive.

Metals emissions data were obtained for only seven of the nine test conditions at Facility A. Table 9 summarizes the removal efficiencies achieved by the DI/FF system for Cd, Pb, and Hg for these seven conditions. The removal efficiencies for Cd and Pb were 99 percent or greater irrespective of process conditions. However, the Hg removal efficiencies were obviously affected by carbon addition. During the six conditions that involved no carbon injection (Nos. 1, 3, 5, 6, 7, and 1A), essentially no Hg removal was achieved. At a carbon injection rate of 0.45 kg/hr (1 lb/hr) (Test Condition 8), the average removal efficiency was 86 percent, and at a carbon injection rate of 1.13 kg/hr (2.5 lb/hr) (Test Condition 9), an average Hg removal efficiency of about 95 percent was achieved. Taken together, these data indicate that the DI/FF system can consistently achieve Cd and Pb removal efficiencies of

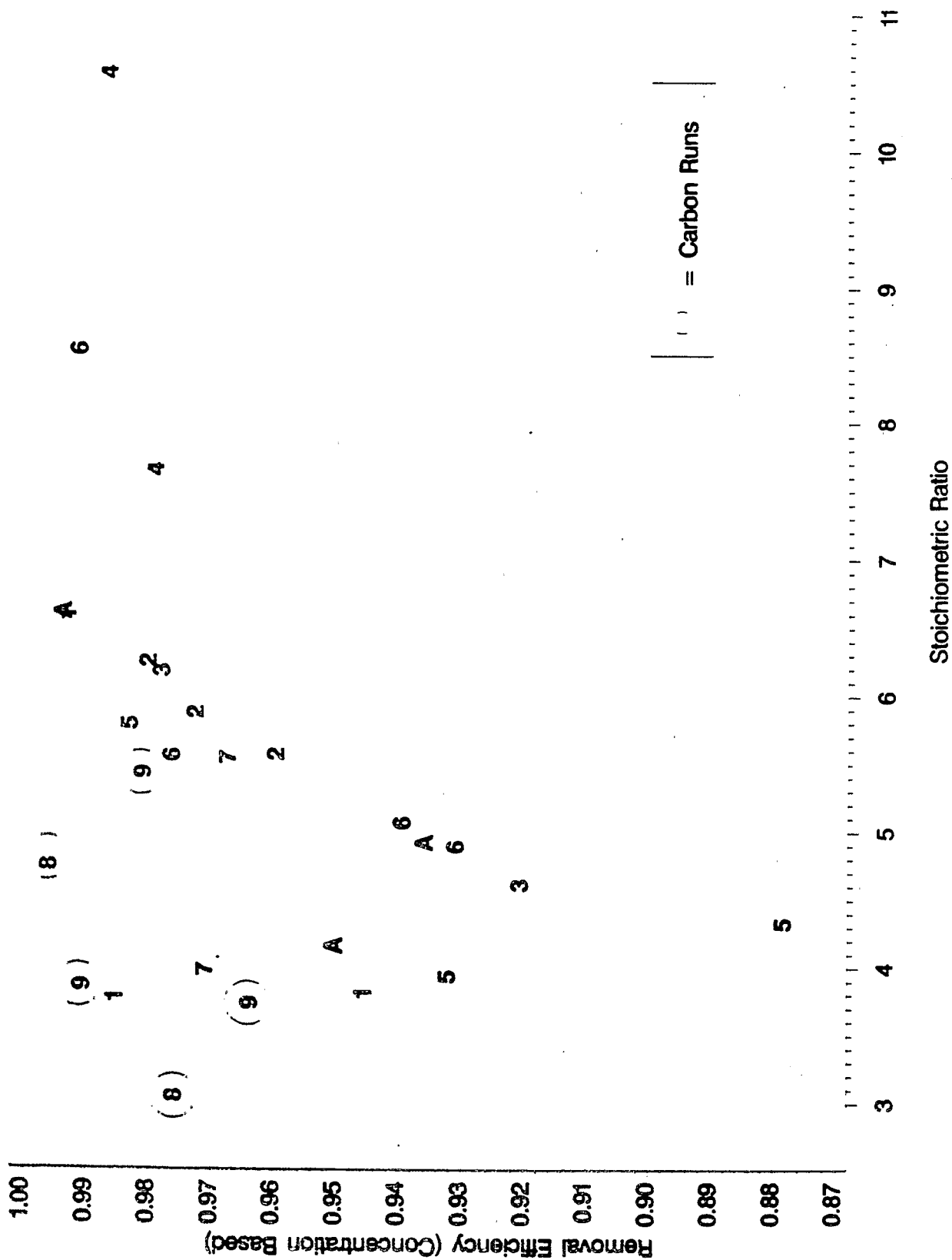


Figure 36. Plot of HCl removal efficiency versus stoichiometric ratio for Facility A.

99 percent, and with carbon injection, the system can achieve Hg removal efficiencies in excess of 85 percent.

TABLE 9. SUMMARY OF METAL EFFICIENCIES BY TEST CONDITIONS AT FACILITY A

Test condition	Cd removal efficiency, %	Pb removal efficiency, %	Hg removal efficiency, %
1	99.5	99.5	9.0
3	99.5	99.3	42.7
5	98.8	99.7	a
6	99.4	99.6	10.7
7	99.1	99.4	a
1A	99.6	99.7	a
8 ^b	99.6	99.7	86.3
9 ^c	98.8	99.5	94.7

^aMeasured outlet Hg concentrations were higher than measured inlet Hg concentrations.

^bActivated carbon at 1.0 lb/hr.

^cActivated carbon at 2.5 lb/hr.

The run-specific CDD/CDF inlet and outlet concentrations for Facility A are presented in Appendix B. Analysis of these data suggest that in the absence of carbon injection, the DI/FF system at Facility A achieves essentially no reduction in CDD/CDF. The CDD/CDF mass flux data averaged across test conditions, which are presented in Table 10, provide further insight into the performance of the system relative to CDD/CDF emissions.

Table 10 contains average CDD/CDF mass flux rates by conditions in units of μg total CDD/CDF per hour for three different DI/FF streams--the postcombustion gas stream to the DI unit, the stack gas stream exhausted from the FF (post-APCS), and the FF catch discharge. Table 10 also presents the ratio of CDD/CDF stack gas mass flux to the postcombustion CDD/CDF mass flux and the ratio of the total APCS CDD/CDF discharge rate (stack gas plus FF catch) to postcombustion CDD/CDF mass flux.

For the test conditions involving no carbon injection (Conditions 1, 2, 3, 6, 7, and 1A), the post-APCS to postcombustion ratio ranges from 0.47 to 1.24 with an average of

TABLE 10. SUMMARY OF CDD/CDF PERFORMANCE DATA FOR THE DI/FF AT FACILITY A

CDD/CDF mass flux, $\mu\text{g/hr}$				Post-APCS to postcombustion ratio	Total APCS discharge to postcombustion ratio ^a
Test condition	Post-combustion	Post-APCS	FF catch		
1 ^b	759	943	285	1.24	1.62
2	615	514	467	0.84	1.60
3	623	520	892	0.83	2.27
6	745	353	625	0.47	1.31
7	786	884	502	1.12	1.76
1A ^c	325	201	245	0.62	1.37
8 ^{c,d}	591	23.8	540	0.040	0.95
9 ^{c,e}	576	10.2	1,140	0.018	2.00

^aSum of the CDD/CDF measured in the post-APCS and FF catch streams.

^bData from 1990 test series.

^cData from 1991 test series.

^dActivated carbon at 1.0 lb/hr.

^eActivated carbon at 2.5 lb/hr.

0.85. These ratios are consistent with essentially zero CDD/CDF control in the absence of carbon injection. However, when carbon was injected at a rate of 1 lb/hr, the ratio fell to 0.04 which is equivalent to a 96 percent reduction in CDD/CDF emissions. When the carbon injection rate was increased to 2.5 lb/hr, the ratio fell to 0.018, which represents a 98.2 percent CDD/CDF removal efficiency. On balance, these data suggest that a DI/FF system with carbon injection can achieve average CDD/CDF removal efficiencies of 95 percent or greater.

While the data in Table 10 indicate that DI/FF systems with carbon injection can reduce stack emissions of CDD/CDF, they also indicate that CDD/CDF formation occurs within the DI/FF system. With the exception of the 1 lb/hr carbon injection conditions, which comprised only two runs with variable results, the ratio of total CDD/CDF discharged to postcombustion CDD/CDF range from 1.3 to 2.3. These ratios suggest that at this facility with

incinerator APCS inlet levels in the range of 300 to 500 ng/dscm at 7 percent O_2 the amount of CDD/CDF formed in the system can be 50 to 100 percent of that entering with the combustion gas. To date, no relationship between this formation rate and DI/FF operating conditions has been found.

4.2.6.3 Performance of the SD/FF Control System. The SD/FF system at Facility M was tested under two sets of operating conditions. During Condition 1, normal facility operating conditions for both the incinerator and APCS were used. The same operating levels were used during Condition 2, except that activated carbon was added to the lime slurry to produce a carbon rate of about 1.1 kg/hr (2.5 lb/hr). In general, most process parameters were maintained at nearly constant levels for all runs except stoichiometric ratio. Because the lime feed rate was nearly constant, the stoichiometric ratio fluctuated somewhat with inlet HCl loadings. The only major operating difference occurred during Run 1. For that run the lime concentration in the slurry was maintained at 6 percent by weight in contrast to 9 percent by weight for the other five tests. Consequently, the lime feed rate and stoichiometric ratio were lower for Run 1 than for the other five runs. Because all other parameters varied so little, the only factor that was examined in detail was the effect of carbon addition. The paragraphs below provide a general discussion of the performance of the system with respect to PM, HCl, CDD/CDF, and metals and discuss the effect of carbon addition on CDD/CDF and metals performance.

The SD/FF system yielded outlet PM concentrations that ranged from 0.0006 to 0.0098 gr/dscf at 7 percent O_2 , and with the exception of Run 2, all concentrations were below 0.002 gr/dscf at 7 percent O_2 . Average outlet PM concentrations were 0.0038 for Condition 1 and 0.0011 for Condition 2, and carbon appeared to have no effect on emissions.

Because analytical data were outside allowable quality control limits for two runs, HCl performance data are available for only four test runs. These data are shown in Table 11. Although the data are somewhat limited, they do indicate that

stoichiometric ratio is important to the system's performance. Additionally, the data indicate that if a stoichiometric ratio of two or greater is maintained, HCl control efficiencies of at least 99 percent were achieved by the system.

TABLE 11. HCl PERFORMANCE DATA FOR FACILITY M^a

Run No.	Lime rate, lb/hr	SR	Activated carbon rate, lb/hr	HCl concentration, ppmdv at 7% O ₂		Removal efficiency
				Inlet	Outlet	
3	37	3.39	0	724	4.50	99.3
4	34	1.91	2.8	1,220	26.1	97.8
5	31	2.29	2.5	946	<0.049	>99.99
6	32	2.11	2.5	1,030	<0.045	>99.99

^aHCl analytical data for run number 1 and 2 were outside control limits and are not reported.

The SD/FF performance data for metals and CDD/CDF are summarized in Table 12. These data indicate that for Cd and Pb, the SD/FF is highly efficient (99.7 percent or greater) under both test conditions. These findings were consistent across test runs within each condition. However, for both Hg and CDD/CDF, the system yielded substantially greater reduction with activated carbon addition than without. For Hg, the average removal efficiency without activated carbon was about 30 percent with the efficiencies on individual runs ranging from no control to 50 percent. When activated carbon was added not only was the average removal efficiency higher (90 percent), but system performance also was more consistent with efficiencies for individual runs ranging from 84 to 96 percent. These data show that an overall Hg removal efficiency achieved by a SD/FF system with activated carbon injection is similar to that achieved by a DI/FF system with activated carbon injection.

With no activated carbon added to the system, the average CDD/CDF removal efficiency was 84 percent with a range of 56 to 95 percent. As was the case with Hg, addition of activated carbon both increased average efficiency and provided more consistent performance. The average removal efficiency was about

TABLE 12. SUMMARY OF CDD/CDF AND METALS PERFORMANCE
FOR SD/FF SYSTEM^a

Pollutant	Parameter	Condition 1 (no carbon)	Condition 2 (with carbon)
Cd	postcombustion, $\mu\text{g/dscm}$	471	492
	post-APCS, $\mu\text{g/dscm}$	1.77	0.84
	Removal efficiency, %	99.7	99.8
Pb	postcombustion, $\mu\text{g/dscm}$	3,590	4,410
	post-APCS, $\mu\text{g/dscm}$	5.7	2.5
	Removal efficiency, %	99.9	99.9
Hg	postcombustion, $\mu\text{g/dscm}$	2,590	2,630
	post-APCS, $\mu\text{g/dscm}$	1,980	284
	Removal efficiency, %	29.6	90.0
CDD/CDF	postcombustion, $\mu\text{g/dscm}$	192	199
	post-APCS, $\mu\text{g/dscm}$	32.2	3.30
	Removal efficiency, %	94.0	98.3
CDD/CDF (balance)	postcombustion, $\mu\text{g/hr}$	820	848
	post-APCS, $\mu\text{g/hr}$	131	14.5
	SD catch, $\mu\text{g/hr}$	12.8	5.27
	FF catch, $\mu\text{g/hr}$	589	484
	post-APCS: postcombustion ratio	0.16	0.017
	Total out: Total in ratio	0.89	0.59

98 percent with individual runs having efficiencies in the range of 95 to 99 percent. Two additional observations concerning the CDD/CDF data in Table 12 are worth noting. First, even without activated carbon addition a substantial reduction in CDD/CDF emissions was achieved by the system, a dramatic contrast to the absence of control found with the DI/FF system. Second, unlike the results obtained for the DI/FF system, the mass balance around the control system shows no evidence of CDD/CDF formation across the system. Although no definitive explanation was found for why CDD/CDF formation occurred in the DI/FF system but not in the SD/FF system, the system characteristics that may have the greatest effect are the quick cooling/adsorption obtained with the slurry spray in the SD/FF, the longer gas/lime residence time prior to the FF provided by the SD vessel, and the lower FF temperatures of the SD/FF system (146°C [295°F]) compared to the DI/FF system (163°C [325°F]). In addition, it should be noted

that the MWI preceding the SD/FF system is a rotary kiln design with significantly higher post-combustion levels of PM. This increased level of PM would indicate that significantly more carbon existed in the gas stream entering the SD/FF than in the gas stream entering the DI/FF, which may have aided the performance of the SD/FF. The results from these tests indicate that an overall CDD/CDF removal efficiency of at least 98 percent can be achieved by this SD/FF system with activated carbon injection.

4.3 DEMONSTRATED EMISSION CONTROL LEVELS

The purpose of this section is to present demonstrated emission control levels (i.e., emission limits) associated with each of the emission control techniques discussed earlier. Each of nine pollutants is presented in a separate subsection. Each subsection includes tables showing the emission limits and figures presenting the data used to establish these limits.

The emission limits were developed from actual test data from EPA-sponsored emission tests conducted at seven MWI's. Table 13 presents a summary of information on the type and size of each MWI tested. Other data were also considered (e.g., emission test reports submitted to State agencies), but none of these data were used in establishing emission limits because the test reports were incomplete (i.e., lacked process or design information and/or lacked information on sampling techniques).

In establishing the emission limits for all pollutants, the amount of data available and variation in that data were taken into consideration. Except for HCl controlled by DI/FF systems, the emission limits were set above the highest 3-run average shown by the data. For HCl controlled by DI/FF systems, the emission limit is set above the highest individual runs with SR's above 6:1. For pollutants and/or MWI types where limited test data are available, appropriate data from related pollutants and/or MWI types were considered.

The numerical emission limit only has meaning when coupled with an averaging time. During each of the tests conducted at the seven MWI facilities, emissions were measured over three

TABLE 13. TESTED MWI FACILITIES

Facility	Description
A	650 lb/hr, intermittent, ram-fed; 2-sec residence time in secondary chamber; DI/FF system tested with and without activated carbon injection
B	1,500 lb/hr, continuous, ram-fed; 2-sec residence time in secondary chamber; VS/PB system
J	750 lb/batch, batch, manually fed; 1.75-sec residence time in secondary chamber; FF/PB system
K	300 lb/hr, intermittent, manually fed; 0.33-sec residence time in secondary chamber
M	800 lb/hr, continuous, ram-fed; 2-sec residence time in secondary chamber; SD/FF system tested with and without activated carbon injection
S	250 lb/hr, intermittent, manually fed; 0.2-sec residence time in secondary chamber; conditions 1 and 2 = pathological waste, condition 3 = mixed medical waste
W	300 lb/hr, intermittent, ram-fed; 1-sec residence time in secondary chamber

4-hour periods. Therefore, the emission limits are based on a 12-hour average consisting of three 4-hour test runs.

Continuous, intermittent, batch, and pathological MWI's are four different MWI types (based on their physical design characteristics, operating characteristics, and overall emission profiles). However, for continuous, intermittent, and batch units, there is a period in the combustion cycle when the emission profiles are similar. In continuous and intermittent units, this period occurs during waste-charging. In a batch unit, this period occurs in what is sometimes referred to as the "high-air" or "burndown" phase. In all three MWI types, this period can be distinguished by the temperature in the primary chamber. This is also the period of highest emissions. Consequently, data taken during this period from these three MWI types have been combined in establishing one set of emission limits for continuous, intermittent, and batch MWI's. There is no corresponding period in a pathological unit during which emissions are comparable to the other types of units. Therefore, data from only pathological units have been used to set emission limits for pathological MWI's.

The nine pollutants discussed in this section fall into two categories: those dependent upon the composition of the waste being burned and those dependent upon the MWI combustion process. Waste-related pollutants (HCl, SO₂, Cd, Pb, and Hg) are formed as a result of the presence of components within the waste and are unaffected by combustion controls. Combustion-related pollutants (PM, CO, and CDD/CDF) are emitted at different levels from different MWI's depending on the waste-charging patterns, the temperature maintained in the secondary chamber, and the gas residence time in the secondary chamber. Nitrogen oxides can be considered both waste-related and combustion-related. However, neither the combustion controls nor the add-on controls evaluated in this analysis achieved any NO_x reduction (see Section 4.3.9).

Because combustion conditions do not affect waste-related pollutants, applying only combustion control options result in uncontrolled emission levels of these pollutants. As a result, combustion control limits have not been established for these pollutants.

Establishing emission limits for the combustion-related pollutants was difficult because not all possible combinations of combustion control and MWI type were tested. Of the four MWI types, only intermittent units were tested at each of the three combustion control levels (see Table 14).

TABLE 14. COMBUSTION CONTROL DATA vs. MWI TYPES

	Uncontrolled	1-sec	2-sec
Continuous			B, M
Intermittent	K, S (condition 3)	W	A
Batch			J
Pathological	S (conditions 1 and 2)		

For continuous, intermittent, and batch MWI's, data from facility K (conditions 1 and 2) and facility S (condition 3) represent uncontrolled emission levels; data from facility W (conditions 1 and 2) were used to establish the emission limits

for 1-sec combustion; and data from facilities A, B, J (condition 2), and M were used to establish the emission limits for 2-sec combustion. Data from test condition 3 at facilities K and W were not considered in establishing emission limits based on combustion control because both MWI's were purposely overcharged during these test conditions to show the effects of poor MWI operation.

For pathological MWI's, only one level of combustion control was tested (uncontrolled at facility S). To establish emission limits for pathological MWI's at each combustion control level, the relationships of the emission limits established for the other types of MWI's were applied to the data for the pathological MWI's to calculate emission limits for the untested conditions.

Control options reflecting add-on controls combine 2-sec combustion with an add-on control device. Emission limits for these control options were established based on inlet/outlet tests conducted on MWI's with add-on control. Typically, the emission reduction capability is expressed as a percent reduction relative to the 2-sec combustion emission limit. Exceptions to this approach are PM, Pd, and Cd emissions from fabric filter systems, which are capable of achieving constant outlet levels for these pollutants. For pollutants that are unaffected by combustion controls (waste-related pollutants for all MWI's and PM for pathological MWI's) the 2-sec combustion emission limit is equivalent to the uncontrolled emission level (the highest 3-run average of uncontrolled emission data).

The remainder of this section is divided into nine subsections, one for each pollutant. These subsections present the emission limits for each MWI type and show the data used to determine the emission limits.

4.3.1 Particulate Matter

Table 15 presents the PM emission limits under each control option for continuous, intermittent, batch, and pathological MWI's. Figures 37 through 39 present the data used to develop

these emission limits. At the facilities tested, the PM emissions were reported in gr/dscf. However, to be consistent with emission limits for other pollutants, the PM emission limits in this section are expressed in metric units (milligrams per dry standard cubic meter [mg/dscm]).

TABLE 15. PM EMISSION LIMITS FOR CONTINUOUS, INTERMITTENT, BATCH, AND PATHOLOGICAL MWI'S

Control option	PM emission limits, mg/dscm at 7 percent O ₂	
	Continuous, intermittent, batch	Pathological
1-sec	600	NA ^a
2-sec	300	NA ^a
Wet systems ^b	150	58
FF/PB ^b	30	30
DI/FF ^b	30	30
SD/FF ^b	30	30
Fabric filter systems with carbon injection ^b	30	30

^aNo applicable limit. Highest 3-run average of uncontrolled data = 115 mg/dscm (facility S condition 2).

^bIncludes 2-sec combustion.

4.3.1.1 Combustion Controls--PM. Figure 37 presents PM emission data for continuous, intermittent, and batch MWI's burning general medical waste. Data from facilities K and S reflect uncontrolled PM emission levels. The PM emission limit for 1-sec combustion is based on facility W, and was set relatively close to the majority of individual test runs because 1-sec combustion will exhibit less variation in PM emissions than uncontrolled levels. Test data show that at higher residence time, combustion-related emissions are less affected by the MWI operation. The PM emission limit for 2-sec combustion is based on facilities A, B, and J. In this case, the emission limit has been set very close to the highest 3-run average and very close to most of the individual test runs because the large amount of

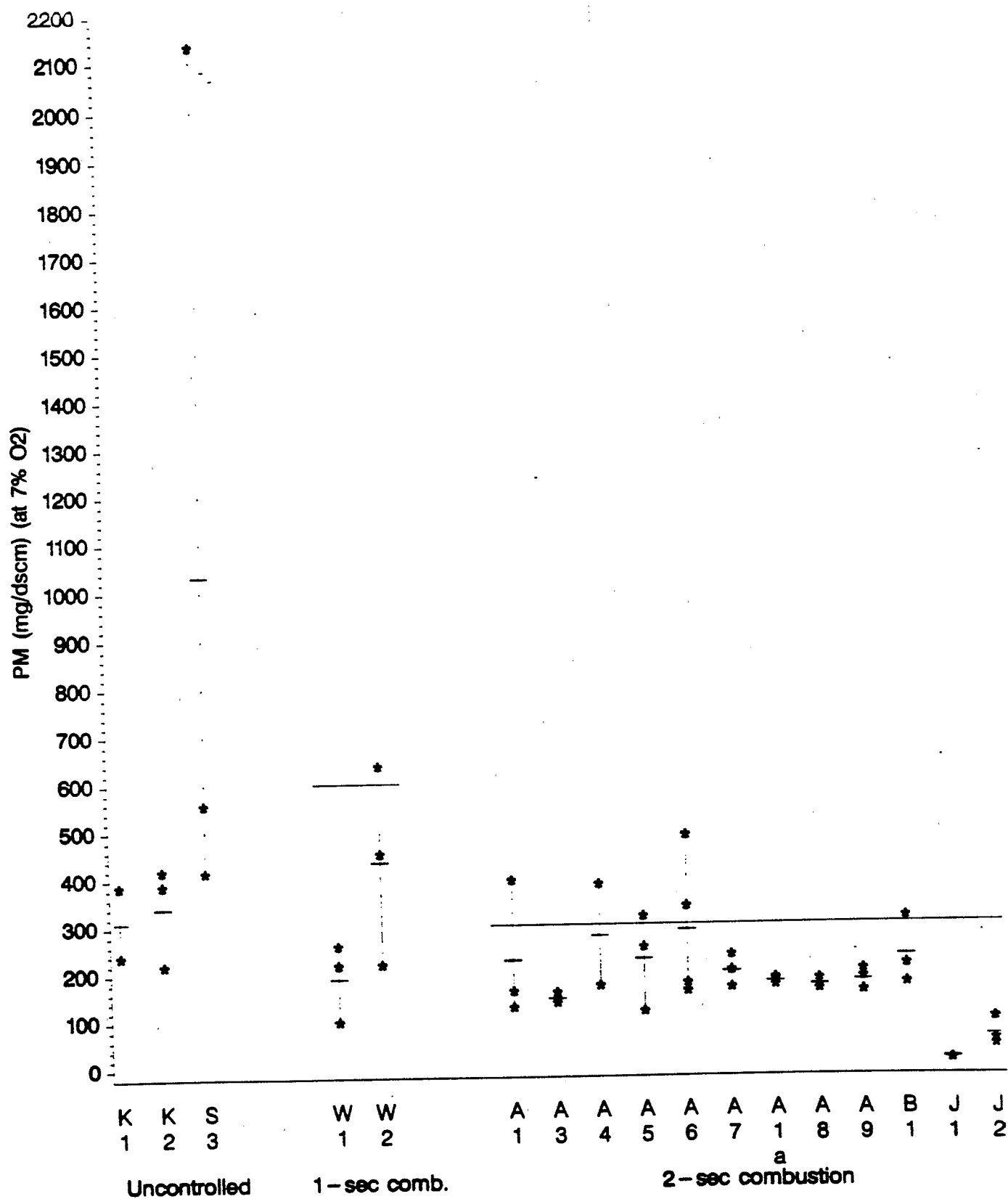


Figure 37. PM emissions for continuous, intermittent, and batch MWI's with combustion controls.

data available for these units indicate that this limit can consistently be achieved. Facility M was not considered in developing the PM limit for 2-sec combustion because the unit at this facility is a rotary kiln MWI that, as expected, had higher PM emissions due to the turbulence of the waste in the primary chamber. This turbulence results in entrainment of non-combustible ash, which will not be affected by combustion control.

Figure 38 presents PM emission data for pathological MWI's (facility S, uncontrolled). Compared to PM emissions from an MWI firing general medical waste, PM emissions from a pathological MWI will be lower, more stable, and less affected by combustion control. Pathological MWI's operate with excess air in the primary chamber, which limits the generation of incomplete combustion products but increases the entrainment of ash. The result is a higher fraction of non-combustible material (not affected by combustion control) in the PM emissions. Emissions of PM from pathological MWI's will be very stable because of the homogeneous nature of pathological waste and the absence of incomplete combustion products. Because combustion controls do not reduce PM emissions from pathological MWI's, no limits were established for the 1-sec and 2-sec control options.

4.3.1.2 Add-On Controls--PM. Figure 39 presents PM removal efficiencies and outlet levels achieved with the add-on control technologies tested. The PM outlet concentrations achievable with wet systems depend on the inlet loadings and therefore are based on a percent reduction rather than a constant outlet value. Facility B data indicate that wet systems are capable of achieving a PM removal efficiency of at least 50 percent. This performance is applicable to all MWI types.

The remaining control technologies use a fabric filter to control PM emissions. The emission limit for these technologies is based on a constant outlet value achievable with a fabric filter as demonstrated at facilities A, J, and M. Test conditions 1 through 7 at facility A were not considered in establishing the PM emission limit for fabric filter systems.

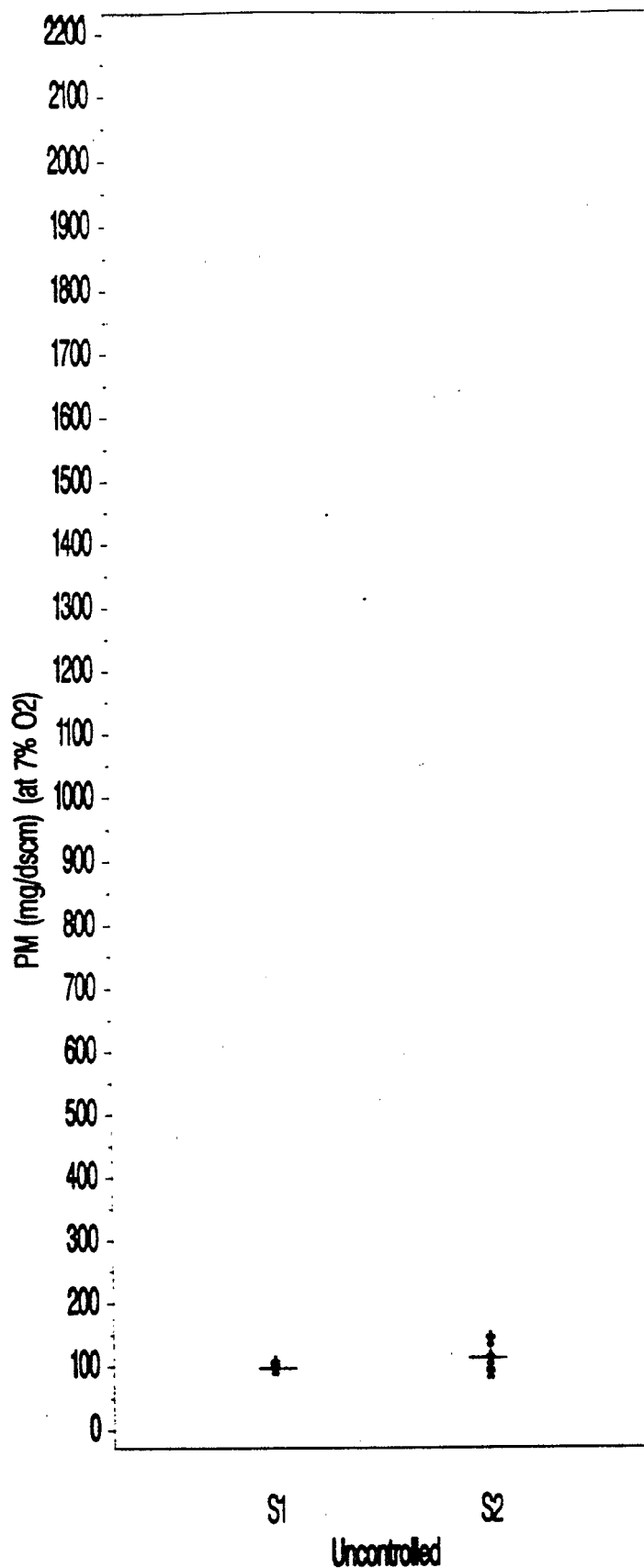


Figure 38. PM emissions for uncontrolled pathological MWI's.

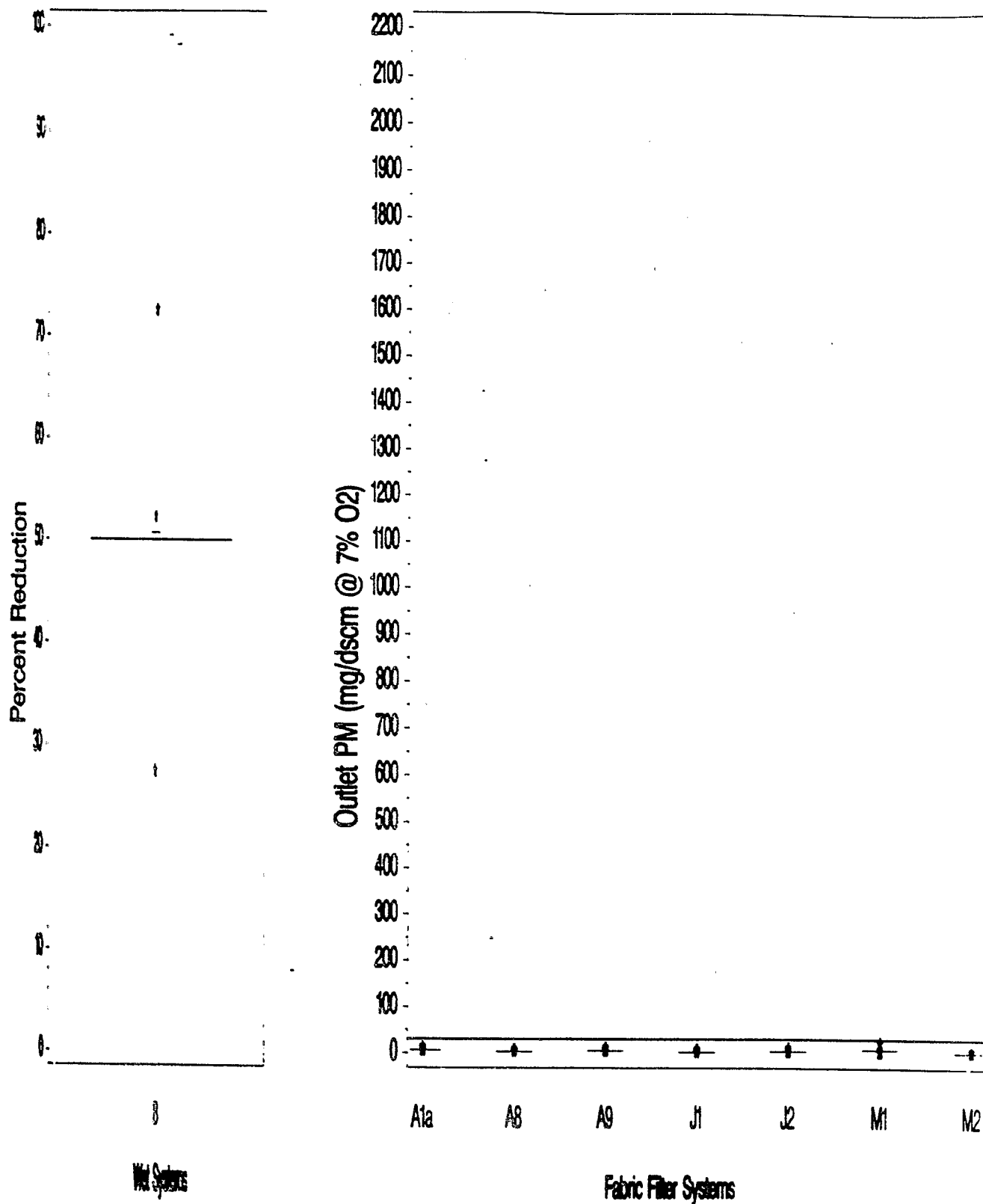


Figure 39. PM emissions for continuous, intermittent, batch, and pathological MWI's with add-on controls.

Outlet PM concentrations varied significantly for these tests, which were obtained during the first series of tests at facility A. Prior to the second series of tests, the fabric filter bags were replaced. The consistently low outlet PM levels achieved during this second series of tests, along with data from facilities J and M, indicate that the fabric filter was not functioning properly during the first series of tests at facility A, which invalidates PM runs 1 through 7 at facility A. Based on facility A (conditions 1A, 8, and 9), and on facilities J and M, PM concentrations of 30 mg/dscm are achievable by fabric filter systems.

4.3.2 Carbon Monoxide

Table 16 presents the CO emission limits under each control option for continuous, intermittent, batch, and pathological MWI's. Figures 40 and 41 present the data used to develop these emission limits.

TABLE 16. CO EMISSION LIMITS FOR CONTINUOUS, INTERMITTENT, BATCH, AND PATHOLOGICAL MWI'S

Control option	CO emission limits, ppm _{dv} at 7 percent O ₂	
	Continuous, intermittent, batch	Pathological
1-sec	500	50
2-sec	50	10
Wet systems ^a	50	10
FF/PB ^a	50	10
DI/FF ^a	50	10
SD/FF ^a	50	10
Fabric filter systems with carbon injection ^a	50	10

^aIncludes 2-sec combustion.

4.3.2.1 Combustion Controls--CO. Figure 40 presents CO emission data for continuous, intermittent, and batch MWI's burning general medical waste. Data from facilities K and S reflect uncontrolled CO emission levels. The CO emission limit

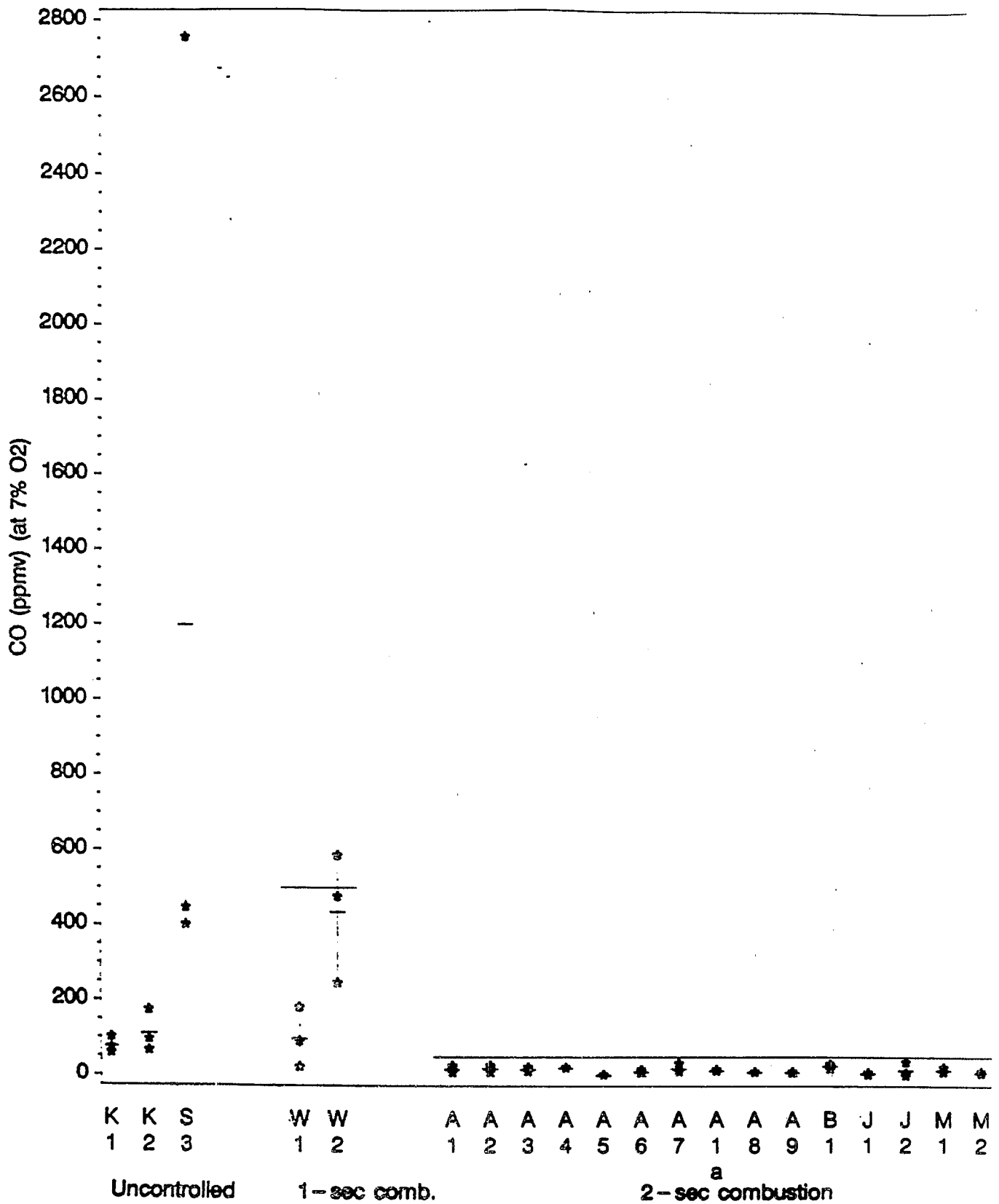


Figure 40. CO emissions for continuous, intermittent, and batch MWI's iwth combustion controls.

for 1-sec combustion is based on facility W, and was set relatively close to the majority of individual test runs, because 1-sec combustion will exhibit less variation in CO emissions than uncontrolled levels (as previously discussed for PM emissions). The CO emission limit for 2-sec combustion is based on facilities A, B, J, and M. In this case, the emission limit has been set very close to the highest 3-run average and very close to each of the individual test runs because the large amount of data available for these units indicate that this limit can consistently be achieved.

Figure 41 presents CO emission data for pathological MWI's (facility S, uncontrolled). Compared to CO emissions from an MWI firing general medical waste, CO emissions from a pathological MWI will be lower and more stable, but improved combustion control will further reduce CO emissions. Pathological MWI's operate with excess air in the primary chamber, which limits the generation of incomplete combustion products. However, combustion control will further reduce these emissions. Emissions of CO from pathological MWI's will be very stable because of the homogeneous nature of pathological waste. The CO limit for 1-sec combustion control is calculated using the ratio of the 1-sec CO limit to the uncontrolled CO emission level for general-waste units (500/1,200) and applying this ratio to the uncontrolled CO emission level for pathological MWI's (130). Uncontrolled emission levels are represented by the highest 3-run averages of the uncontrolled emissions data (facility S condition 3 for continuous, intermittent, and batch MWI's and facility S condition 2 for pathological MWI's). The CO limit for 2-sec combustion control is calculated using the ratio of the 2-sec CO limit to the uncontrolled CO emission level for general-waste units (50/1,200) and applying this ratio to the uncontrolled CO level for pathological MWI's (130).

4.3.2.2 Add-On Controls--CO. Add-on control devices are not effective in further removing CO emissions. As a result, the limits for all add-on control techniques are the same as those of 2-sec combustion control.

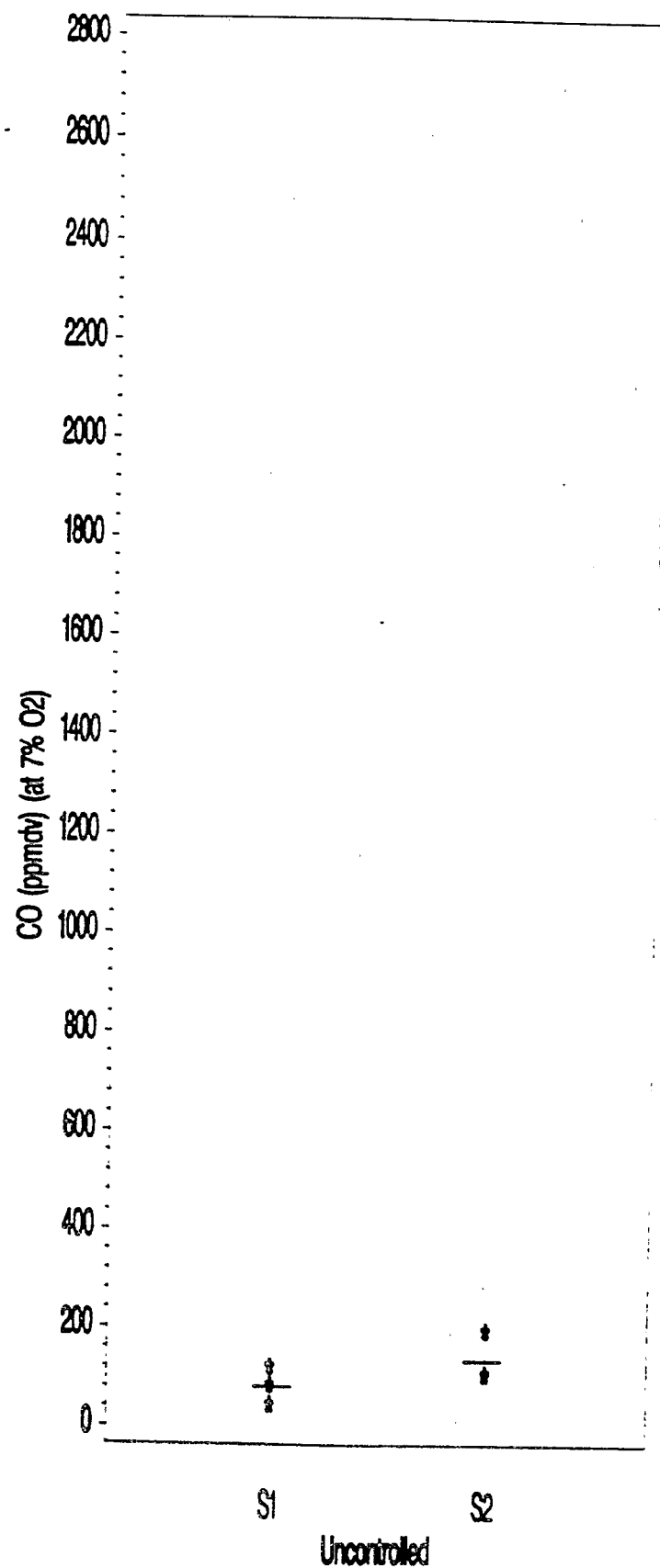


Figure 41. CO emissions for uncontrolled pathological MWI's.

4.3.3 Dioxins and Furans

Table 17 presents the CDD/CDF emission limits under each control option for continuous, intermittent, batch, and pathological MWI's. Figures 42 through 44 present the data used to develop these emission limits.

TABLE 17. CDD/CDF EMISSION LIMITS FOR CONTINUOUS, INTERMITTENT, BATCH, AND PATHOLOGICAL MWI'S

Control option	CDD/CDF emission limits, ng/dscm at 7 percent O ₂	
	Continuous, intermittent, batch	Pathological
1-sec	7,000	260
2-sec	1,500	60
Wet systems ^a	450	20
FF/PB ^a	7,000 ^b	260 ^b
DI/FF ^a	1,500	60
SD/FF ^a	1,500	60
Fabric filter systems with carbon injection ^a	80 ^c	3 ^c

^aIncludes 2-sec combustion.

^bLimits reflect CDD/CDF generation across FF/PB system.

^cThe CDD/CDF emission limits achievable with a FF/PB system with activated carbon injection are not known.

4.3.3.1 Combustion Controls--CDD/CDF. Figure 42 presents CDD/CDF emission data for continuous, intermittent, and batch MWI's burning general medical waste. Data from facilities K and S reflect uncontrolled PM emission levels. The CDD/CDF emission limit for 1-sec combustion is based on facility W, and was set relatively close to the majority of the individual test runs because 1-sec combustion will exhibit less variation in CDD/CDF emissions at uncontrolled levels (as discussed earlier for PM and CO). The CDD/CDF emission limit for 2-sec combustion is based on facilities A, B, J, and M. In this case, the emission limit has been set very close to the highest 3-run average and very close to each of the individual test runs because the large amount of

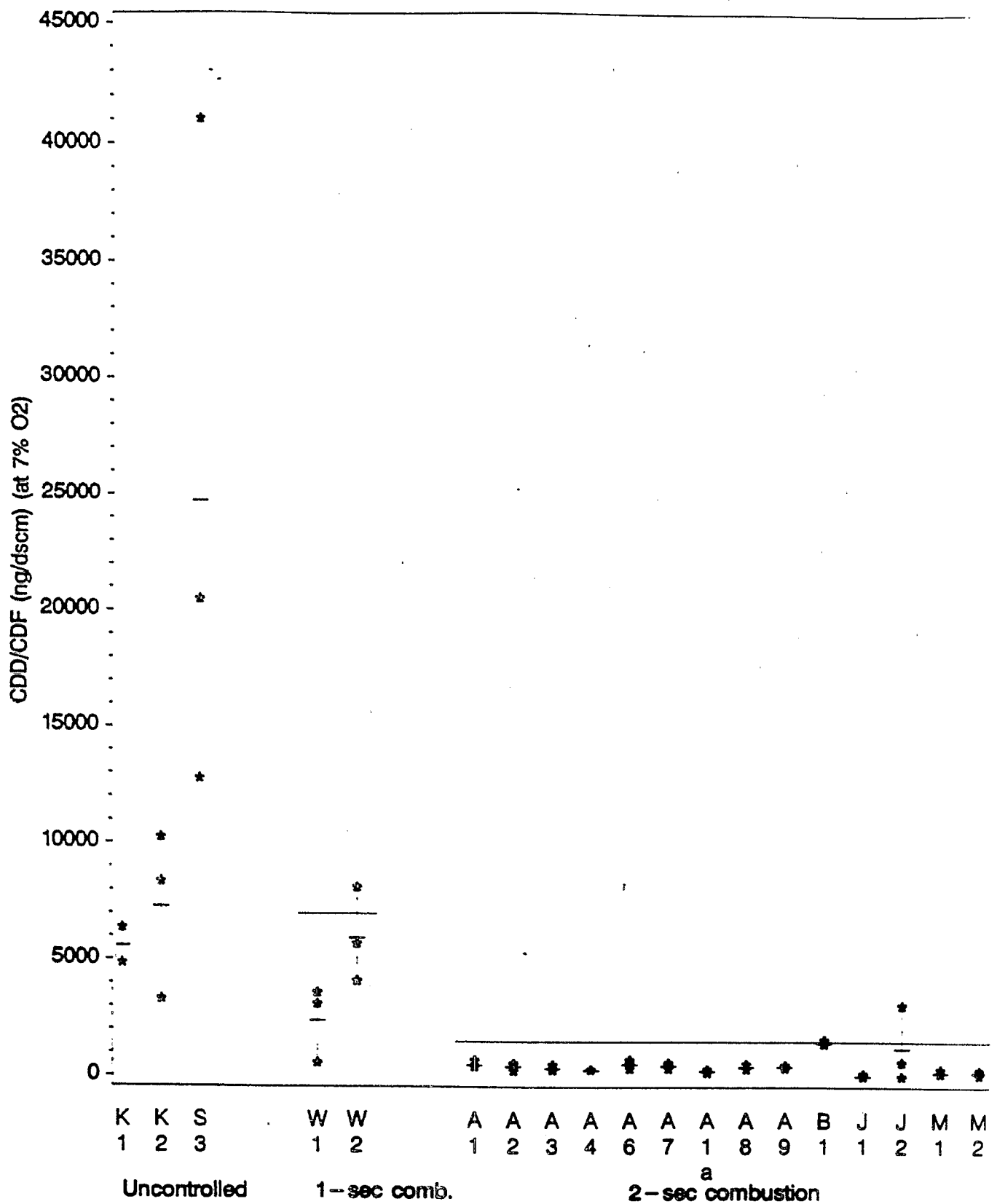


Figure 42. CDD/CDF emissions for continuous, intermittent, and batch MWI's with combustion controls.

data available for these units indicate that this limit can consistently be achieved.

Figure 43 presents CDD/CDF emission data for pathological MWI's (facility S, uncontrolled). Compared to CDD/CDF emissions from an MWI firing general medical waste, CDD/CDF emissions from a pathological MWI will be lower and more stable, but improved combustion control will reduce CDD/CDF emissions. Pathological MWI's operate with excess air in the primary chamber, which limits the generation of incomplete combustion products. However, CDD/CDF emissions can be further reduced by combustion control. Emissions of CDD/CDF from pathological MWI's will be very stable because of the homogeneous nature of pathological waste. The CDD/CDF limit for 1-sec combustion control is calculated using the ratio of the 1-sec CDD/CDF limit to the uncontrolled CDD/CDF emission level for general-waste units (7,000/25,000) and applying this ratio to the uncontrolled CDD/CDF emission level for pathological MWI's (910). Uncontrolled emission levels are represented by the highest 3-run averages of the uncontrolled emissions data (facility S condition 3 for continuous, intermittent, and batch MWI's and facility S condition 1 for pathological MWI's). The CDD/CDF limit for 2-sec combustion control is calculated using the ratio of the 2-sec CDD/CDF limit to the uncontrolled CDD/CDF emission level for general-waste units (1,500/25,000) and applying this ratio to the uncontrolled CDD/CDF emissions for pathological MWI's (910).

4.3.3.2 Add-On Controls--CDD/CDF. Figure 44 presents the CDD/CDF removal efficiencies and outlet concentrations of the add-on control technologies tested. The CDD/CDF emission limit for the wet systems is based on the 70-percent removal efficiency demonstrated at facility B. The three fabric filter systems without activated carbon injection achieved varying levels of CDD/CDF control. In fact, formation of CDD/CDF occurred in one system.

Formation of CDD/CDF occurs when there is intimate contact between a gas stream containing CDD/CDF precursors and fly ash, which acts as a catalyst. The optimum temperature window for fly

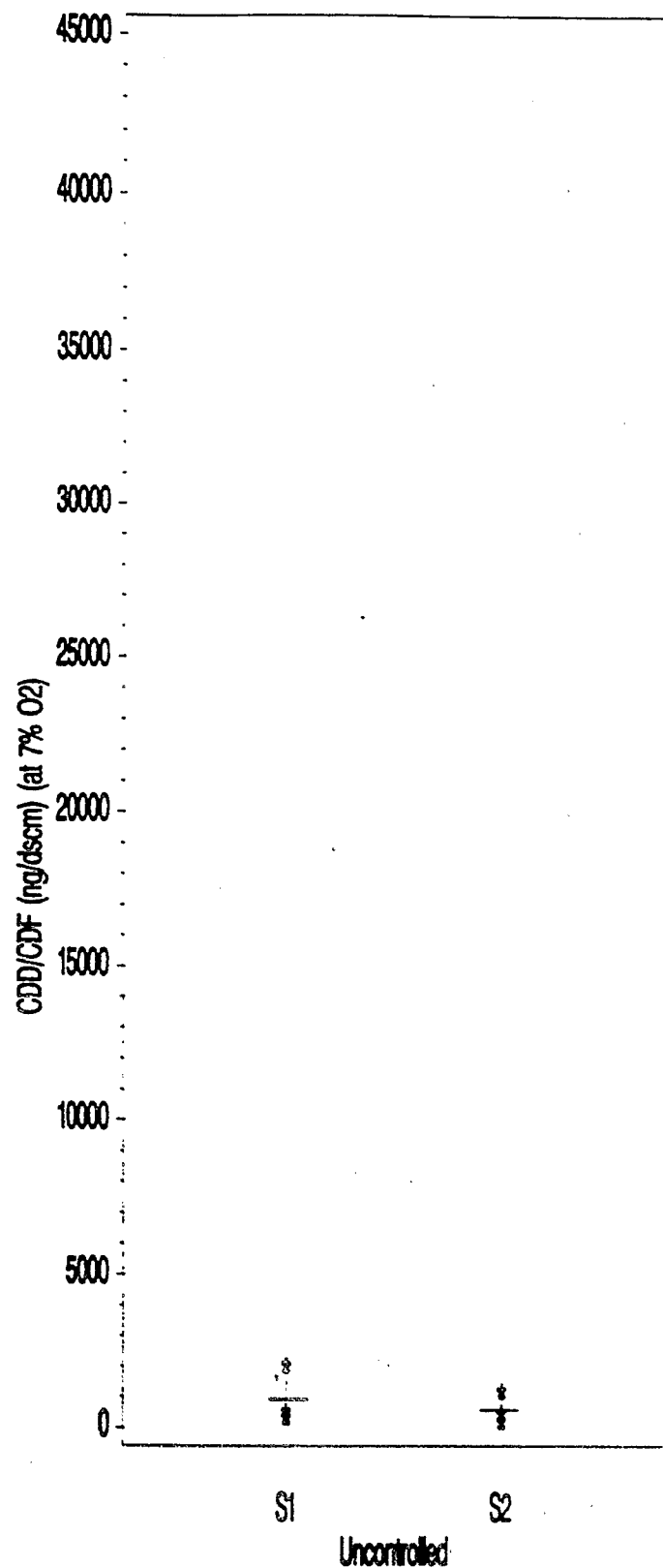


Figure 43. CDD/CDF emissions for uncontrolled pathological MWI's.

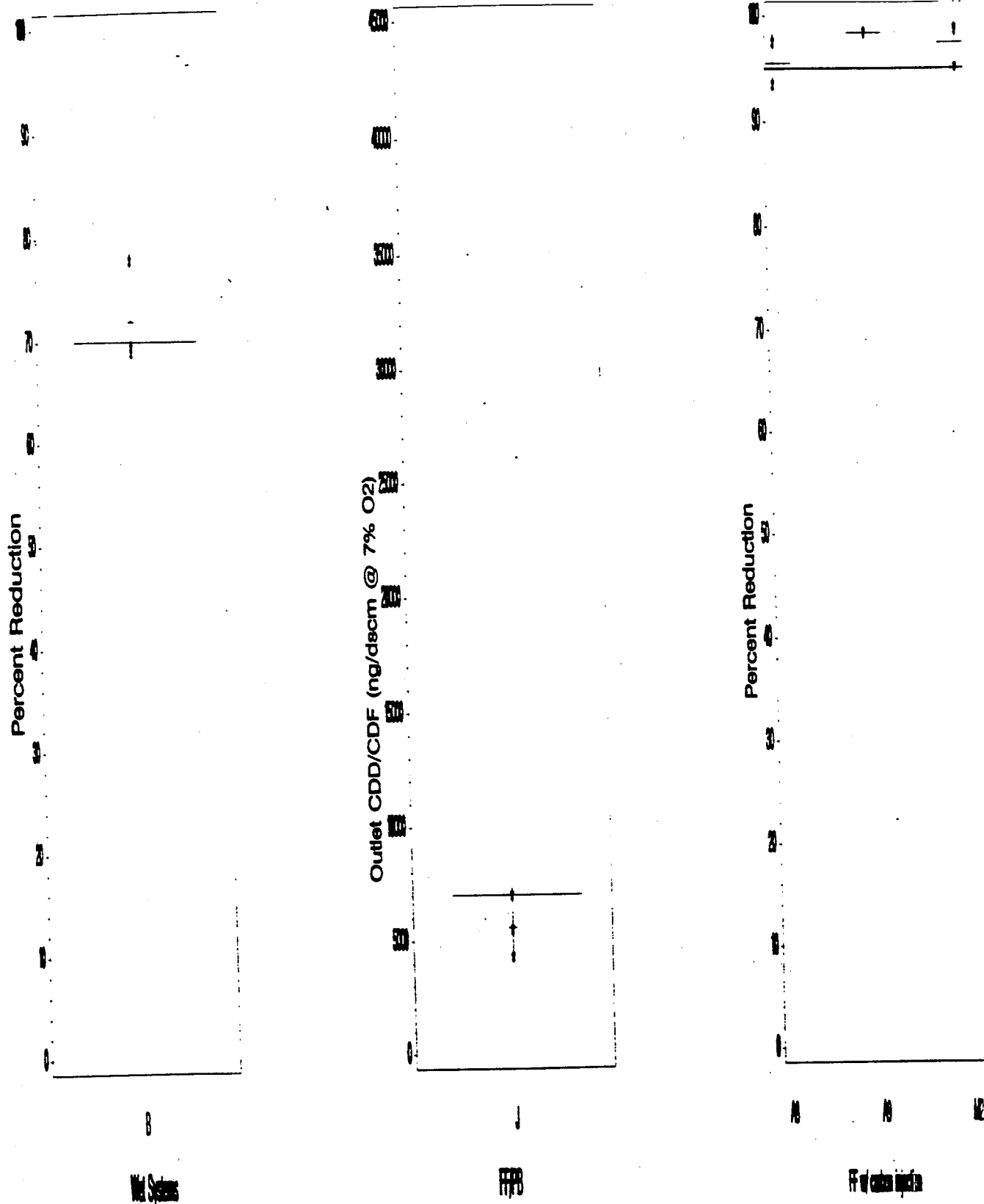


Figure 44. CDD/CDF emissions for continuous, intermittent, batch, and pathological MWI's with add-on controls.

ash catalyzed CDD/CDF formation is between 300°F and 600°F. The CDD/CDF formation is minimized when using combustion control or wet systems because these options provide: (1) rapid cooling of the gas stream through the temperature window and (2) quick dispersion (or removal in the case of wet systems) of CDD/CDF precursors and fly ash. In DI/FF and SD/FF systems, the presence of an acid gas sorbent (lime, for example) also limits the formation of CDD/CDF. The fabric filter in a FF/PB system, on the other hand, can provide those conditions conducive to CDD/CDF formation. In fact, test data have shown CDD/CDF formation in a FF/PB system.

The emission limit for the FF/PB system is based on test data from facility J, which shows a generation of CDD/CDF across the system. Figure 44 shows the outlet CDD/CDF emissions at facility J. Because facility J burns general medical waste, the actual test data could not be used directly in establishing an emission limit for pathological MWI's. As a result, the limit for the pathological MWI has been calculated based on the CDD/CDF generation rate at facility J. The generation rate is based on the FF/PB outlet limit (7,000 nanograms [ng]/dry standard cubic meter [dscm]) and the 2-sec combustion limit (1,500 ng/dscm) at facility J. This generation rate was applied to the 2-sec combustion limit for pathological MWI's to determine the FF/PB limit for this MWI.

The CDD/CDF emission limit for the DI/FF system is based on test data from facility A. This test data showed no consistent CDD/CDF removal from the DI/FF system without carbon injection. Therefore, the limit for this technology is the same as that of 2-sec combustion control.

Test data from facility M indicate that a SD/FF system on a rotary kiln MWI is capable of achieving 80-percent CDD/CDF reduction. However, this significant reduction may be due to the rotary kiln design (the higher PM emissions may aid in the removal of CDD/CDF). It is not known if a SD/FF system (without activated carbon injection) can achieve this same level of control on the other MWI designs. On the other hand, a SD/FF

system is not expected to generate CDD/CDF for the reasons described above. Therefore, the limit for this technology is the same as that of 2-sec combustion control.

Test data from facilities A and M indicate that the DI/FF and SD/FF systems with activated carbon injection are effective in significantly reducing CDD/CDF emissions (see Figure 44). These two fabric filter systems (with activated carbon injection) are able to achieve at least 95-percent CDD/CDF control. Because data are not available from a FF/PB system with activated carbon injection, and because the FF/PB system tested without carbon injection generated CDD/CDF, it is not known what CDD/CDF reductions are achievable with the activated carbon in a FF/PB system.

4.3.4 Hydrogen Chloride

Table 18 presents the HCl emission limits under each control option for continuous, intermittent, batch, and pathological MWI's. Figures 45 through 47 present the data used to establish these emission limits.

4.3.4.1 Combustion Controls--HCl. Figure 45 presents HCl emission data for continuous, intermittent, and batch MWI's burning general medical waste, and Figure 46 presents these data for pathological MWI's. Because emissions of HCl are waste-related, combustion controls do not reduce HCl emissions.

4.3.4.2 Add-on Controls--HCl. Figure 47 presents the HCl removal efficiencies of the add-on control technologies tested. The emission limit for wet systems is based on test data from facility B, while the emission limit for fabric filter systems is based on data for a DI/FF system from facility A and a SD/FF system from facility M. The data show that each of these systems can reduce HCl emissions by at least 97 percent. This corresponds to an emission level of 42 ppm_{dv} for a typical continuous, intermittent, or batch unit (97 percent reduction from a typical uncontrolled level of 1,400 ppm_{dv}); and 4 ppm_{dv} for pathological units (97 percent reduction from a typical uncontrolled level of 120 ppm_{dv}).

TABLE 18. HCl EMISSION LIMITS FOR CONTINUOUS, INTERMITTENT, BATCH, AND PATHOLOGICAL MWI'S

Control option	HCl emission limits, ppm _{dv} at 7 percent O ₂	
	Continuous, intermittent, batch	Pathological
1-sec	NA ^a	NA ^a
2-sec	NA ^a	NA ^a
Wet systems ^b	42 ^c	4 ^c
FF/PB ^b	42 ^c	4 ^c
DI/FF ^b	42 ^c	4 ^c
SD/FF ^b	42 ^c	4 ^c
Fabric filter systems with carbon injection ^b	42 ^c	4 ^c

^aNo applicable limit.

^bIncludes 2-sec combustion.

^cThese emission limits correspond to a reduction of 97 percent.

For the DI/FF system without a retention chamber, as at facility A, greater than 97 percent reduction is achieved when the stoichiometric ratio is at least 6:1. (In some cases, similar reductions can also be achieved with lower stoichiometric ratios). The 3-run test averages at facility A were not used in establishing the HCl emission limit because, as shown on Figure 47, the stoichiometric ratio was below 6:1 for at least 1 run at each of the test conditions, except test condition 4. Test data for a DI/FF with a retention chamber are unavailable. However, as noted earlier in this report, vendors indicate that a 50 percent lower stoichiometric ratio can be used in a system with a retention chamber to achieve the same reduction as a system without a retention chamber.

For the SD/FF system at facility M, test runs were conducted with stoichiometric ratios between 1.9 and 3.4, and the resulting emission reductions were greater than 98 percent for each run.

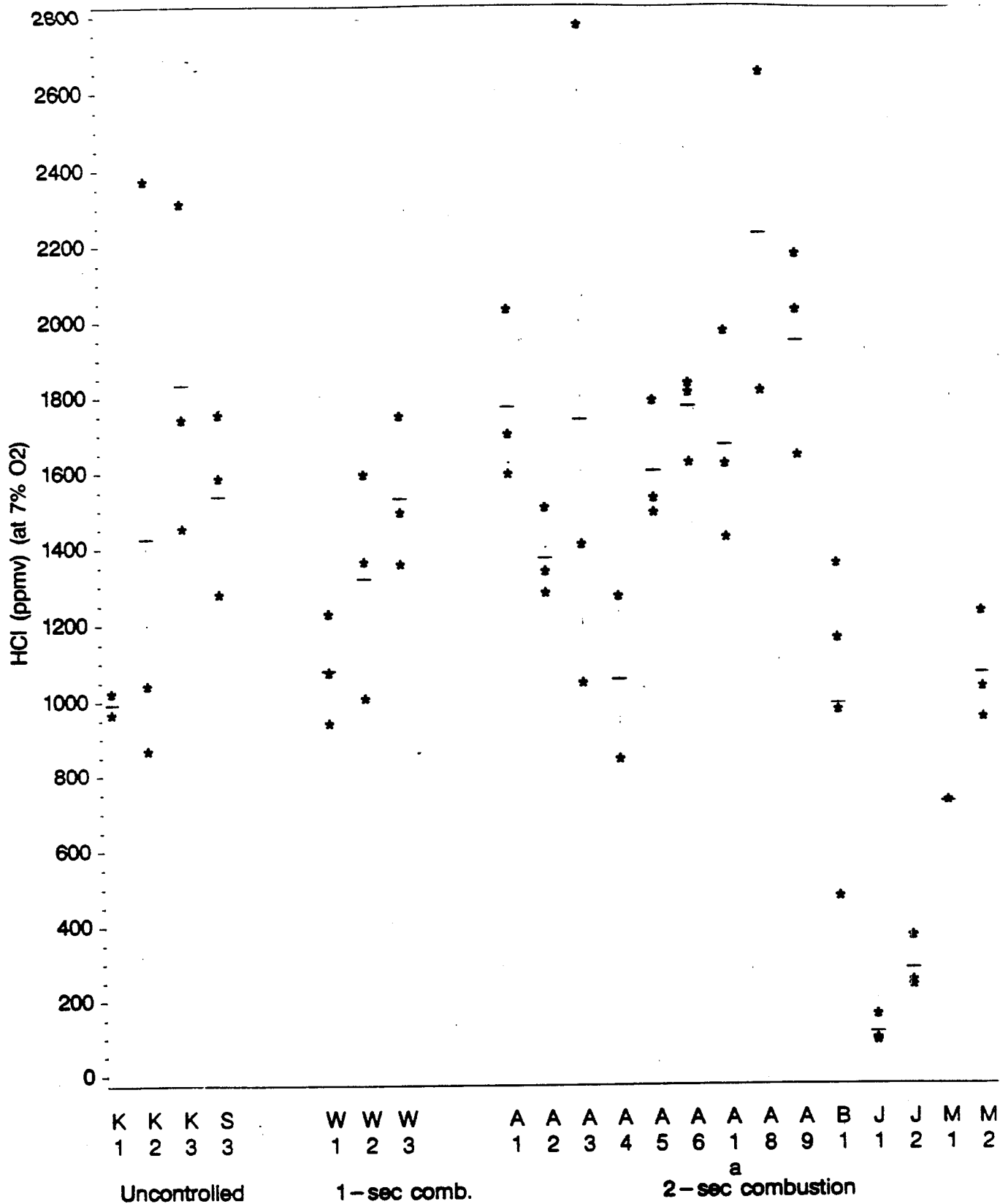


Figure 45. HCl emissions for continuous, intermittent, and batch MWI's with combustion controls.

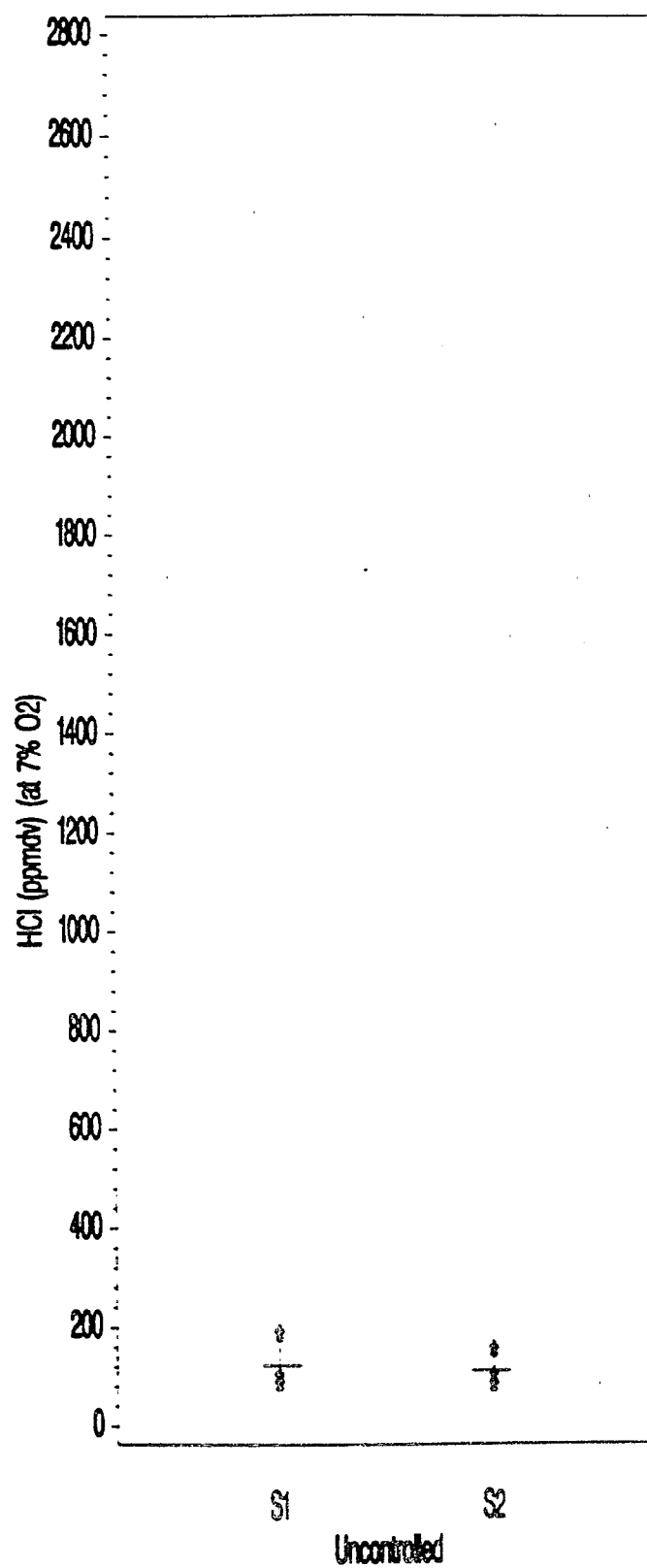


Figure 46. HCl emissions for uncontrolled pathological MWI's.

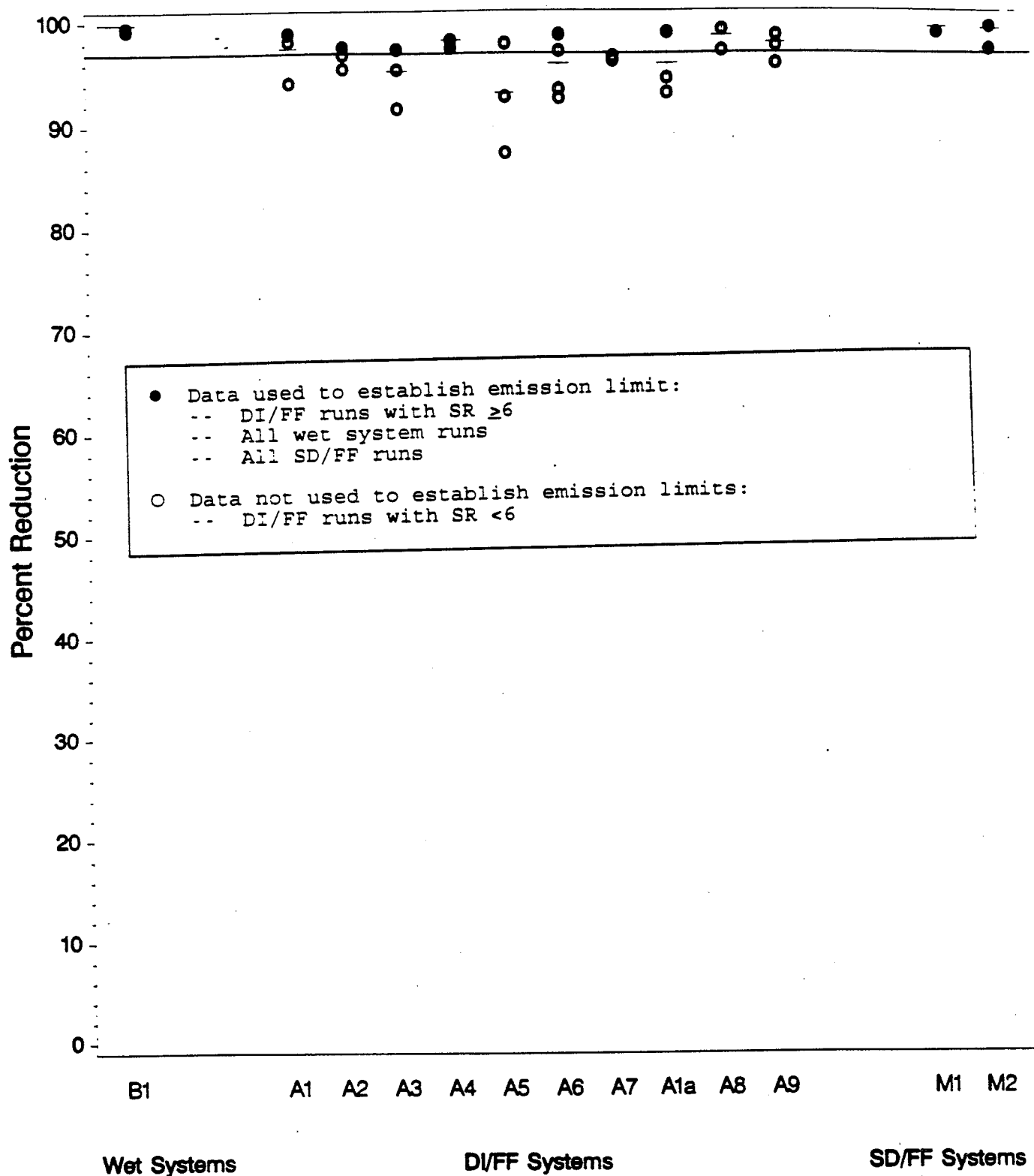


Figure 47. HCl emissions for continuous, intermittent, batch, and pathological MWI's with add-on controls.

The SD is a retention chamber, which allows the stoichiometric ratio to be lower at Facility M than at Facility A.

The HCl removal efficiencies at facility J were relatively low and were also not considered in establishing the HCl emission limits for the fabric filter systems. During the tests conducted at this facility, nozzle plugging resulted in poor performance, thereby invalidating these tests.

4.3.5 Sulfur Dioxide

Table 19 presents the SO₂ emission limits under each control option for continuous, intermittent, batch, and pathological MWI's. Figures 48 and 49 present the data used to establish these emission limits.

TABLE 19. SO₂ EMISSION LIMITS FOR CONTINUOUS, INTERMITTENT, BATCH, AND PATHOLOGICAL MWI'S

Control option	SO ₂ emission limits, ppmv at 7 percent O ₂	
	Continuous, intermittent, batch	Pathological
1-sec	NA ^a	NA ^a
2-sec	NA ^a	NA ^a
Wet systems ^b	NA ^a	NA ^a
FF/PB ^b	NA ^a	NA ^a
DI/FF ^b	NA ^a	NA ^a
SD/FF ^b	NA ^a	NA ^a
Fabric filter systems with carbon injection ^b	NA ^a	NA ^a

^aNo applicable limit.

^bIncludes 2-sec combustion.

4.3.5.1 Combustion Controls--SO₂. Figure 48 presents SO₂ emission data for continuous, intermittent, and batch MWI's burning general medical waste, and Figure 49 presents these data for pathological MWI's. Because emissions of SO₂ are waste-related, combustion controls do not reduce SO₂.

4.3.5.2 Add-On Controls--SO₂. At the low inlet SO₂ levels associated with MWI's, test data indicate that add-on controls

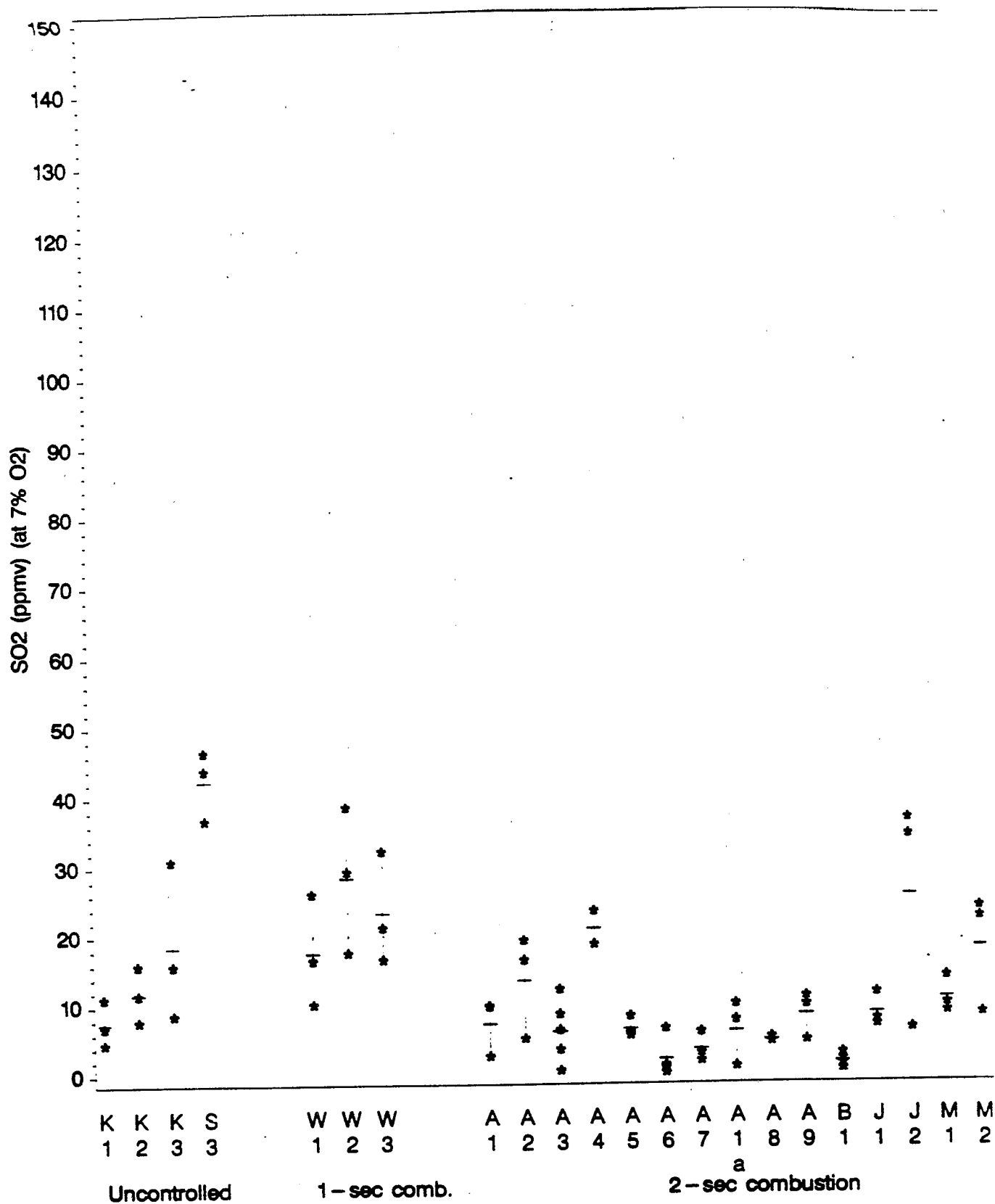


Figure 48. SO₂ emissions for continuous, intermittent, and batch MWI's with combustion controls.

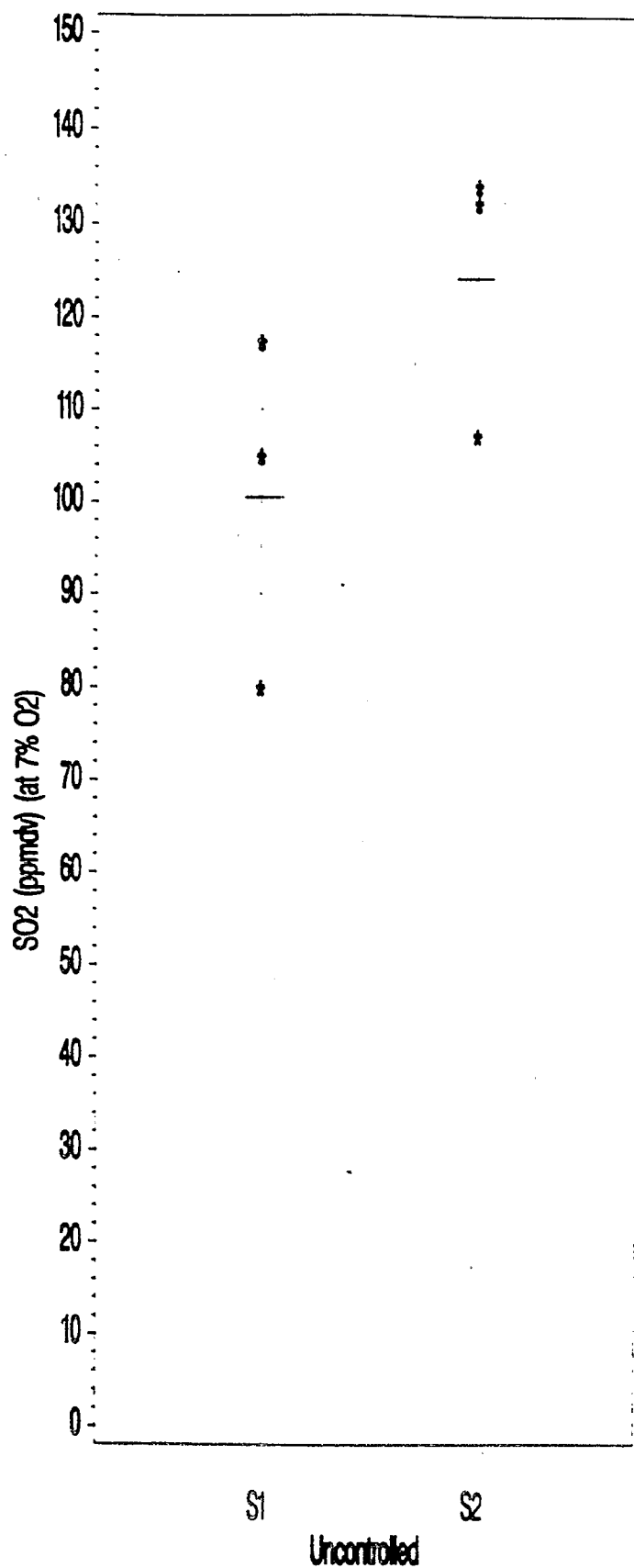


Figure 49. SO₂ emissions for uncontrolled pathological MWI's.

are not effective in reducing these emissions. Therefore, SO₂ emission limits have not been established for these remaining control technologies.

4.3.6 Lead

Table 20 presents the Pb emission limits under each control option for continuous, intermittent, batch, and pathological MWI's. Figures 50 through 52 present the data used to develop the emission limits.

TABLE 20. Pb EMISSION LIMITS FOR CONTINUOUS, INTERMITTENT, BATCH, AND PATHOLOGICAL MWI'S

Control option	Pb emission limits, mg/dscm at 7 percent O ₂	
	Continuous, intermittent, batch	Pathological
1-sec	NA ^a	NA ^b
2-sec	NA ^a	NA ^b
Wet systems ^c	3.7	0.24
FF/PB ^c	0.10	0.10
DI/FF ^c	0.10	0.10
SD/FF ^c	0.10	0.10
Fabric filter systems with carbon injection ^c	0.10	0.10

^aNo applicable limit. Highest 3-run average of uncontrolled emissions data = 6.8 mg/dscm (facility A, condition 6).

^bNo applicable limit. Highest 3-run average of uncontrolled emissions data = 0.44 mg/dscm (facility S, condition 1).

^cIncludes 2-sec combustion.

4.3.6.1 Combustion Controls--Pb. Figure 50 presents the Pb emission data for continuous, intermittent, and batch MWI's burning general medical waste, and Figure 51 presents this data for pathological MWI's. Because emissions of Pb are waste-related, combustion controls do not reduce Pb emissions.

4.3.6.2 Add-On Controls--Pb. Figure 52 presents Pb removal efficiencies and outlet levels achieved with the add-on control technologies tested. The limit for wet systems is based on test data from facility B, which indicate that wet systems are capable of achieving at least 45-percent reduction in Pb emissions. The

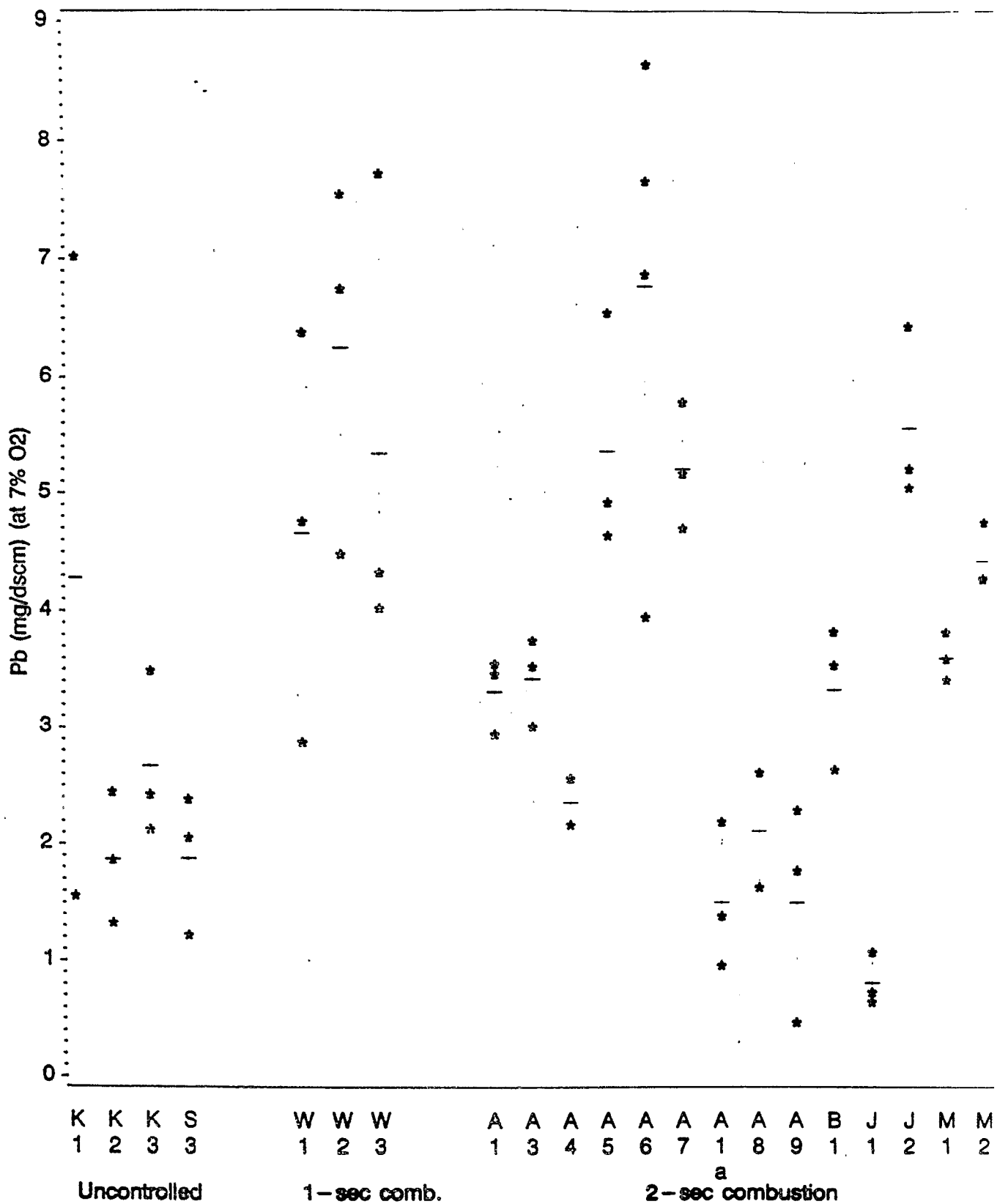


Figure 50. Pb emissions for continuous, intermittent, and batch MWI's with combustion controls.

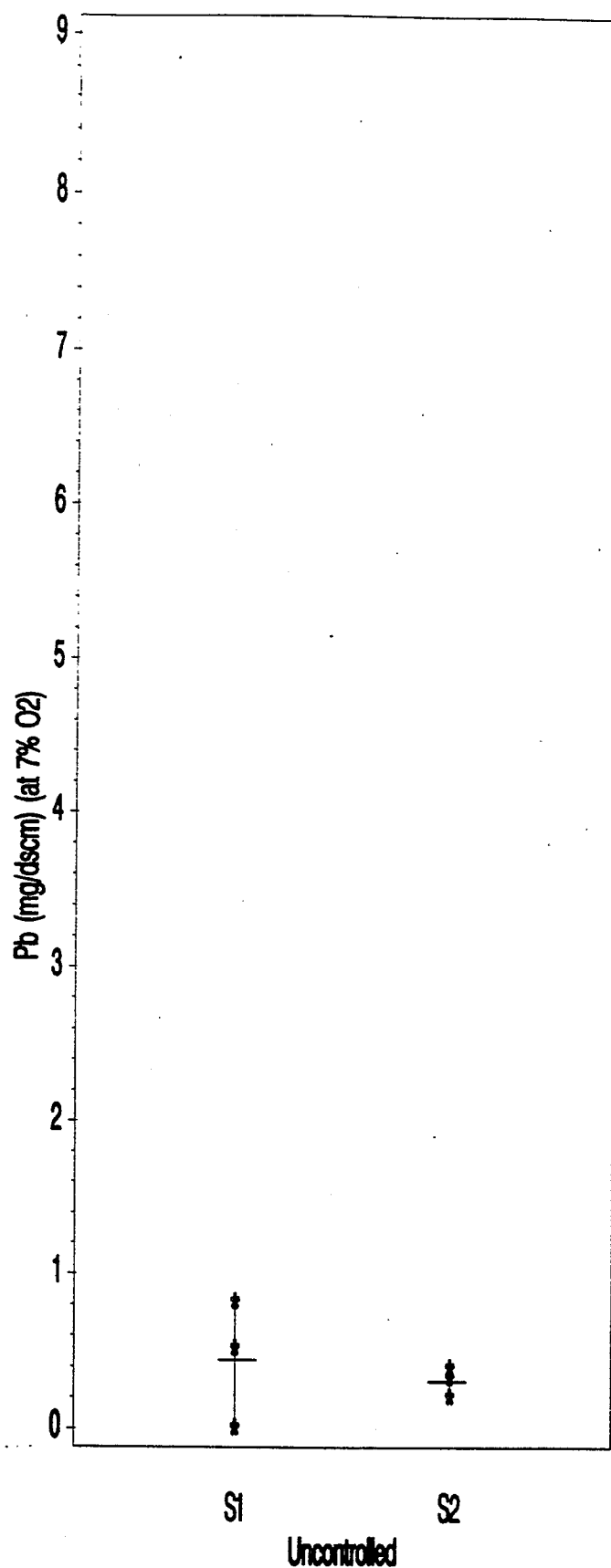


Figure 51. Pb emissions for uncontrolled pathological MWI's.

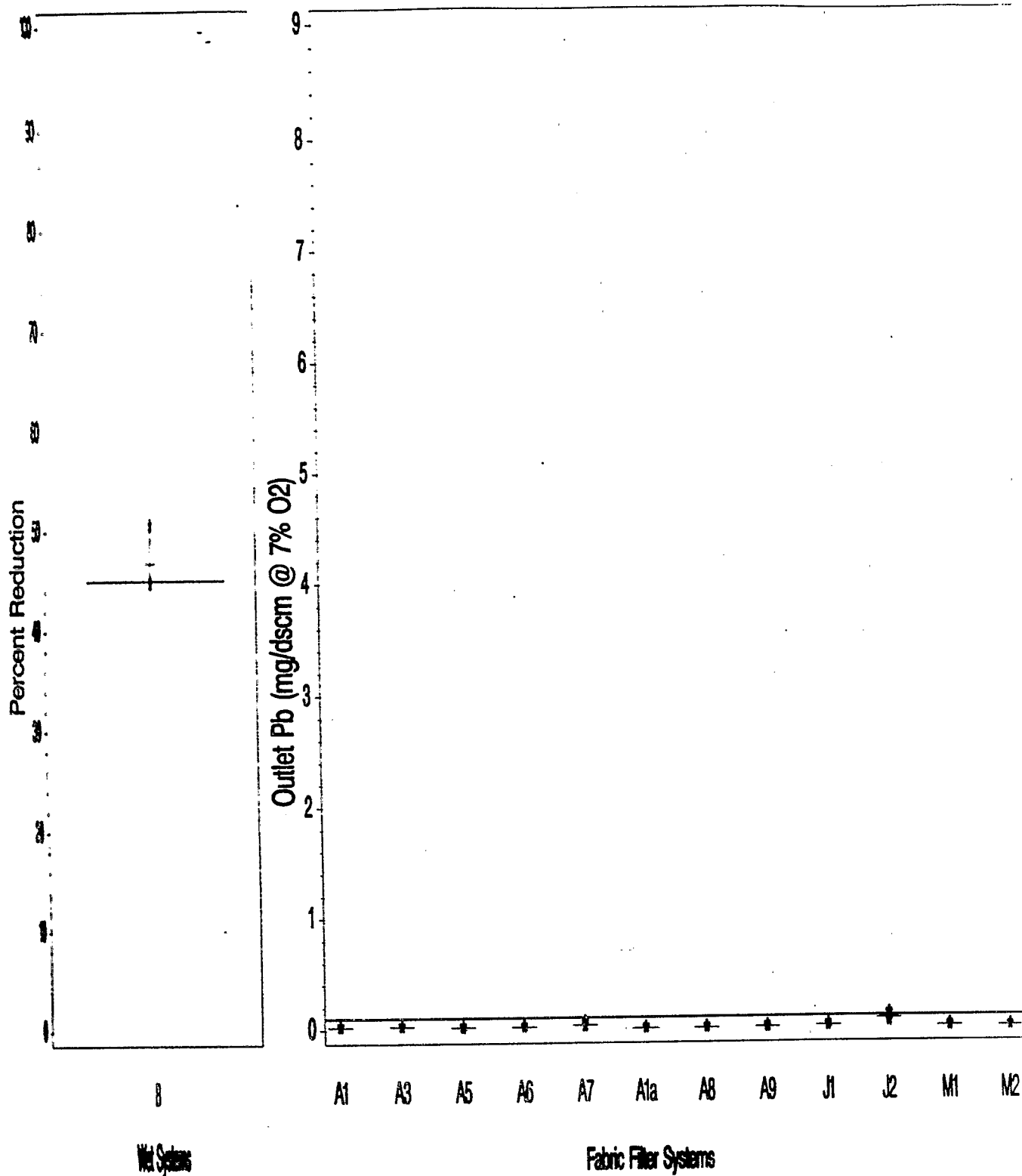


Figure 52. Pb emissions for continuous, intermittent, batch, and pathological MWI's with add-on controls.

remaining control technologies use a fabric filter to control Pb emissions. As is the case for PM, the Pb emission limit is based on a constant outlet achievable with a fabric filter. Test data from facilities A, J, and M indicate that fabric filter systems can achieve a Pb level of 0.10 mg/dscm.

4.3.7 Cadmium

Table 21 presents the Cd emission limits under each control option for continuous, intermittent, batch, and pathological MWI's. Figures 53 through 55 present the data used to develop the emission limits.

TABLE 21. Cd EMISSION LIMITS FOR CONTINUOUS, INTERMITTENT, BATCH, AND PATHOLOGICAL MWI'S

Control option	Cd emission limits, mg/dscm at 7 percent O ₂	
	Continuous, intermittent, batch	Pathological
1-sec	NA ^a	NA ^b
2-sec	NA ^a	NA ^b
Wet systems ^c	1.1	0.10
FF/PB ^c	0.05	0.05
DI/FF ^c	0.05	0.05
SD/FF ^c	0.05	0.05
Fabric filter systems with carbon injection ^c	0.05	0.05

^aNo applicable limit. Highest 3-run average = 1.9 mg/dscm (facility A condition 8).

^bNo applicable limit. Highest 3-run average = 0.17 mg/dscm (facility S condition 1).

^cIncludes 2-sec combustion.

4.3.7.1 Combustion Controls--Cd. Figure 53 presents the Cd emission data for continuous, intermittent, and batch MWI's burning general medical waste, and Figure 54 presents the data for pathological MWI's. Because emissions of Cd are waste-related, combustion controls do not reduce Cd emissions.

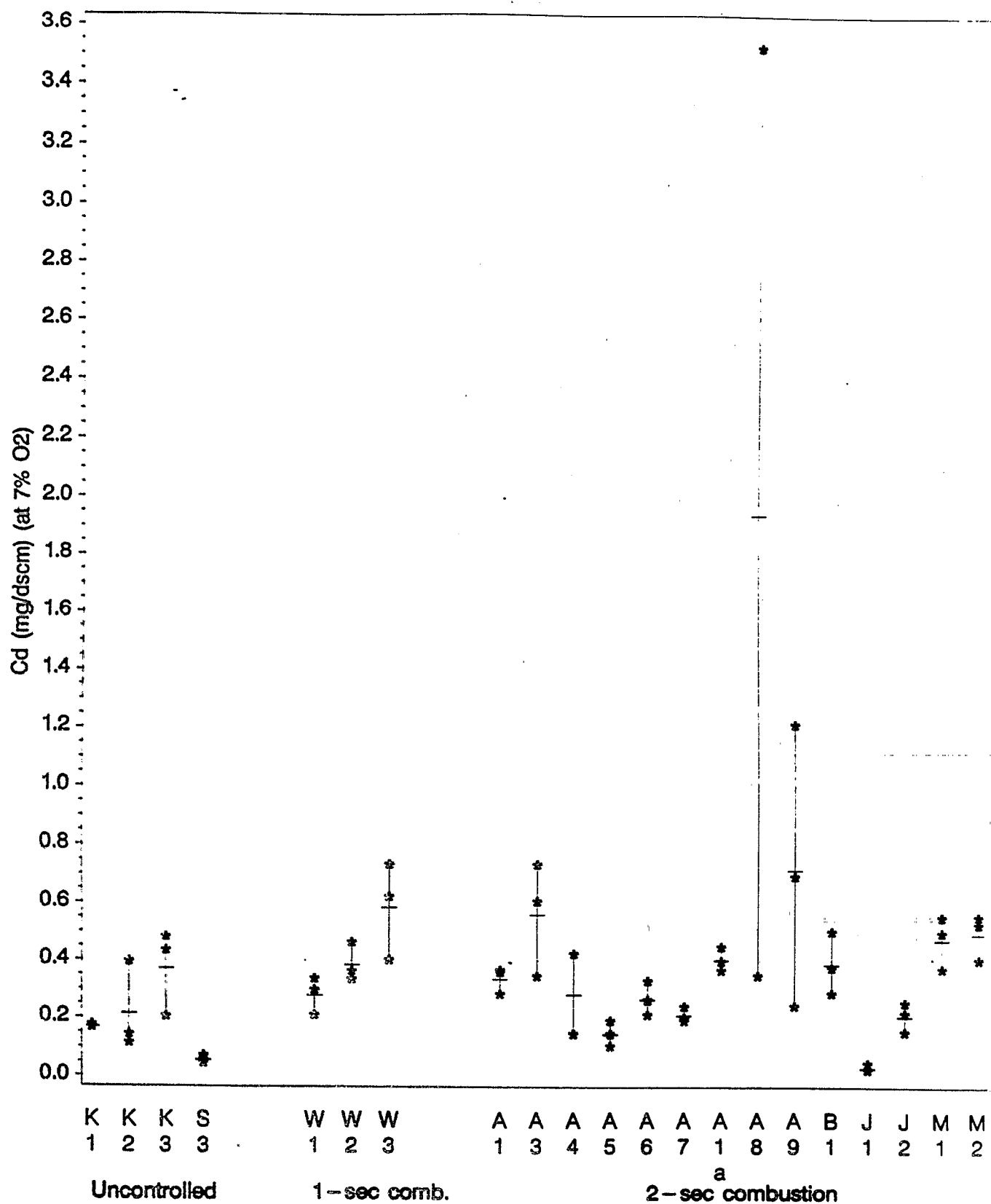


Figure 53. Cd emissions for continuous, intermittent, and batch MWI's with combustion controls.

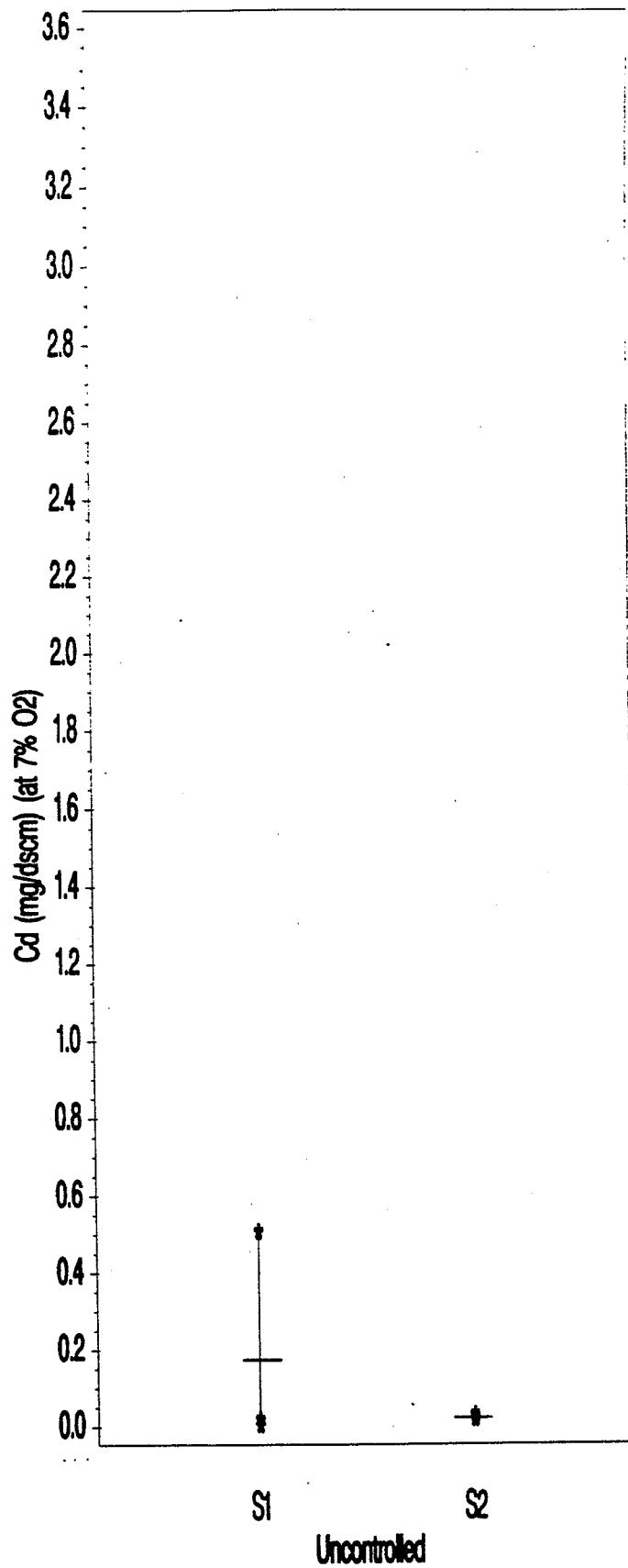


Figure 54. Cd emissions for uncontrolled pathological MWI's.

4.3.7.2 Add-On Controls--Cd. Figure 55 presents Cd removal efficiencies and outlet levels achieved with the add-on control technologies tested. The limit for wet systems is based on test data from facility B, which indicate that wet systems are capable of achieving at least 40 percent reduction in Cd emissions. The remaining control technologies use a fabric filter to control Cd emissions. As is the case for PM and Pb, the Cd emission limit is based on a constant outlet achievable with a fabric filter. Test data from facilities A, J, and M indicate that fabric filter systems can achieve a Cd level of 0.05 mg/dscm.

4.3.8 Mercury

Table 22 presents the Hg emission limits under each control option for continuous, intermittent, batch, and pathological MWI's. Figures 56 through 58 present the data used to develop the emission limits.

TABLE 22. Hg EMISSION LIMITS FOR CONTINUOUS, INTERMITTENT, BATCH, AND PATHOLOGICAL MWI'S

Control option	Hg emission limits, mg/dscm at 7 percent O ₂	
	Continuous, intermittent, batch	Pathological
1-sec	NA ^a	NA ^a
2-sec	NA ^a	NA ^a
Wet systems ^b	NA ^a	NA ^a
FF/PB ^b	NA ^a	NA ^a
DI/FF ^b	NA ^a	NA ^a
SD/FF ^b	NA ^a	NA ^a
Fabric filter systems with carbon injection ^b	0.47 ^c	0.01 ^c

^aNo applicable limit.

^bIncludes 2-sec combustion.

^cThis emission limit corresponds to an 85 percent reduction.

4.3.8.1 Combustion Controls--Hg. Figure 56 presents the Hg emission data for continuous, intermittent, and batch MWI's burning general medical waste, and Figure 57 presents this data for pathological MWI's. Because emissions of Hg are waste-related, combustion controls do not reduce Hg emissions.

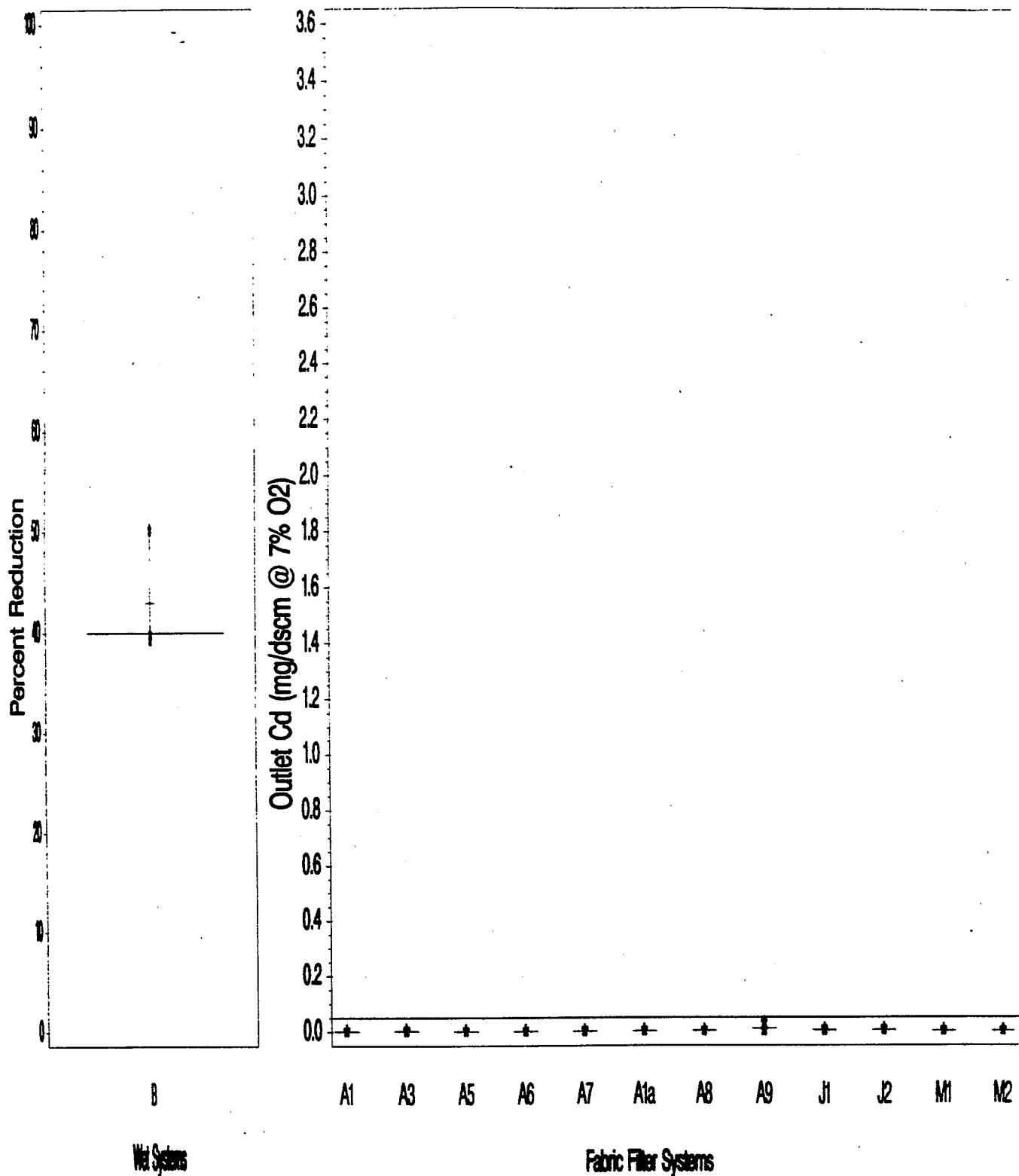


Figure 55. Cd emissions for continuous, intermittent, batch, and pathological MWI's with add-on controls.

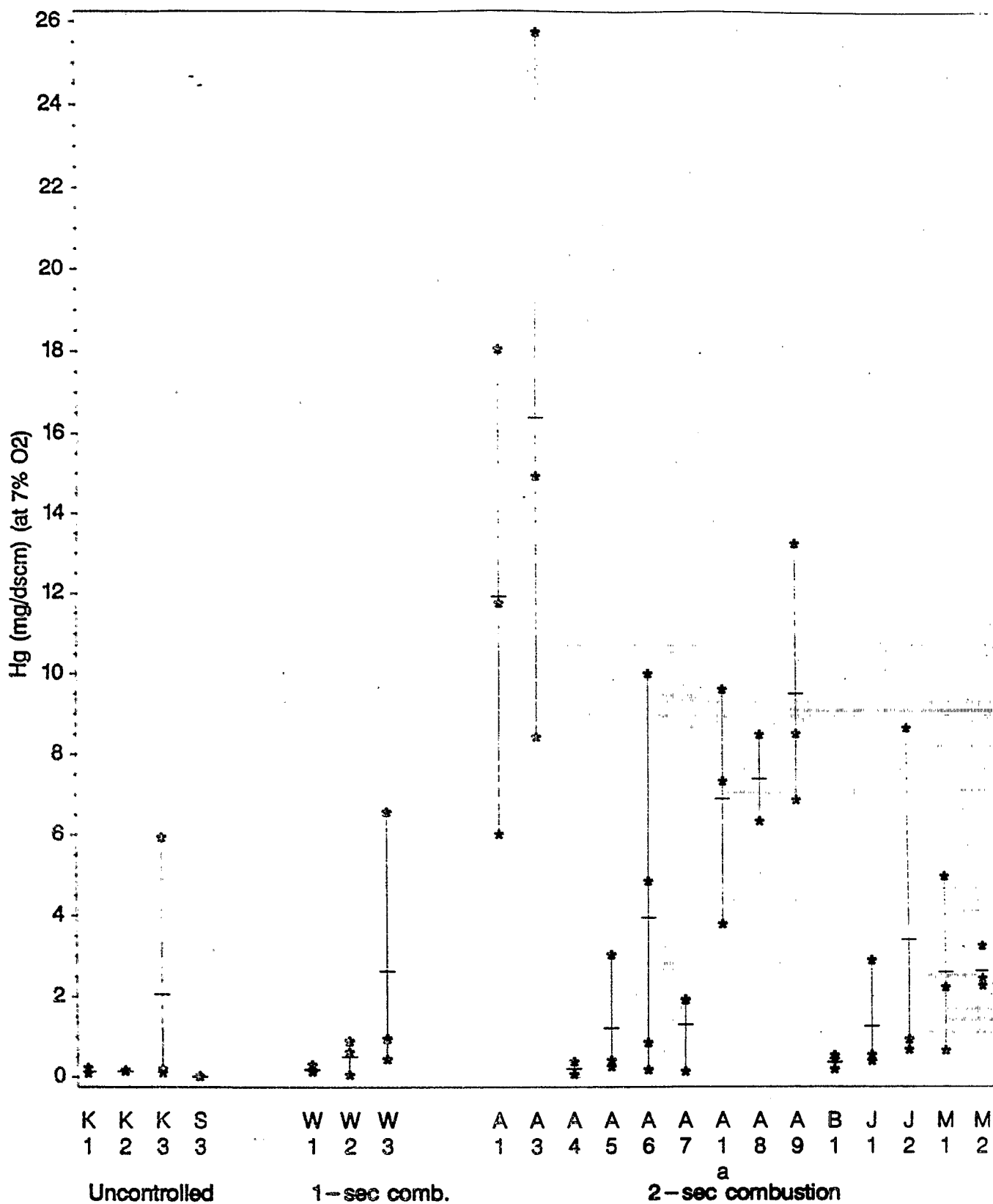


Figure 56. Hg emissions for continuous, intermittent, and batch MWI's with combustion controls).

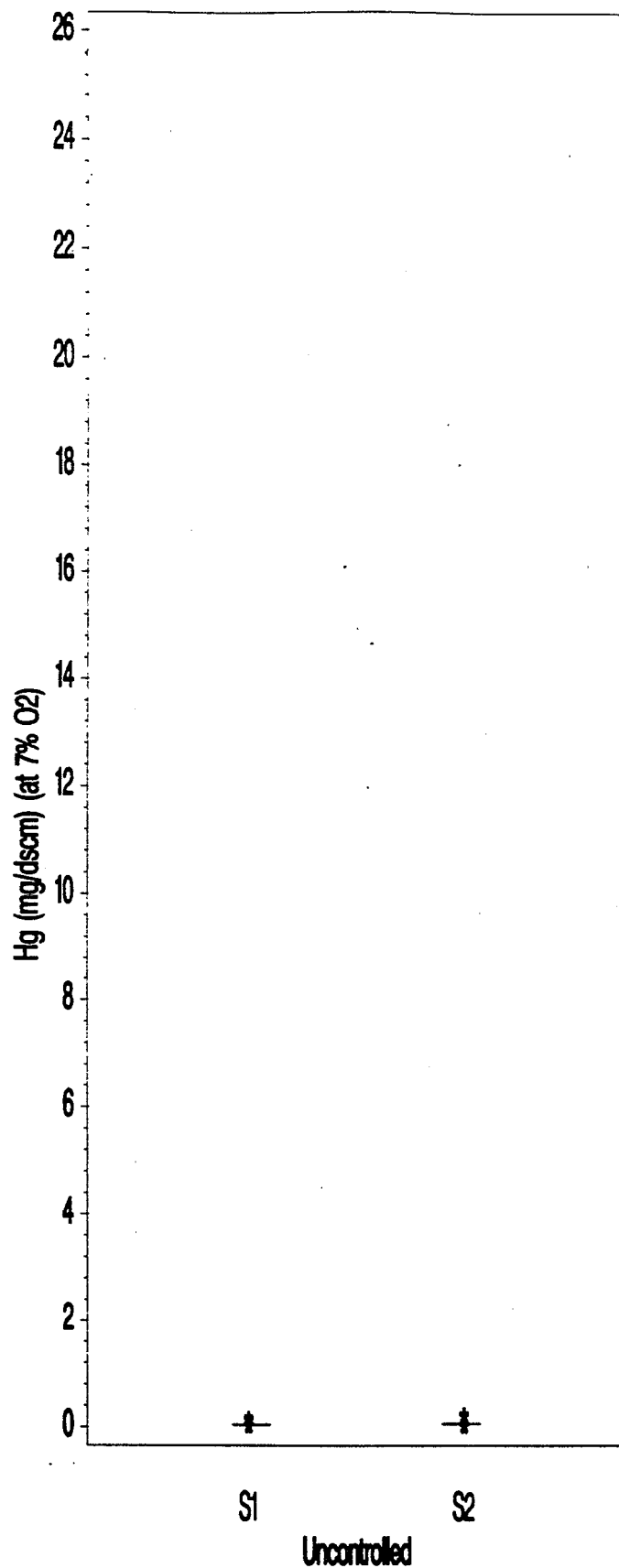


Figure 57. Hg emissions for uncontrolled pathological MWI's.

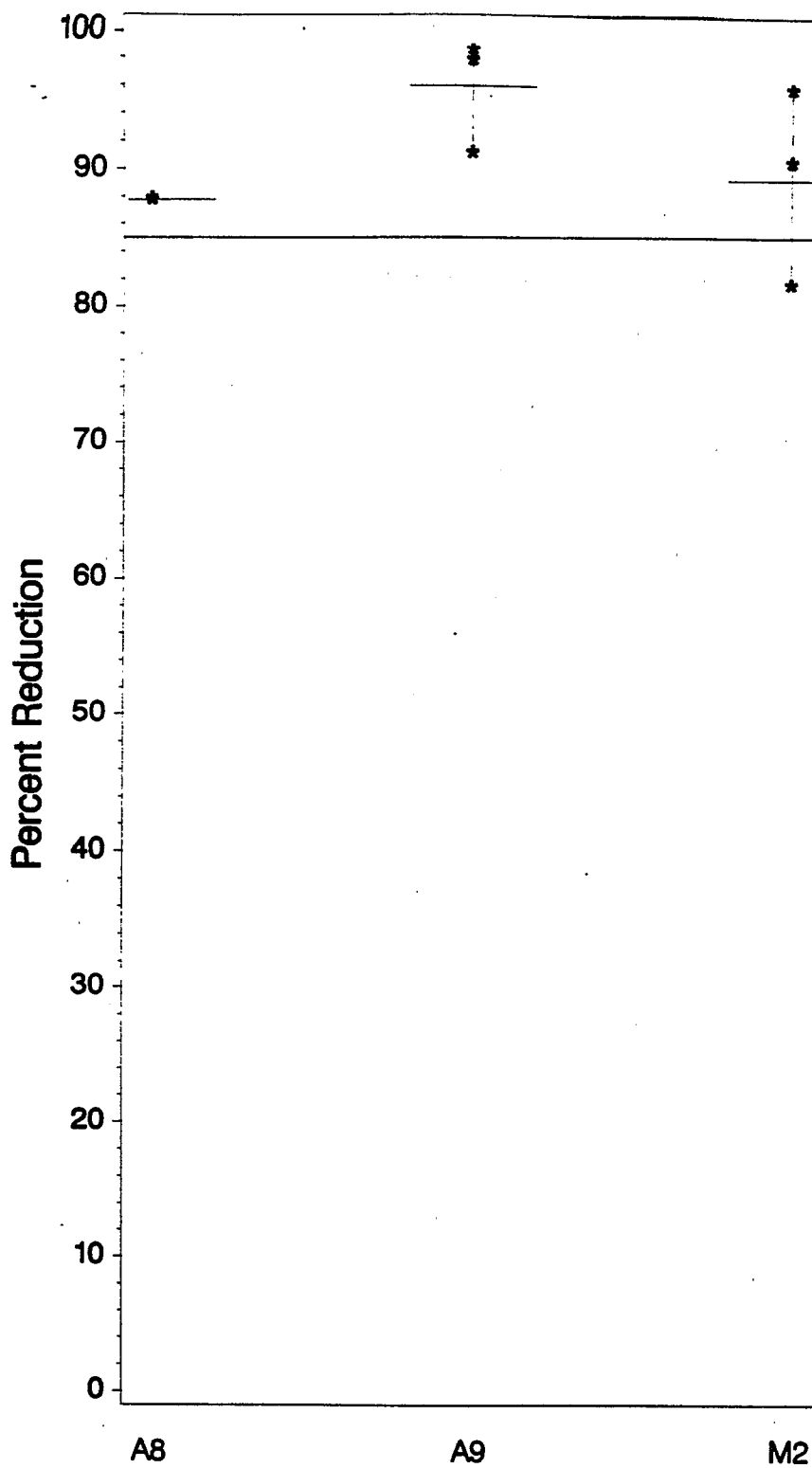
4.3.8.2 Add-On Controls--Hg. Test data from facilities A, B, J, and M (wet systems and fabric filter systems without carbon injection) showed no consistency in removing Hg emissions from MWI's. Control of Hg is dependent on the presence of carbon at relatively low temperature for a sufficient period of residence time. There is not enough carbon in an MWI exhaust gas stream to consistently reduce Hg. Therefore, emission limits have not been established for these devices. On the other hand, as shown in Figure 58, test data from facilities A and M show that injection of activated carbon into fabric filter systems can achieve at least 85-percent control of Hg. This reduction corresponds to 0.47 mg/dscm for a typical continuous, intermittent, or batch unit; (85-percent reduction from a typical uncontrolled level of 3.1 mg/dscm) and an emission level of 0.01 mg/dscm for pathological units (85-percent reduction from a typical uncontrolled level of 0.05 mg/dscm). It is not known whether carbon injection in a wet system will reduce Hg.

4.3.9 Nitrogen Oxides

Table 23 presents the NO_x emission limits under each control option for continuous, intermittent, batch, and pathological MWI's. Figures 59 and 60 present the data used to establish these emission limits.

4.3.9.1 Combustion Controls-- NO_x . Figure 59 presents NO_x emission data for continuous, intermittent, and batch MWI's burning general medical waste, and Figure 60 presents this data for pathological MWI's. Because emissions of NO_x are not affected by increased residence time in the secondary chamber, the 1-sec and 2-sec control options will not reduce emissions of NO_x .

4.3.9.2 Add-On Controls-- NO_x . None of the control systems evaluated reduced NO_x emissions. Therefore, NO_x emission limits have not been established for the add-on control technologies.



Fabric Filter w/ carbon

Figure 58. Hg emissions for continuous, intermittent, batch, and pathological MWI's with add-on controls.

TABLE 23. NO_x EMISSION LIMITS FOR CONTINUOUS, INTERMITTENT, BATCH, AND PATHOLOGICAL MWI'S

Control option	NO _x emission limits, ppm _{dv} at 7 percent O ₂	
	Continuous, intermittent, batch	Pathological
1-sec	NA ^a	NA ^a
2-sec	NA ^a	NA ^a
Wet systems ^b	NA ^a	NA ^a
FF/PB ^b	NA ^a	NA ^a
DI/FF ^b	NA ^a	NA ^a
SD/FF ^b	NA ^a	NA ^a
Fabric filter systems with carbon injection ^b	NA ^a	NA ^a

^aNo applicable limit.

^bIncludes 2-sec combustion.

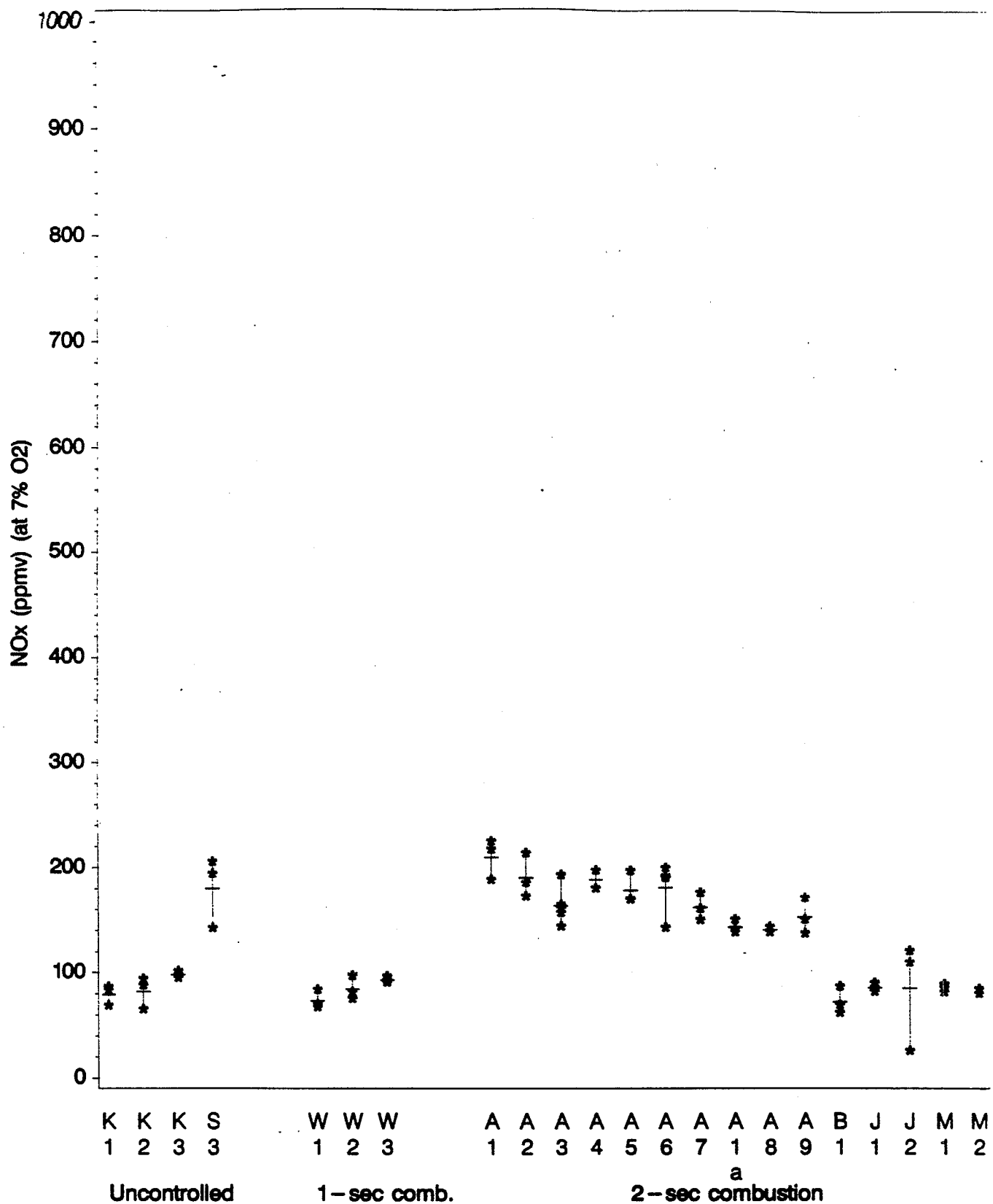


Figure 59. NO_x emissions for continuous, intermittent, and batch MWI's with combustion controls.

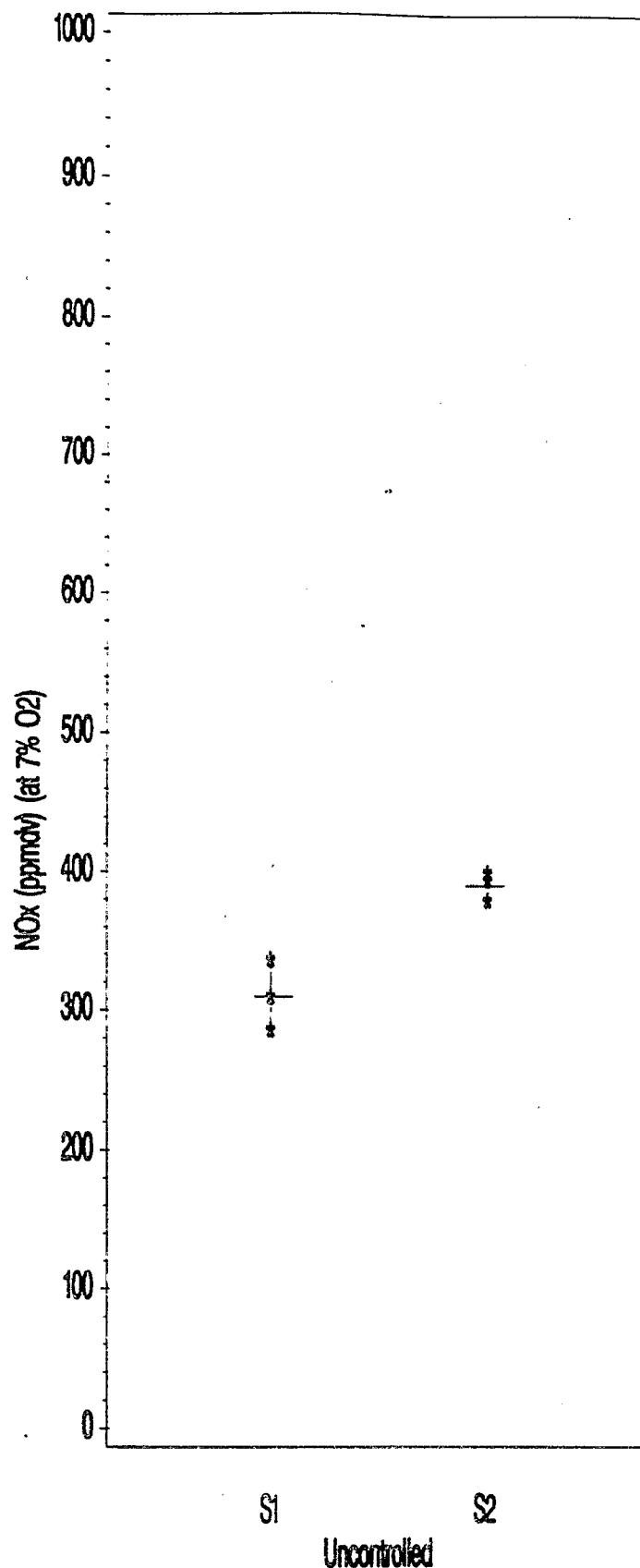


Figure 60. NO_x emissions for uncontrolled pathological MWI's.

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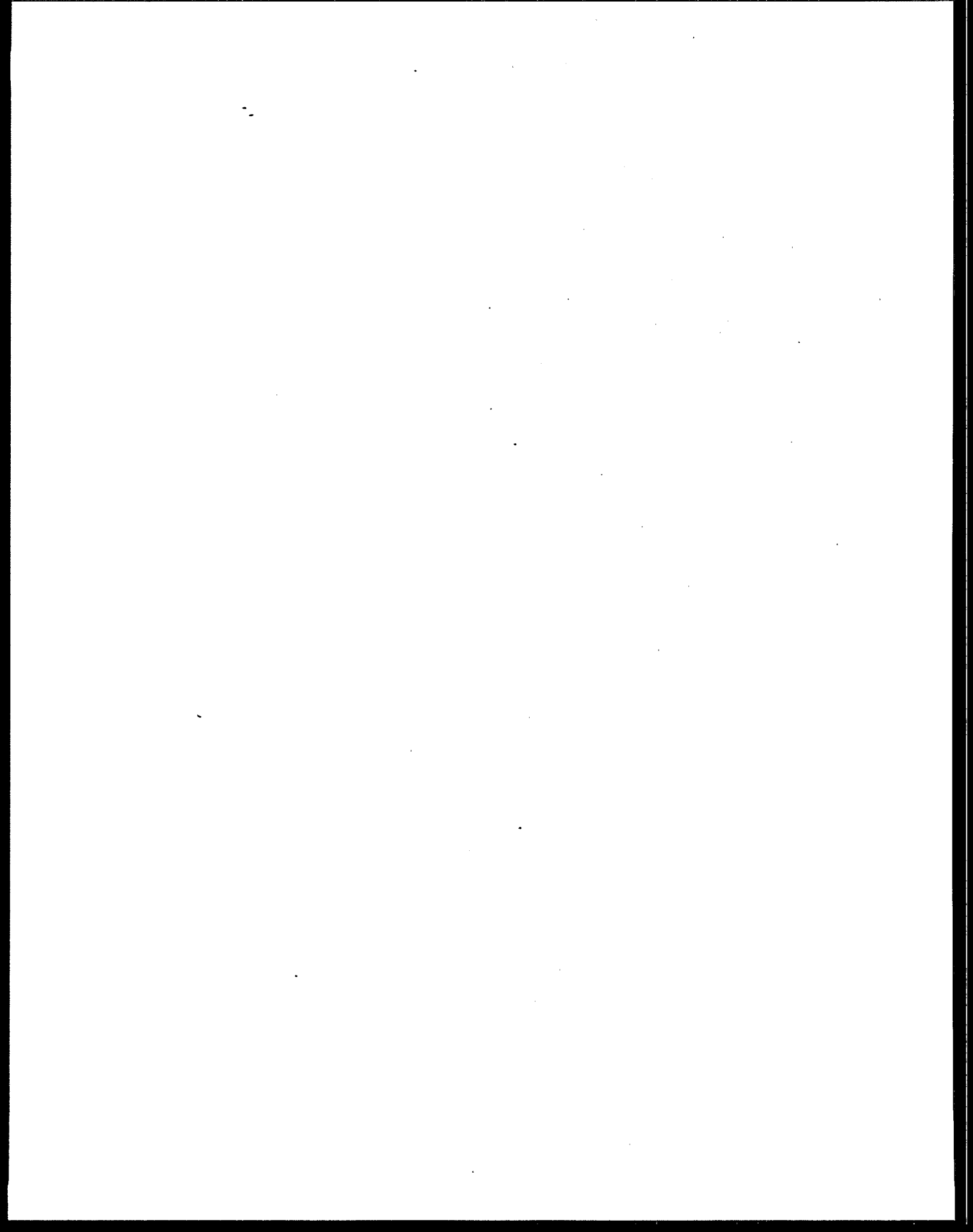
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APPENDIX A.

SUMMARY OF TEST PROGRAM OPERATING DATA

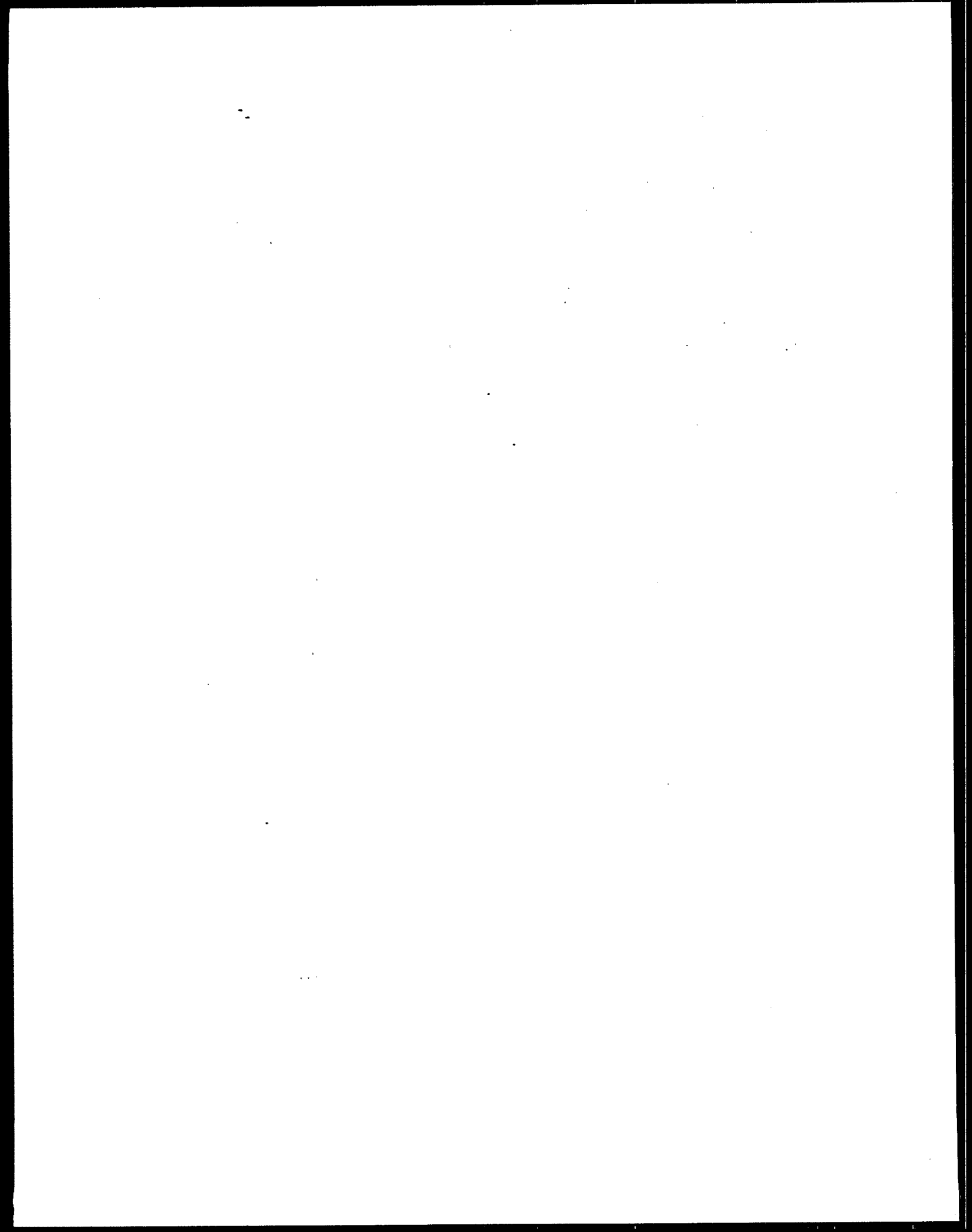


TABLE A-1. SUMMARY OF MWI PROCESS INFORMATION FOR EPA TEST PROGRAM

Facility	Test	Waste type ^a	Condition	Primary chamber temp., °F	Secondary chamber temp., °F ^b	Secondary/tertiary chamber temp., °F ^c	Residence time, sec	Charge rate, lb/hr	Exhaust gas O ₂ , percent
A	MB1_1523	G500	1	1271	1861	1843	1.29	524	13.0
A	MB1_2524	G500	1	1305	1825	1814	1.37	491	12.0
A	MB1_3531	G500	1	1282	1868	1832	1.32	551	13.1
A	MB3_1505	G500	2	1304	1607	1649	1.64	476	11.7
A	MB3_2507	G500	2	1296	1628	1644	1.65	424	11.7
A	MB3_3508	G500	2	1314	1621	1636	1.61	404	12.0
A	EB1_1517	G500	3	1272	2060	2024	1.23	578	12.0
A	EB1_2518	G500	3	1284	2062	2019	d	592	12.1
A	EB1_3521	G500	3	1275	2067	2005	1.20	623	11.2
A	EB1_4522	G500	3	1272	2050	2018	1.18	591	12.3
A	EB1_5525	G500	3	1302	2056	2020	1.17	561	11.6
A	MB131502	G100	4	1301	1829	1815	1.46	662	10.9
A	MB132515	G100	4	1254	1869	1818	1.31	579	13.2
A	EB6_1426	RB	5	1275	1658	1694	1.41	399	13.1
A	EB6_2427	RB	5	1314	1655	1679	1.44	457	13.0
A	EB6_3430	RB	5	1304	1651	1681	1.46	351	12.8
A	EB7_1509	RB	6	1354	1805	1804	1.57	492	11.5
A	EB7_2511	RB	6	1304	1838	1813	1.49	422	12.3
A	EB7_3514	RB	6	1253	1851	1823	1.52	425	11.6
A	EB7_4516	RB	6	1290	1835	1808	1.30	458	13.9
A	EB8_1529	RB	7	1312	2052	2013	1.24	536	10.7
A	EB8_2530	RB	7	1273	2075	2029	1.28	427	11.4
A	EB8_3601	RB	7	1286	2089	2014	1.26	483	11.6
A	B2_90791	General	1A	1281	1854	1839	1.53	577	13.5
A	B3_90991	General	1A	1220	1888	1846	1.11	506	13.8
A	B4_91091	General	1A	1291	1860	1831	1.19	565	14.9
A	B5_91191	General	8	1298	1856	1836	1.09	554	14.4

TABLE A-1. (continued)

Facility	Test	Waste type ^a	Condition	Primary chamber temp., °F	Secondary chamber temp., °F ^b	Secondary/tertiary chamber temp., °F ^c	Residence time, sec	Charge rate, lb/hr	Exhaust gas O ₂ , percent
A	B6_91291	General	8	1298	1883	1866	0.78	551	14.3
A	B7_91391	General	9	1294	1846	1827	1.40	591	14.4
A	B8_91491	General	9	1293	1850	1819	1.16	528	14.4
A	B9_91691	General	9	1305	1848	1823	1.18	525	12.9
B	MM1_1622	General	1	1732	2053	1737	1.66	803	13.5
B	MM1_3624	General	1	1729	2067	1802	1.67	784	12.5
B	MM1_4626	General	1	1824	2065	1799	1.82	874	12.7
B	MM1_5627	General	1	1663	2092	1803	d	845	12.3
J	J1_BR305	General	1	609		1788	1.45	30	8.8
J	J2_BD305	General	2	1196		1866	1.52	30	8.9
J	J3_BR307	General	1	600		1789	1.67	30	9.6
J	J4_BD307	General	2	1205		1846	1.91	30	2.6
J	J5_BR309	General	1	640		1799	1.77	31	11.2
J	J6_BD309	General	2	1197		1922	2.16	31	8.6
K	LM4_602	General	1	1504		1617	0.33	191	11.4
K	LM4R_604	General	1	1796		1764	0.33	189	14.0
K	LM6_605	General	1	1566		1660	0.36	190	11.9
K	LM1_530	General	2	1781		1764	0.32	220	10.9
K	LM2_531	General	2	1920		1831	0.31	250	10.1
K	LM3_601	General	2	1764		1781	0.30	294	14.3
K	LM7_606	General	3	1838		1679	0.36	266	13.0
K	LM8_607	General	3	1850		1640	0.35	296	14.6
K	LM9_608	General	3	1819		1657	0.36	285	13.2

TABLE A-1. (continued)

Facility	Test	Waste type ^a	Condition	Primary chamber temp., °F	Secondary chamber temp., °F ^b	Secondary/tertiary chamber temp., °F ^c	Residence time, sec	Charge rate, lb/hr	Exhaust gas O ₂ , percent
M	MW1_1118	General	1	1476		1798	2.23	723	11.1
M	MW2_1119	General	1	1457		1789	2.24	734	11.1
M	MW3-1120	General	1	1444		1787	2.16	789	10.6
M	MW4-1121	General	2	1451		1787	2.24	663	10.4
M	MW5_1122	General	2	1438		1786	2.21	638	10.8
M	MW6_1123	General	2	1445		1787	2.23	716	10.7
S	CC1_920	Path	1	1418		1485	0.12	106	15.8
S	CC3_922	Path	1	1499		1499	0.13	118	16.1
S	CC10_102	Path	1	1445		1474	0.12	100	15.7
S	CC5_924	Path	2	1444		1481	0.12	169	15.6
S	CC6_925	Path	2	1421		1462	0.12	144	15.7
S	CC9_928	Path	2	1445		1523	0.11	168	15.3
S	CC2_921	General	3	1397		1734	0.11	163	15.7
S	CC4_923	General	3	1555		1576	0.11	153	15.2
S	CC8_927	General	3	1458		1691	0.11	161	15.5
W	CF1_815	General	1	1885		2019	0.92	176	8.5
W	CF5_821	General	1	1611		1833	0.81	193	9.3
W	CF6_822	General	1	1569		1808	0.83	192	9.8
W	CF2_818	General	2	1988		2088	1.05	167	7.2
W	CF3_819	General	2	1857		2039	0.96	212	9.4
W	CF4_820	General	2	1585		1958	0.79	266	7.7
W	CF7_826	General	3	1673		1637	1.05	297	11.8
W	CF8_827	General	3	1637		1668	1.10	290	9.2
W	CF9_828	General	3	1659		1676	1.14	303	9.0

TABLE A-1. (continued)

^a G500 - General medical waste from 500-bed hospital.
G100 - General medical waste from 100-bed hospital.
RB - Red bag waste.
General - General medical waste.
Path - Pathological waste only.
^b Secondary chamber for those units with 3 chambers. Blank cells indicate these units that have a secondary chamber only.
^c Secondary chamber for those units with 2 chambers, and tertiary chamber for those units with three chambers.
^d Cannot be determined because flue gas flow rate was not measured.
^e Data not measured.

TABLE A-2. APCD OPERATING PARAMETERS FOR FACILITY A

Test	Condition	Boiler outlet temp., °F	FF inlet temp., °F	Boiler inlet temp., °F	Stack temp., °F	FF inlet flow rate, dscfm ^a	FF pressure drop (in. H ₂ O)	Lime rate, kg/hr	Carbon rate, lb/hr	Stoichio-metric ratio
MB1_1523	1	371	312	b	298	1,577	2.9	26.5	0.0	6.6
MB1_2524	1	371	311	b	282	1,458	2.9	14.6	0.0	3.8
MB1_3531	1	385	327	b	315	1,548	2.5	17.8	0.0	3.8
MB3_1505	2	377	314	b	298	1,285 ^c	2.4	17.8	0.0	6.3
MB3_2507	2	378	315	b	298	1,312 ^c	2.1	19.0	0.0	5.6
MB3_3508	2	376	315	b	300	1,332 ^c	2.1	17.6	0.0	5.9
EB1_1517	3	385	326	b	297	1,509	3.1	16.3	0.0	4.6
EB1_2518	3	379	319	b	b	b	3.2	15.7	0.0	b
EB1_3521	3	377	312	b	295	1,523	2.6	18.0	0.0	6.2
EB1_4522	3	378	321	b	b	1,585 ^d	3.0	22.7	0.0	b
EB1_5525	3	377	341	b	293	1,570 ^c	3.0	25.5	0.0	b
MB131502	4	b	326	b	b	1,349 ^d	2.3	22.7	0.0	10.6
MB132515	4	377	318	b	b	1,554	3.2	22.0	0.0	7.7
EB6_1426	5	717	327	b	b	1,536 ^d	2.4	20.0	0.0	5.8
EB6_2427	5	b	334	b	b	1,508 ^d	2.4	14.5	0.0	4.3
EB6_3430	5	b	329	b	b	1,469 ^d	2.4	15.9	0.0	3.9
EB7_1509	6	381	319	b	367	1,246	2.3	22.3	0.0	5.6
EB7_2511	6	377	310	b	298	1,365	2.4	20.7	0.0	5.1
EB7_3514	6	371	305	b	b	1,332 ^d	2.4	21.1	0.0	4.9
EB7_4516	6	378	320	b	298	1,586	3.2	29.1	0.0	8.5
EB8_1529	7	382	326	b	307	1,474	2.3	27.8	0.0	5.5
EB8_2530	7	398	342	b	315	1,460	2.5	28.2	0.0	3.8
EB8_3601	7	390	338	b	309	1,482	2.5	28.4	0.0	4.0
B2_90791	1A	b	303	1077	292	1,625	0.8	18.4	0.0	4.9

TABLE A-2. (continued)

Test	Condition	Boiler outlet temp., °F	FF inlet temp., °F	Boiler inlet temp., °F	Stack temp., °F	FF inlet flow rate, dscfm ^a	FF pressure drop (in. H ₂ O)	Lime rate, kg/hr	Carbon rate, lb/hr	Stoichiometric ratio
B3_90991	1A	b	334	1259	296	1,824	1.2	19.9	0.0	4.2
B4_91091	1A	b	294	1064	290	1,798	1.0	19.2	0.0	6.6
B5_91191	8	b	326	1298	286	1,865	1.3	18.7	1.0	3.1
B6_91291	8	b	335	1303	291	1,829	1.0	19.8	1.0	4.7
B7_91391	9	b	286	979	292	1,769	1.0	19.1	2.5	5.4
B8_91491	9	b	324	1299	280	1,754	1.2	18.1	2.5	3.9
B9_91691	9	b	337	1467	289	1,660	1.2	18.3	2.5	3.7

^aUnless noted, the flow rate shown is the average of the flow rates for the dioxin and metals trains.^bData not measured.^cThe flow rate is from only the dioxin train.^dThe flow rate is from only the metals train.

TABLE A-3. APCD OPERATING PARAMETERS FOR FACILITY B

Test	Condition	Scrubber inlet temp., °F	Scrubber outlet temp., °F	Pressure drop in H ₂ O
MM1_1622	1	545	136	31
MM1_3624	1	543	138	31
MM1_4626	1	541	142	31
MM1_5627	1	a	a	31

^aData not measured.

TABLE A-4. APCD OPERATING PARAMETERS AT FACILITY J

Test	Condition	FF inlet temp., °F	Scrubber inlet temp., °F	Scrubber pressure drop, in H ₂ O
J1 BR305	1	372	148	0.45
J2 BD305	2	373	134	0.36
J3 BA307	1	371	136	0.46
J4 BD307	2	375	135	0.40
J5 BR309	1	374	133	a
J6 BD309	2	376	a	a

^aData not available.

TABLE A-5. APCD OPERATING PARAMETERS FOR FACILITY M

Test	Condition	SD inlet temp., °F	FF inlet temp., °F	Stack temp., °F	Lime rate, lb/hr	Carbon rate, lb/hr	Stoichiometric ratio	SD inlet flow, scfm	Line slurry rate, gal/min
MW1_1118	1	408	278	285	23	0.0	a	3,370	0.7
MW2_1119	1	408	277	285	34	0.0	a	2,479	0.7
MW3_1120	1	407	278	285	37	0.0	3.4	3,531	0.8
MW4_1121	2	408	280	289	34	2.8	1.9	3,343	0.7
MW5_1122	2	409	283	281	31	2.5	2.3	3,416	0.7
MW6_1123	2	407	284	287	32	2.5	2.1	3,494	0.7

^aData not acceptable.

APPENDIX B.
TEST PROGRAM EMISSION DATA SUMMARY

TABLE B-1. POST-COMBUSTION EMISSION CONCENTRATIONS FOR CRITERIA POLLUTANTS
AND ACID GASES^a

Facility	Test	Condition	PM, gr/dscf	CO, ppmv	HCl, ppmv	SO ₂ , ppmv	NO _x , ppmv
A	MB1_1523	1	0.171	26.0	1,698	2.5	217
A	MB1_2524	1	0.054	16.6	1,591	9.6	188
A	MB1_3531	1	0.070	6.9	2,029	9.8	225
A	MB3_1505	2	b	8.2	1,278	19.2	214
A	MB3_2507	2	b	22.0	1,503	5.1	185
A	MB3_3508	2	b	26.6	1,336	16.3	172
A	EB1_1517	3	0.062	11.7	1,405	8.5	193
A	EB1_2518	3	b	19.0	2,770	0.4	161
A	EB1_3521	3	0.068	10.2	1,043	3.4	143
A	EB1_4522	3	0.058	20.0	1,575 ^c	12.1	164
A	EB1_5525	3	b	22.9	1,521 ^c	6.3	157
A	MB131502	4	0.074	20.8	839	18.5	180
A	MB132515	4	0.167	20.2	1,268	23.4	197
A	EB6_1426	5	0.050	1.9	1,526	5.4	196
A	EB6_2427	5	0.109	2.4	1,488	5.8	170
A	EB6_3430	5	0.138	1.6	1,785	8.2	169
A	EB7_1509	6	0.076	10.0	1,807	0.0	142
A	EB7_2511	6	0.212	14.7	1,831	1.0	199
A	EB7_3514	6	0.146	9.1	1,832	0.7	192
A	EB7_4516	6	0.068	7.2	1,620	6.4	190
A	EB8_1529	7	0.071	11.6	1,764	5.9	176
A	EB8_2530	7	0.087	32.5	2,865	2.8	150
A	EB8_3601	7	0.101	10.4	2,717	1.7	160
A	B2_90791	1A	0.073	6.5	1,616	5.4	75.7
A	B3_90991	1A	0.080	8.1	1,969	3.8	76.6
A	B4_91091	1A	0.078	4.9	1,422	0.4	59.3
A	B5_91191	8	0.079	4.6	2,646	2.5	67.9
A	B6_91291	8	0.069	3.9	1,810	2.2	66.3

TABLE B-1. (continued)

Facility	Test	Condition	PM, gr/dscf	CO, ppmv	HCl, ppmv	SO ₂ , ppmv	NO _x , ppmv
A	B7 91391	9	0.080	3.6	1,636	4.5	63.8
A	B8 91491	9	0.087	4.6	2,171	2.1	69.6
A	B9 91691	9	0.067	4.3	2,025	6.4	97.8
B	MM1_1622	1	0.074	30.3	1,352 ^c	1.8	86
B	MM1_3624	1	0.091	17.5	969 ^c	0.4	61
B	MM1_4626	1	0.135	25.9	473 ^c	1.1	c
B	MM1_5627	1	b	30.3	473 ^c	2.6	69
J	J1_BR305	1	0.004	7.8	92	7.4	90
J	J2_BD305	2	0.016	7.2	236	33.9	120
J	J3_BR307	1	0.004	7.3	158	11.2	81
J	J4_BD307	2	0.022	0.1	248	6.1	25
J	J5_BR309	1	0.004	2.1	87	6.7	85
J	J6_BD309	2	0.042	36.1	368	36.2	109
K	LM4_602	1	b	56.8	964	7.0	86
K	LM4R_604	1	0.168	99.1	b	11.2	68
K	LM6_605	1	0.104	70.8	1,020	4.5	83
K	LM1_530	2	0.095	93.6	1,040	11.6	65
K	LM2_531	2	0.169	172.2	866	15.8	88
K	LM3_601	2	0.182	63.2	2,370	7.8	93
K	LM7_606	3	0.441	1482.4	1,740	15.7	98
K	LM8_607	3	0.483	771.0	2,310	8.6	95
K	LM9_608	3	0.432	1954.1	1,450	30.9	101
M	MW1_1118	1	0.501	15.5	d	5.9	60.3
M	MW2_1119	1	0.528	8.5	d	9.5	57.0
M	MW3_1120	1	0.451	2.1	724	7.1	65.2
M	MW4_1121	2	0.555	6.4	1,224	17.8	63.5
M	MW5_1122	2	0.473	8.7	946	16.0	61.3

TABLE B-1. (continued)

Facility	Test	Condition	PM, gr/dscf	CO, ppmv	HCl, ppmv	SO ₂ , ppmv	NO _x , ppmv
M	MW6_1123	2	0.438	4.7	1,026	6.0	58.6
S	CC1_920	1	0.042	117.3	84	104.7	335
S	CC3_922	1	0.044	40.0	186	117.1	285
S	CC10_102	1	0.042	80.3	99	79.6	309
S	CC5_924	2	0.038	102.2	100	131.9	378
S	CC6_925	2	0.061	192.7	81	133.7	398
S	CC9_928	2	0.048	105.0	153	106.8	393
S	CC2_921	3	0.181	399.8	1,277	36.7	205
S	CC4_923	3	0.931	2753.4	1,583	43.8	142
S	CC8_927	3	0.243	445.4	1,753	46.4	194
W	CF1_815	1	0.112	89.7	1,225	26.0	83
W	CF5_821	1	0.095	180.4	1,070	16.4	70
W	CF6_822	1	0.042	21.0	937	10.1	67
W	CF2_818	2	0.095	245.9	1,003	17.5	75
W	CF3_819	2	0.278	584.9	1,360	38.5	81
W	CF4_820	2	0.197	474.7	1,590	29.2	96
W	CF7_826	3	0.158	158.8	1,746	16.5	92
6W	CF8_827	3	0.223	491.8	1,353	32.1	90
W	CF9_828	3	0.209	427.3	1,490	21.1	96

^aAll concentrations corrected to 7 percent O₂.^bData not measured.^cBased on HCl CEM.^dData not reported because the data are not within acceptable control limits.

TABLE B-2. POST-COMBUSTION EMISSION CONCENTRATIONS FOR
CDD/CDF AND METALS^a

Facility	Test	Condition	CDD/CDF, ng/dscm	Cd, µg/dscm	Pb, µg/dscm	Hg, µg/dscm
A	MB1_1523	1	665	365	3,441	18,007.9
A	MB1_2524	1	410	283	2,928	11,715.5
A	MB1_3531	1	394	358	3,530	5,992.2
A	MB3_1505	2	229	b	b	b
A	MB3_2507	2	531	b	b	b
A	MB3_3508	2	505	b	b	b
A	EB1_1517	3	250	343	3,730	14,848.5
A	EB1_2518	3	b	b	b	b
A	EB1_3521	3	485	729	3,509	25,708.3
A	EB1_4522	3	b	603	2,994	8,403.2
A	EB1_5525	3	318	b	b	b
A	MB131502	4	b	143	2,155	363.5
A	MB132515	4	271	420	2,549	43.1
A	EB6_1426	5	b	144	4,911	402.0
A	EB6_2427	5	b	102	4,625	3,012.5
A	EB6_3430	5	b	190	6,534	238.9
A	EB7_1509	6	691	260	6,855	9,960.8
A	EB7_2511	6	317	329	7,642	154.6
A	EB7_3514	6	b	263	8,629	842.7
A	EB7_4516	6	553	211	3,927	4,816.3
A	EB8_1529	7	319	190	4,685	1,891.0
A	EB8_2530	7	484	201	5,156	1,906.1
A	EB8_3601	7	574	239	5,766	116.7
A	B2_90791	1A	158	396	952	9,580.0
A	B3_90991	1A	274	364	2,180	7,300.0
A	B4_91091	1A	279	446	1,377	3,770.0
A	B5_91191	8	306	346	2,600	6,300.0
A	B6_91291	8	517	3,520	1,620	8,460.0
A	B7_91391	9	471	241	459	8,479.8
A	B8_91491	9	429	1,210	2,280	6,830.0
A	B9_91691	9	347	690	1,760	13,200.0
B	MM1_1622	1	1,554	498	3,810	167.0
B	MM1_3624	1	1,388	285	2,620	414.0
B	MM1_4626	1	1,411	373	3,520	516.0
B	MM1_5627	1	b	b	b	b

TABLE B-2. (continued)

Facility	Test	Condition	CDD/CDF, ng/dscm	Cd, µg/dscm	Pb, µg/dscm	Hg, µg/dscm
J	J1_BR305	1	4	44	718	527.0
J	J2_BD305	2	5	152	5,187	654.0
J	J3_BR307	1	3	23	634	2,862.0
J	J4_BD307	2	599	252	5,028	8,620.0
J	J5_BR309	1	94	22	1,063	383.0
J	J6_BD309	2	3,036	216	6,412	908.0
K	LM4_602	1	4,818	b	b	b
K	LM4R_604	1	b	163	7,012	208.8
K	LM6_605	1	6,325	173	1,549	75.6
K	LM1_530	2	3,247	110	1,316	152.3
K	LM2_531	2	8,336	392	1,855	124.5
K	LM3_601	2	10,213	140	2,439	139.7
K	LM7_606	3	48,571	430	3,482	5,926.0
K	LM8_607	3	27,769	478	2,121	85.4
K	LM9_608	3	30,243	202	2,416	172.4
M	MW1_1118	1	144	494	3,801	2,200.0
M	MW2_1119	1	129	369	3,570	643.0
M	MW3_1120	1	301	548	3,590	4,930.0
M	MW4_1121	2	242	524	4,250	2,420.0
M	MW5_1122	2	292	402	4,730	2,240.0
M	MW6_1123	2	63	549	4,260	3,220.0
S	CC1_920	1	279	16	512	4.3
S	CC3_922	1	1,994	504	814	<0.9
S	CC10_102	1	468	<1	0	116.2
S	CC5_924	2	427	13	329	182.5
S	CC6_925	2	157	26	202	<0.7
S	CC9_928	2	1,144	22	389	<0.5
S	CC2_921	3	12,728	55	2,380	10.7
S	CC4_923	3	40,969	42	1,210	5.2
S	CC8_927	3	20,457	67	2,050	-0.7
W	CF1_815	1	3,084	296	4,754	286.3
W	CF5_821	1	3,562	336	6,372	120.0
W	CF6_822	1	539	209	2,864	146.4
W	CF2_818	2	4,070	333	4,476	613.0

TABLE B-2. (continued)

Facility	Test	Condition	CDD/CDF, ng/dscm	Cd, µg/dscm	Pb, µg/dscm	Hg, µg/dscm
W	CF3_819	2	8,102	461	7,537	880.7
W	CF4_820	2	5,671	361	6,741	35.7
W	CF7_826	3	5,215	731	4,316	6,543.4
W	CF8_827	3	2,679	619	7,710	939.4
W	CF9_828	3	7,198	401	4,008	432.7

^aAll concentrations corrected to 7 percent O₂.

^bData not measured.

TABLE B-3. SUMMARY OF POST-APCS CONCENTRATIONS AND CONTROL EFFICIENCIES^a

Facility	Test	Condition	Post-APCS PM, gr/dscf	PM efficiency, percent	Post-APCS HCl, ppmv	HCl efficiency, percent	Post-APCS CDD/CDF, ng/dscm	CDD/CDF efficiency, percent	Post-APCS Cd, µg/dscm	Cd efficiency, %	Post- APCS Pb, µg/dscm	Pb efficiency, percent	Post-APCS Hg, µg/dscm	Hg efficiency, percent
A	MB1_1523	1	0.068	61.6	11.5	99.4	1,173	b	<1.5	>99.6	22.2	99.4	5,614.0	69.9
A	MB1_2524	1	0.002	97.1	22.7	98.7	323	35.1	<1.4	>99.5	24.9	99.2	7,886.0	33.9
A	MB1_3531	1	0.003	96.1	105.9	94.6	447	b	1.9	99.5	22.2	99.4	6,215.3	b
A	MB3_1505	2	c	c	25.1	98.0	177	21.8	c	c	c	c	c	c
A	MB3_2507	2	c	c	60.2	96.1	508	7.9	c	c	c	c	c	c
A	MB3_3508	2	c	c	36.3	97.0	358	22.8	c	c	c	c	c	c
A	EB1_1517	3	0.002	96.4	110.5	92.9	306	b	<1.8	>99.5	24.7	99.4	10,999.7	32.1
A	EB1_2518	3	c	c	113.8	95.9 ^d	c	c	c	c	c	c	c	c
A	EB1_3521	3	0.002	97.6	22.8	97.8	405	17.9	<5.0	>99.3	24.9	99.3	17,257.9	33.7
A	EB1_4522	3	0.002	97.1	c	c	c	c	1.8	99.8	25.4	99.3	3,764.1	62.5
A	EB1_5525	3	c	c	c	c	247	31.8	c	c	c	c	c	c
A	MB131502	4	c	c	11.1	98.7 ^d	c	c	c	c	c	c	c	c
A	MB132515	4	c	c	26.3	97.9 ^d	c	c	c	c	c	c	c	c
A	EB6_1426	5	e	e	25.4	98.3 ^d	c	c	e	e	e	e	e	e
A	EB6_2427	5	0.056	53.9	179.8	89.1	c	c	<1.6	>98.4	20.6	99.6	4,314.4	b
A	EB6_3430	5	0.088	38.0	119.9	93.5	c	c	<1.8	>99.1	12.9	99.8	291.5	b
A	EB7_1509	6	e	e	42.2	97.9	213	72.3	e	e	e	e	e	e
A	EB7_2511	6	e	e	109.9	93.9	242	22.1	e	e	e	e	e	e
A	EB7_3514	6	0.003	98.2	125.5	93.2	c	c	<1.4	>99.5	20.4	99.8	954.5	b
A	EB7_4516	6	0.002	97.6	13.7	99.2	355	44.7	<1.6	>99.2	19.6	99.5	3,327.8	33.3
A	EB8_1529	7	0.020	73.8	57.0	97.0	256	29.7	2.8	98.6	59.0	98.8	4,604.2	b
A	EB8_2530	7	0.002	97.8	e	e	657	b	1.5	99.3	20.9	99.6	9,925.3	b
A	EB8_3601	7	0.002	98.6	77.5	97.4	721	b	<1.4	>99.5	20.9	99.7	423.9	b
A	B2_90791	1A	0.004	93.2	102.7	92.8	137	b	0.9	99.7	2.9	99.7	9,930.0	b
A	B3_90991	1A	0.002	97.9	97.0	95.0	184	31.8	1.7	99.5	3.0	99.9	8,620.0	b
A	B4_91091	1A	0.002	96.9	8.7	99.3	74	69.8	2.3	99.4	6.8	99.4	3,670.0	b
A	B5_91191	8	0.002	96.3	62.1	97.4	20	93.3	2.1	99.3	6.0	99.7	767.2	85.3
A	B6_91291	8	0.002	96.8	6.7	99.6	13	98.7	2.4	99.9	3.8	99.8	1,040.0	87.4

TABLE B-3. (continued)

Facility	Test	Condition	Post-APCS PM, g/dscf	PM efficiency, percent	Post-APCS HCl, ppmv	HCl efficiency, percent	Post-APCS CDD/CDF, ng/dscm	CDD/CDF efficiency, percent	Post-APCS Cd, µg/dscm	Cd efficiency, %	Post- APCS Pb, µg/dscm	Pb efficiency, percent	Post-APCS Hg, µg/dscm	Hg efficiency, percent
A	B7_91391	9	0.002	97.0	30.7	97.6	8	98.0	1.0	99.5	1.9	99.5	758.9	88.6
A	B8_91491	9	0.004	94.8	19.4	99.0	7	98.3	28.3	97.3	11.2	99.4	105.1	98.2
A	B9_91691	9	0.002	97.2	72.3	95.8	6	98.1	1.8	99.7	7.6	99.5	303.1	97.2
B	MM1_1622	1	0.036	49.7	0.0 ^f	100.0 ^f	483	66.3	298.9	36.6	2,089.4	42.0	38.3	63.2
B	MM1_3624	1	0.066	g	1.3 ^f	99.9 ^f	424	66.5	171.8	g	1,439.5	g	580.3	g
B	MM1_4626	1	0.037	69.6	2.8 ^f	99.8 ^f	313	75.5	182.4	45.0	1,707.0	45.4	259.2	43.7
B	MM1_5627	1	c	c	c	c	c	c	c	c	c	c	c	c
J	J1_BR305	1	<0.001	>94	16.8	91.8	6,543	b	6.6	93.7	11.9	99.3	436.0	65.3
J	J3_BR307	1	0.002	73.7	26.2	88.6	8,427	b	3.2	92.0	19.7	98.2	898.0	82.0
J	J5_BR309	1	0.002	56.8	11.8	89.7	5,516	b	2.1	92.4	14.4	98.9	58.9	87.6
J	J2_BD305	2	0.001	97.6	81.1	81.8	3,320	b	3.4	98.9	72.5	99.3	525.0	59.7
J	J4_BD307	2	0.002	94.4	111.3	68.9	4,061	b	4.1	98.9	46.5	99.4	2,541.0	79.7
J	J6_BD309	2	0.004	95.0	18.7	97.0	1,818	64.1	7.2	98.1	116.0	99.0	486.0	69.5
M	MW1_1118	1	0.001	99.9	7.6	c	65	55.8	2.1	99.6	9.4	99.9	1,200.0	50.8
M	MW2_1119	1	0.001	99.8	6.9	c	16	87.5	0.9	99.8	1.2	100.0	696.9	b
M	MW3_1120	1	0.009	98.1	4.5	99.4	16	94.7	2.4	99.6	11.4	99.7	4,040.3	24.4
M	MW4_1121	2	0.001	99.9	26.1	98.1	3	98.6	0.9	99.9	2.8	99.9	446.2	83.9
M	MW5_1122	2	0.002	99.6	-0.0	100.0	3	98.8	0.9	99.8	3.0	99.9	97.0	95.9
M	MW6_1123	2	0.001	99.8	-0.0	100.0	3	94.9	0.7	99.9	1.8	100.0	308.9	90.6

^aAll concentrations corrected to 7 percent O₂. All pollutant removal efficiencies are based on mass emission rates, unless noted.

^bOutlet concentration is higher than inlet concentration.

^cData not measured.

^dEfficiency based on concentration, not mass.

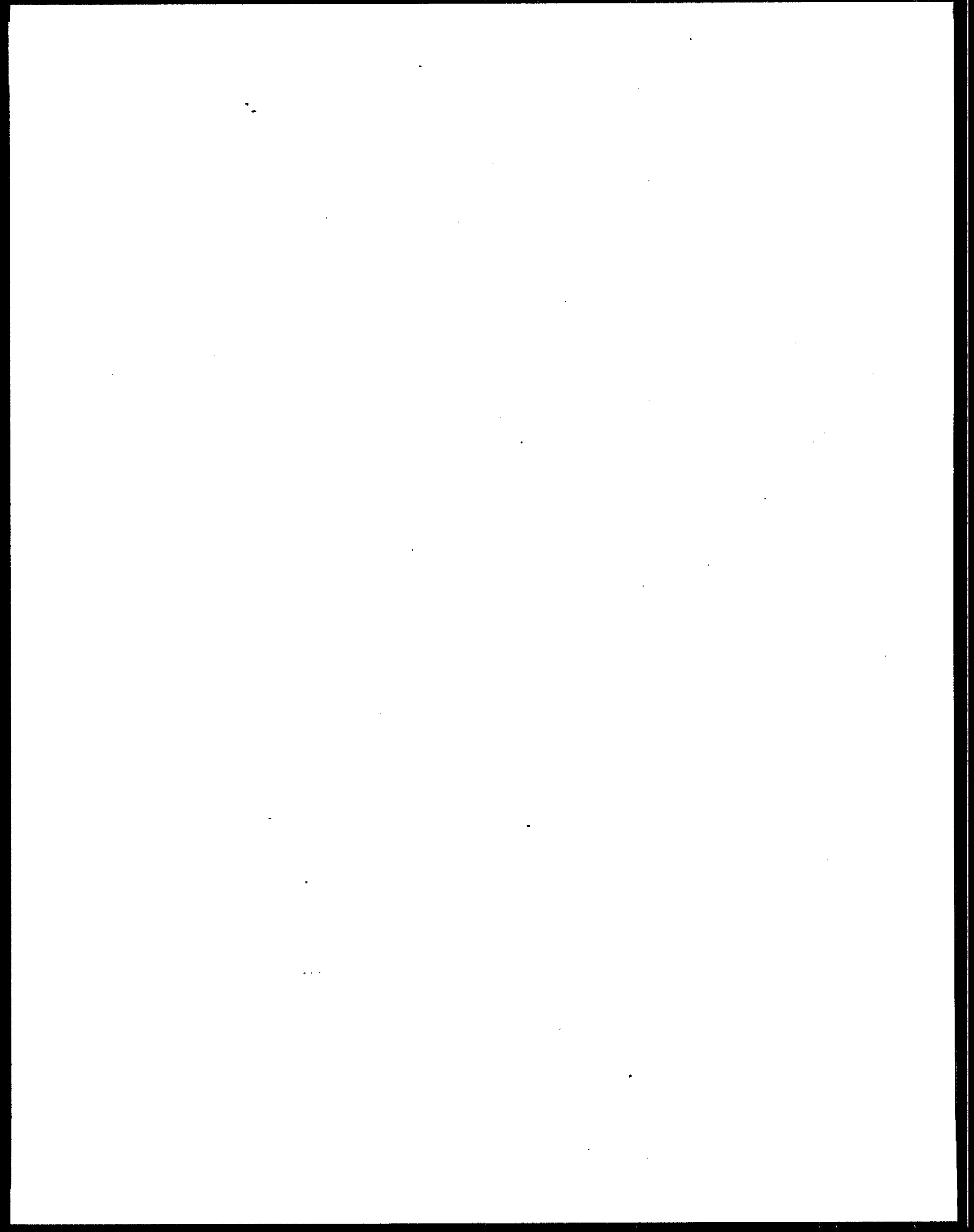
^eData not acceptable.

^fBased on HCl CEM.

^gData not available.

APPENDIX C.

GRAPHS OF POST-COMBUSTION EMISSION DATA



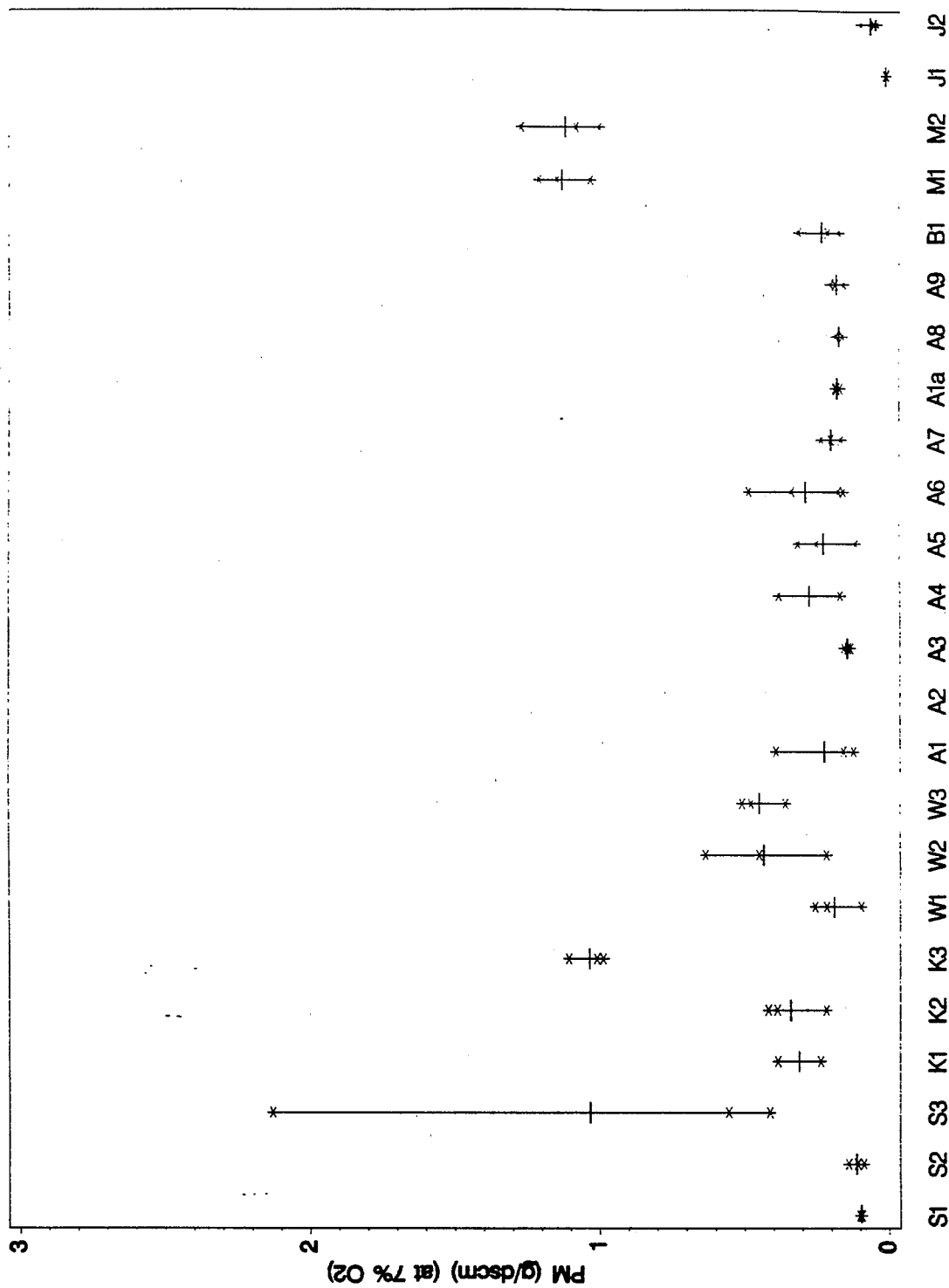


Figure C-1. Schematic plot of post-combustion PM concentrations.

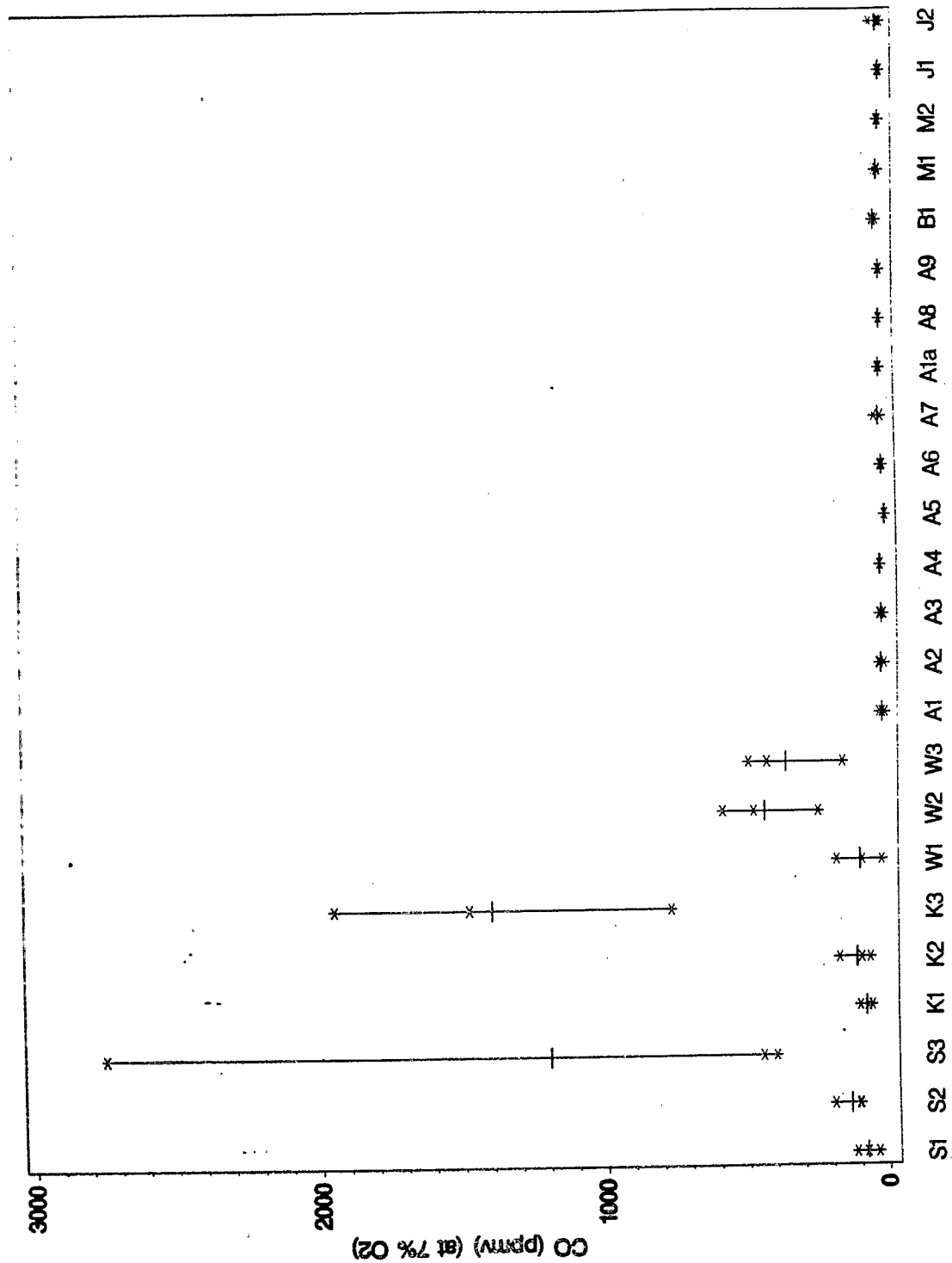


Figure C-2. Schematic plot of mean post-combustion CO concentrations.

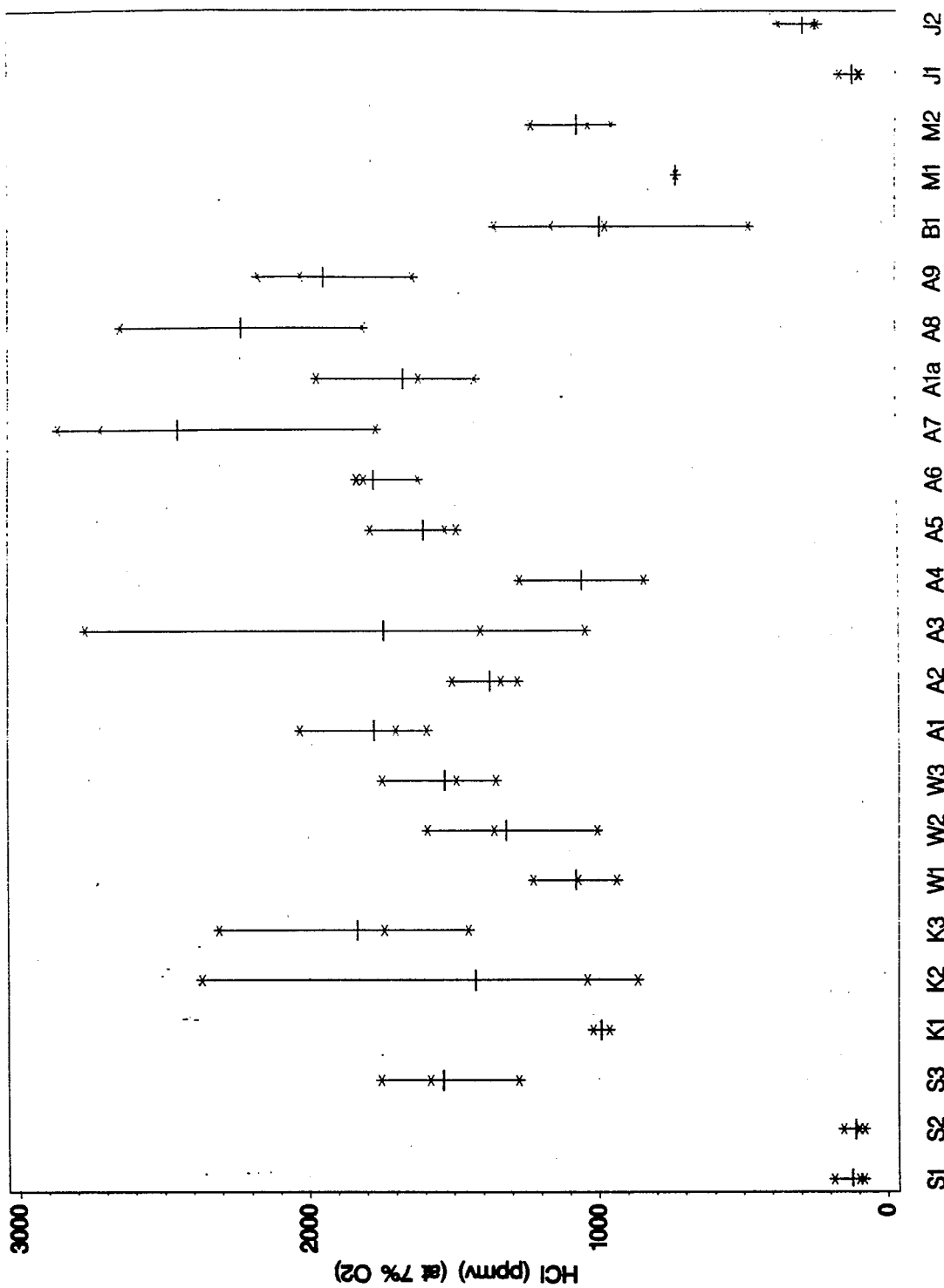


Figure C-3. Schematic plot of post-combustion HCl concentrations.

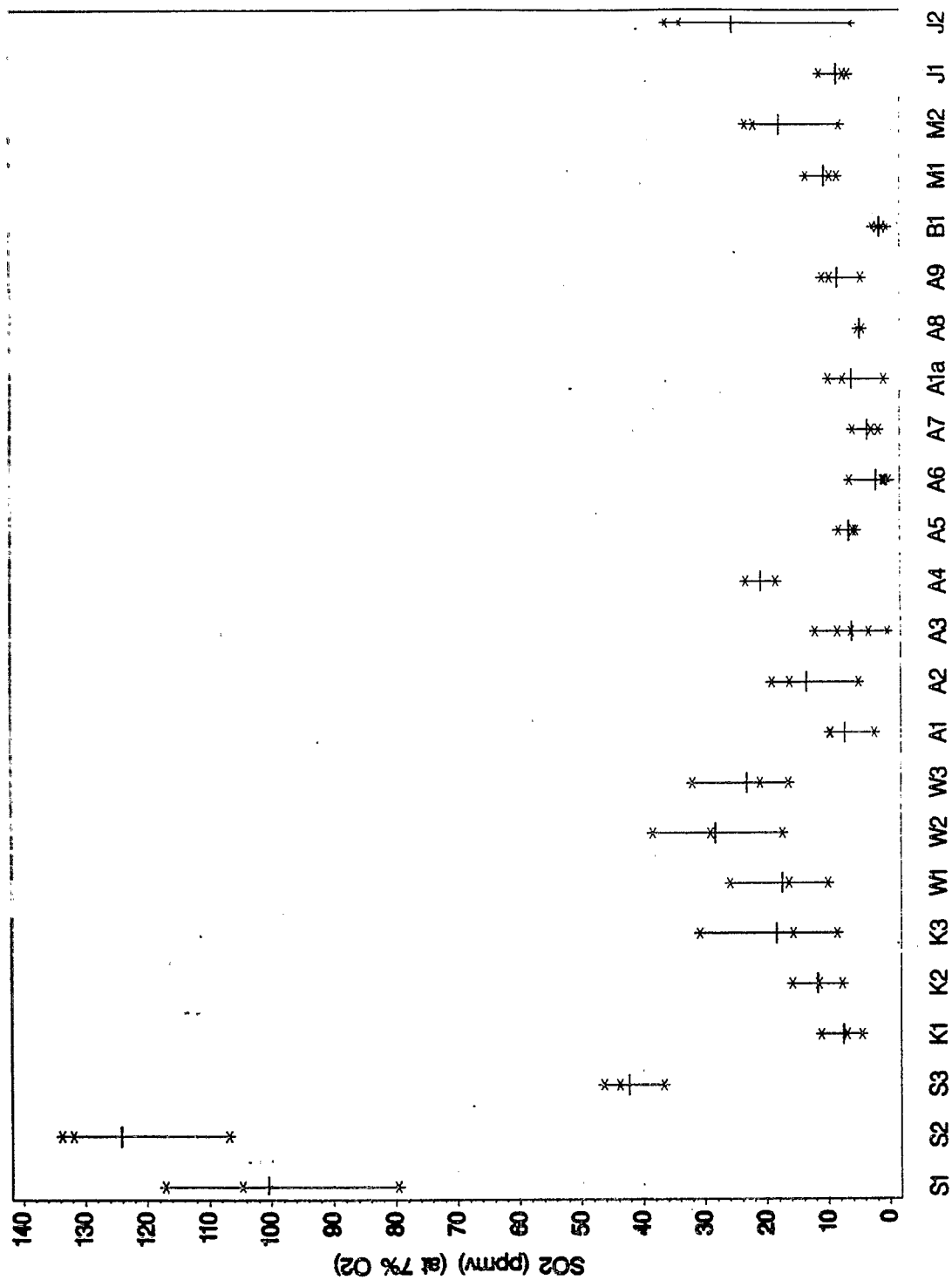


Figure C-4. Schematic plot of mean post-combustion SO₂ concentrations.

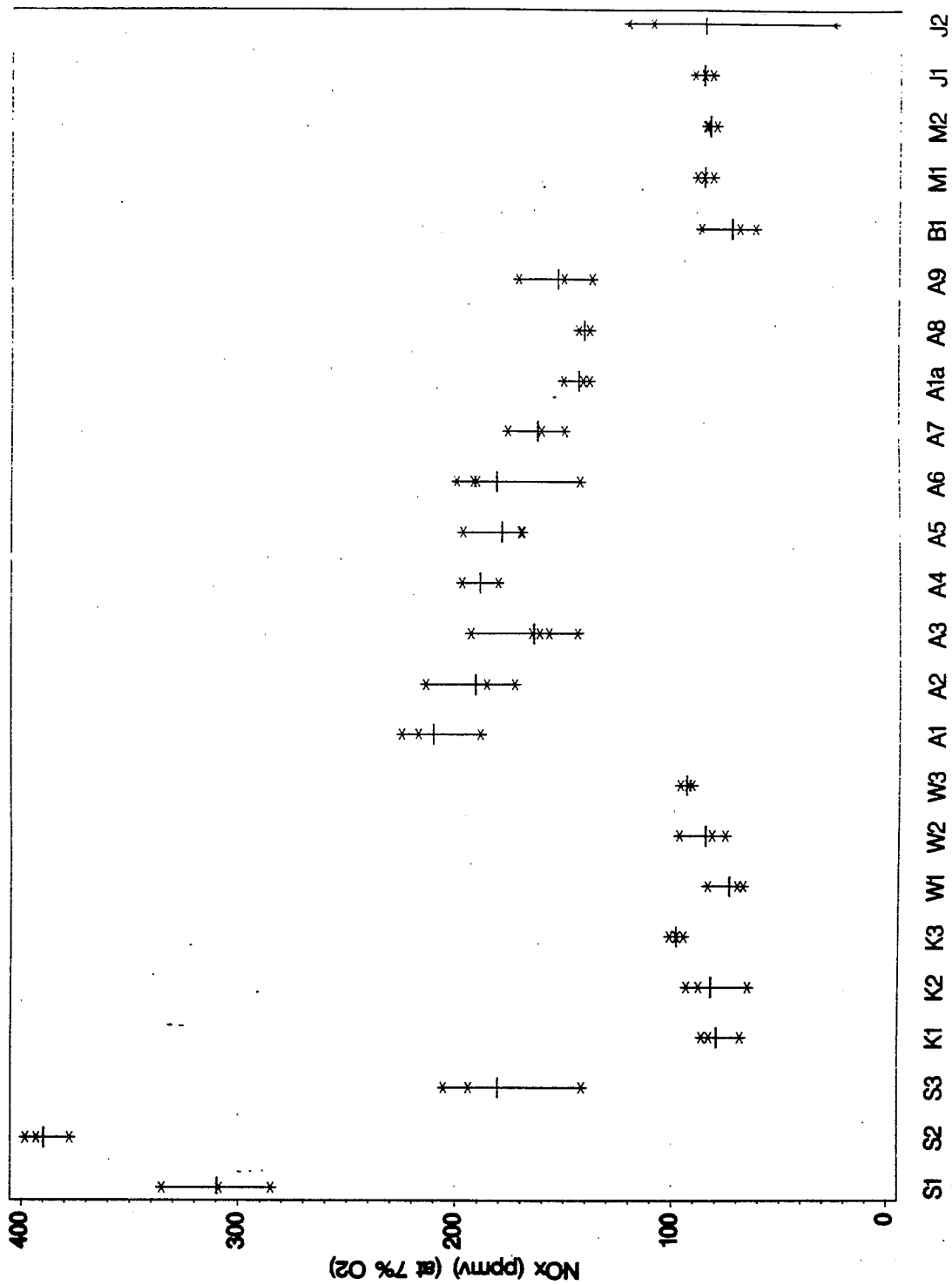


Figure C-5. Schematic plot of mean post-combustion NO_x concentrations.

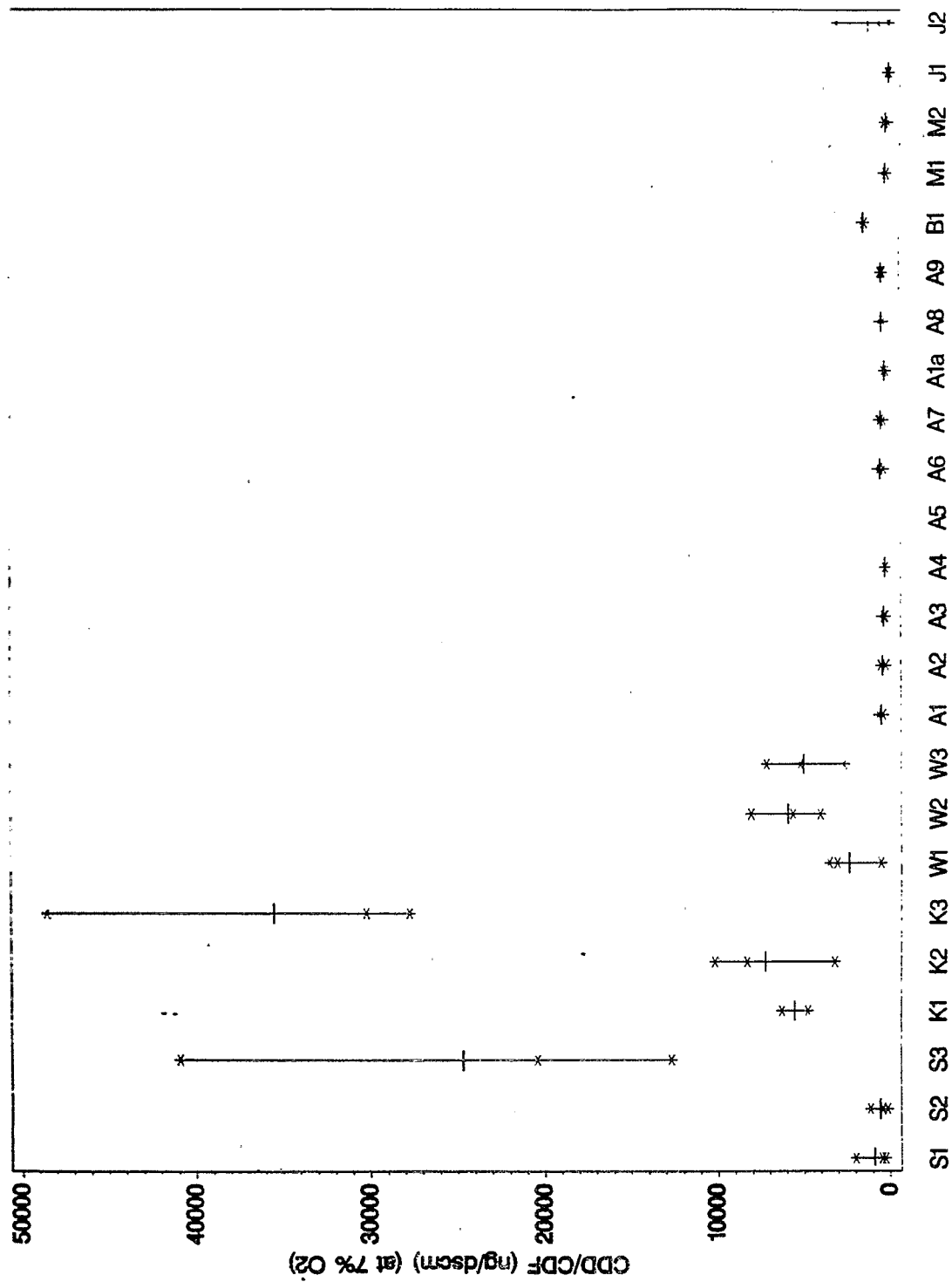


Figure C-6. Schematic plot of post-combustion CDD/CDF concentrations.

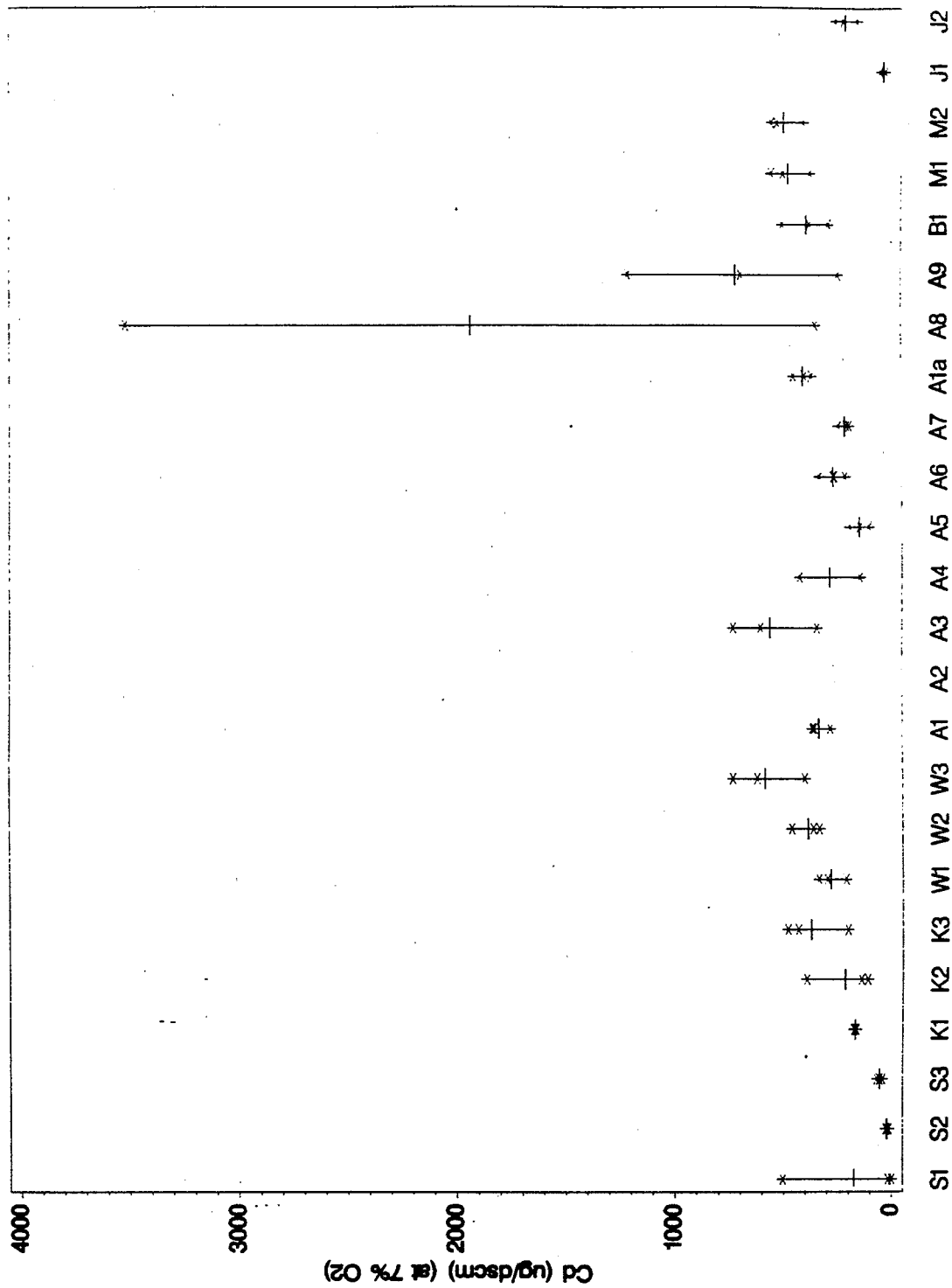


Figure C-7. Schematic plot of post-combustion Cd concentrations.

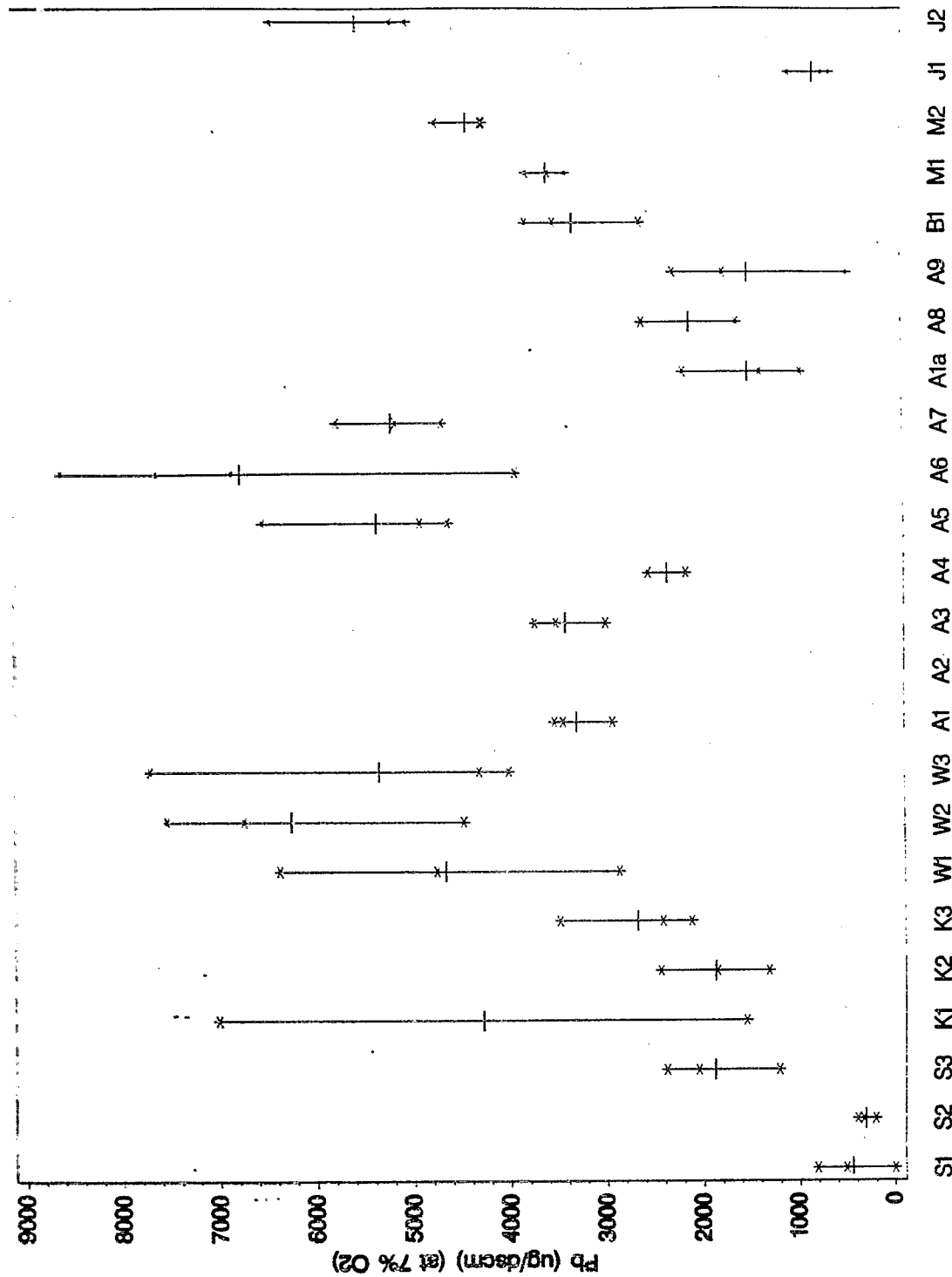


Figure C-8. Schematic plot of post-combustion Pb concentrations.

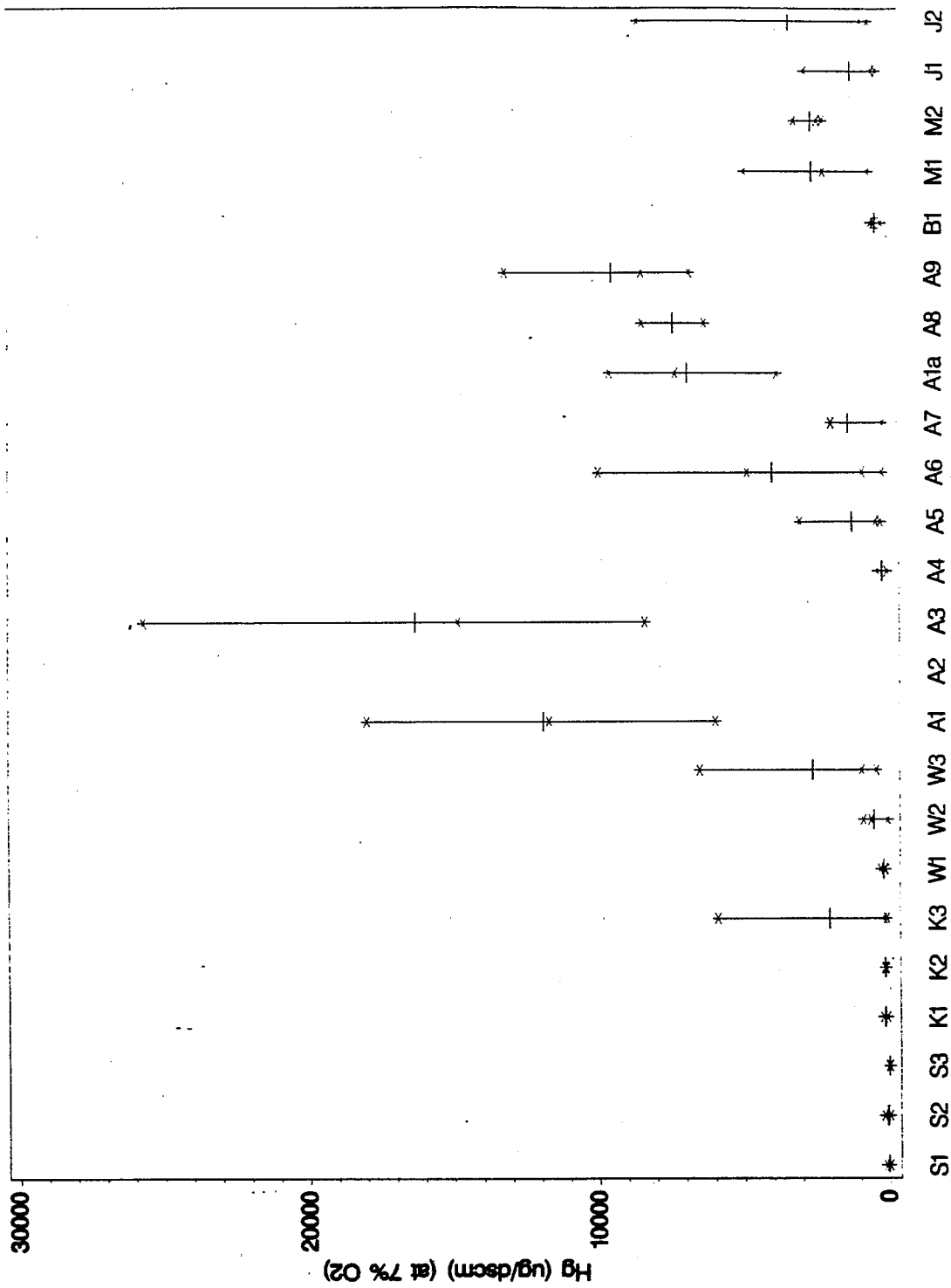
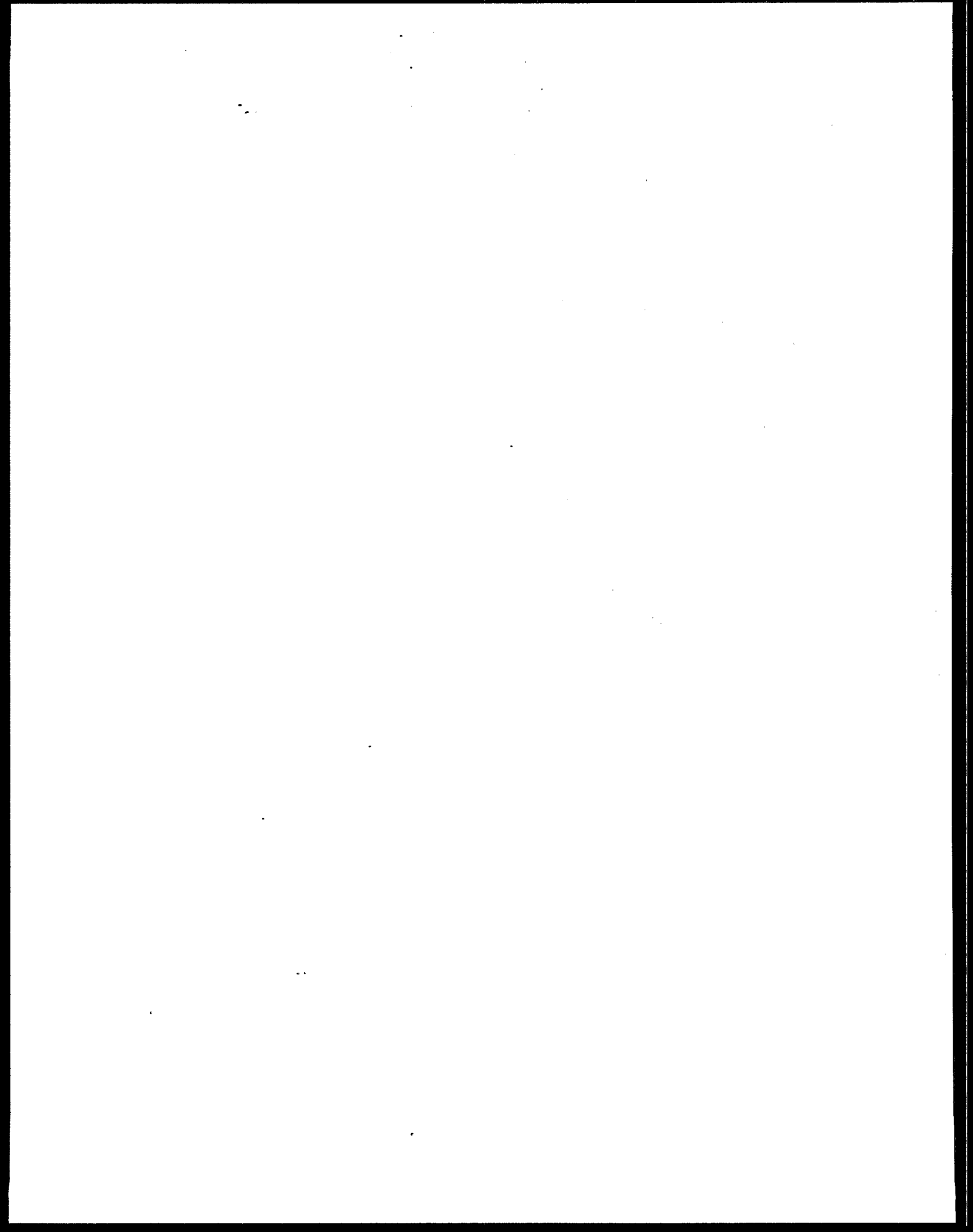
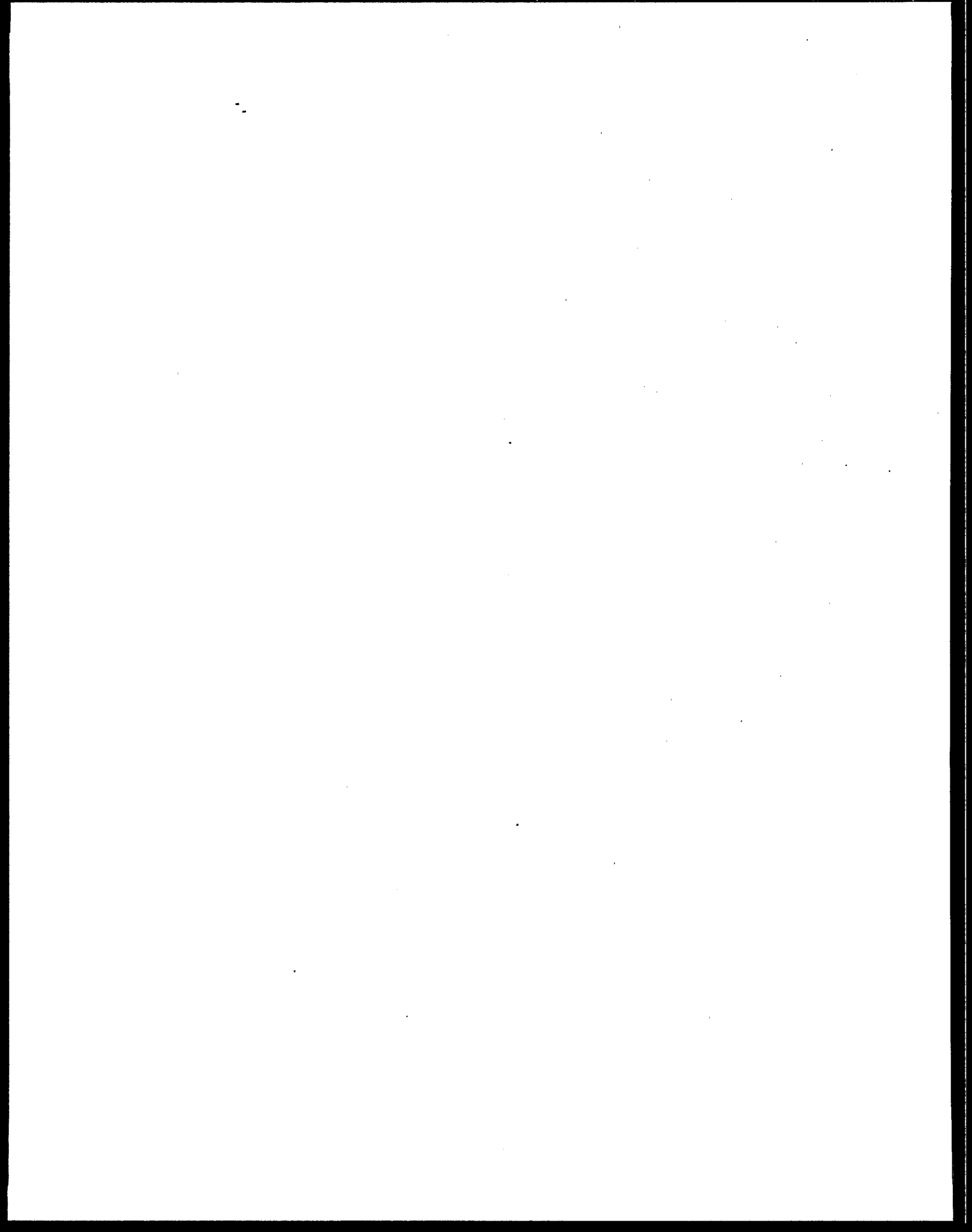


Figure C-9. Schematic plot of post-combustion Hg concentrations.



APPENDIX D.

GRAPHS OF POST-APCS EMISSION CONCENTRATIONS



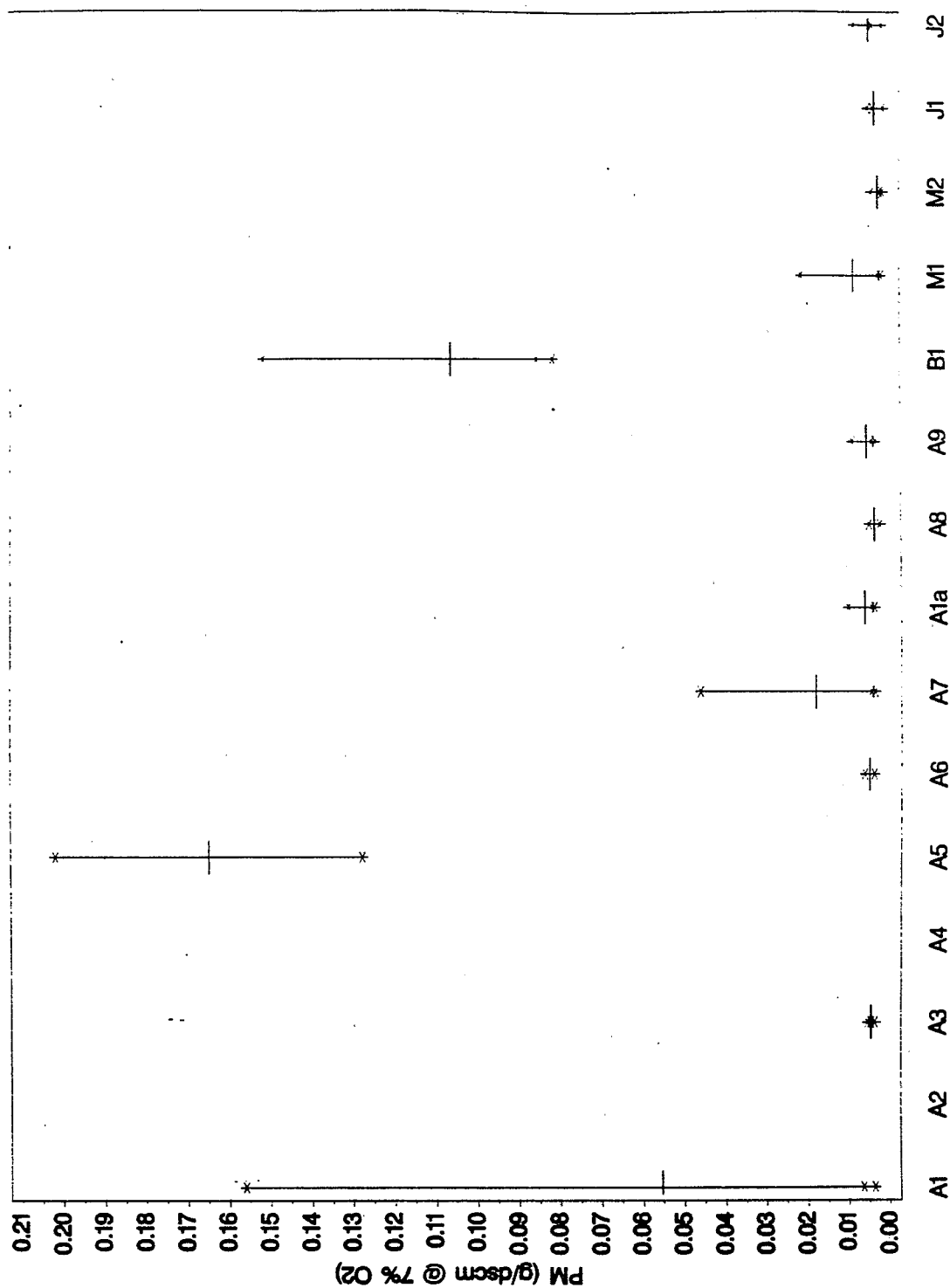


Figure D-1. Schematic plot of post-APCS PM concentrations.

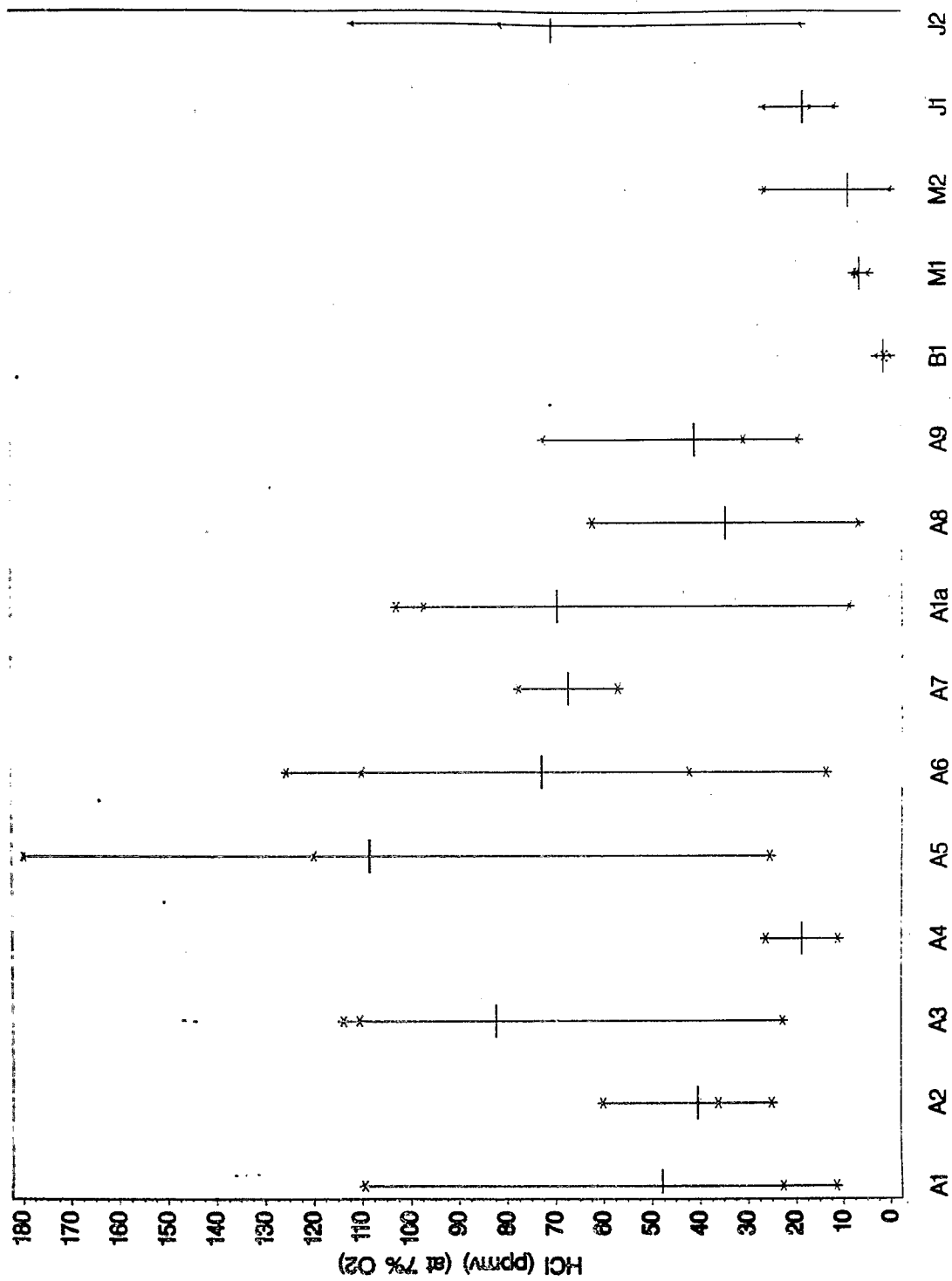


Figure D-2. Schematic plot of post-APCS HCl concentrations.

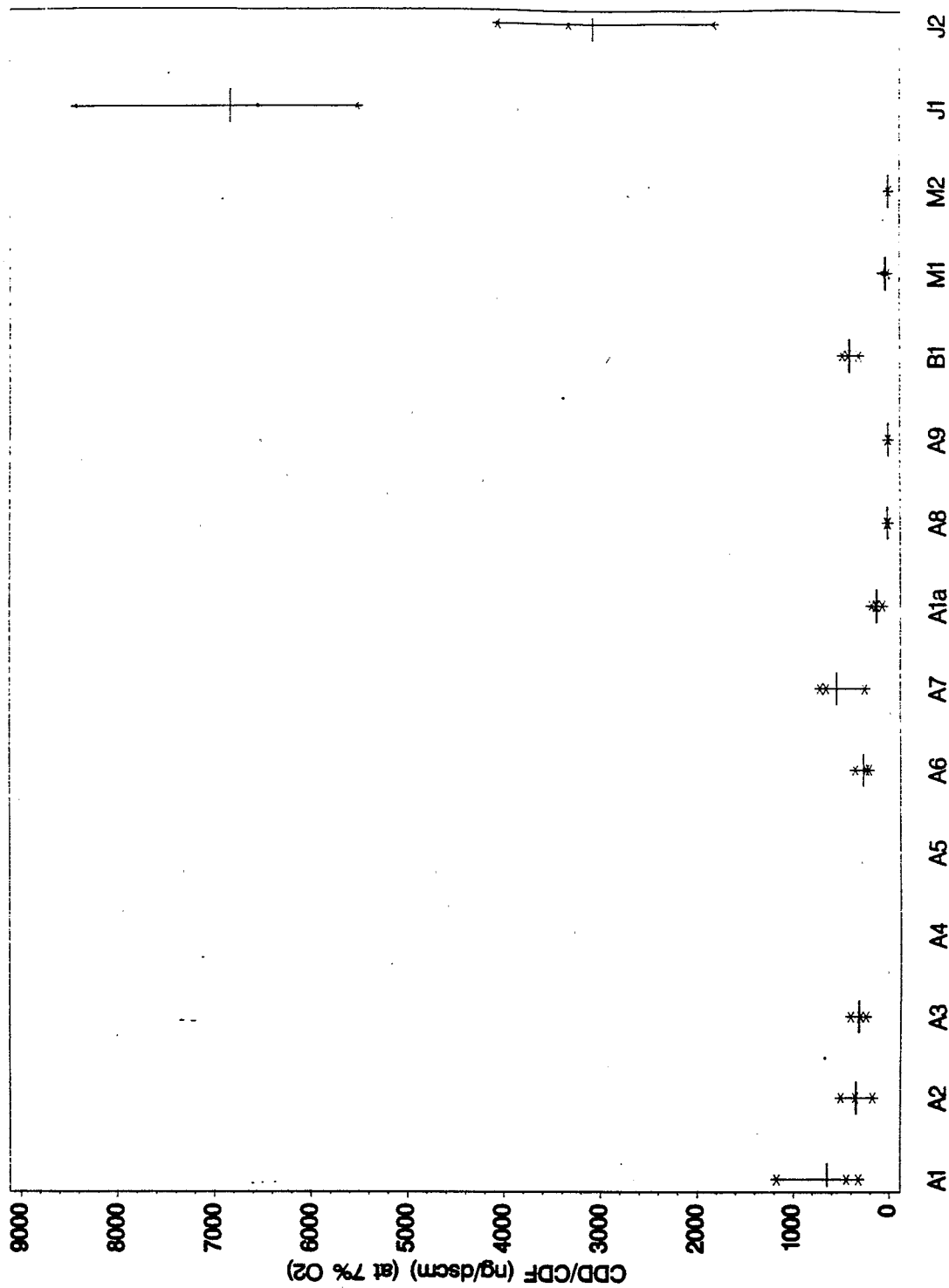


Figure D-3. Schematic plot of post-APCS total CDD/CDF concentrations.

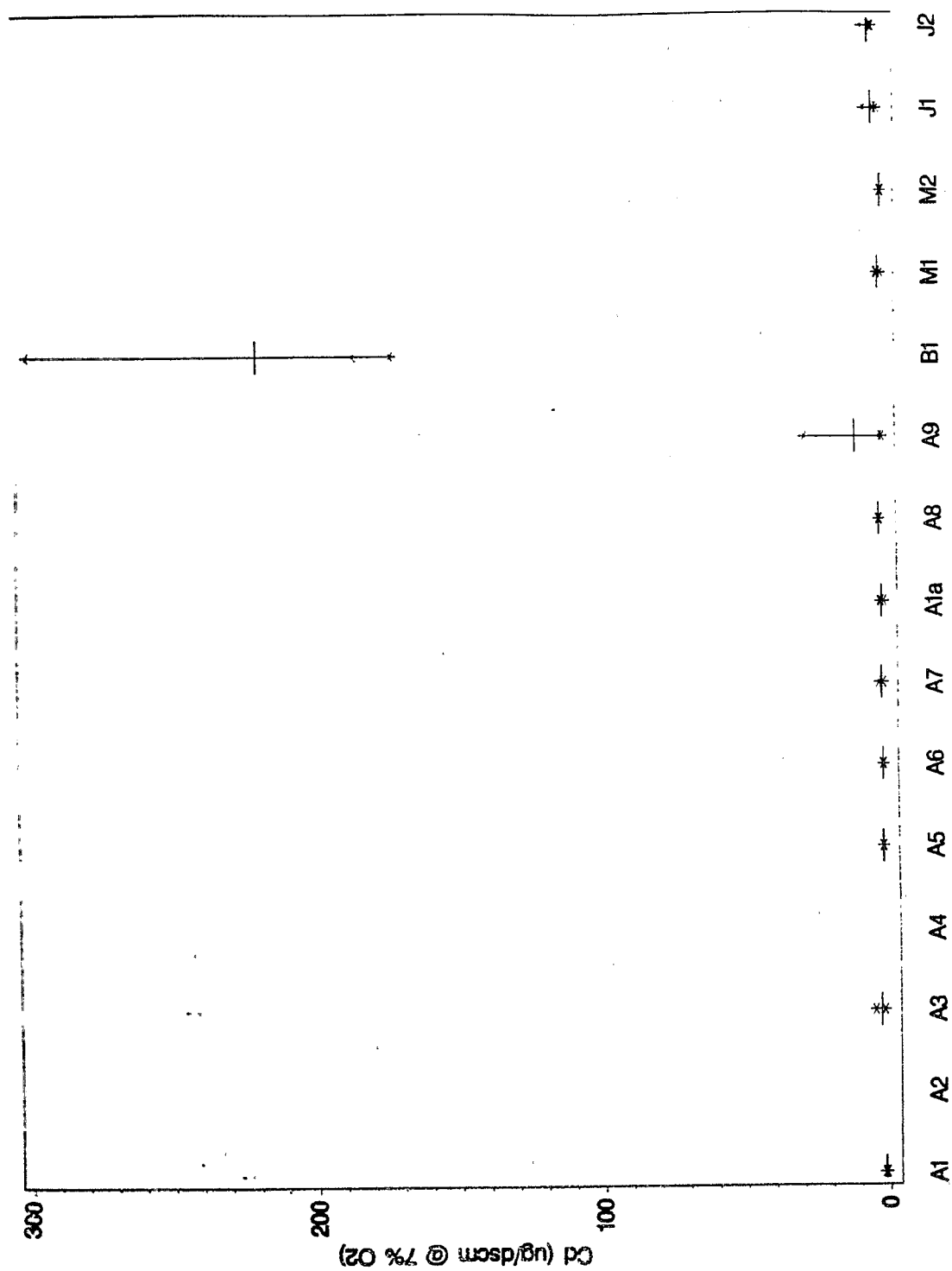


Figure D-4. Schematic plot of post-APCS Cd concentrations.

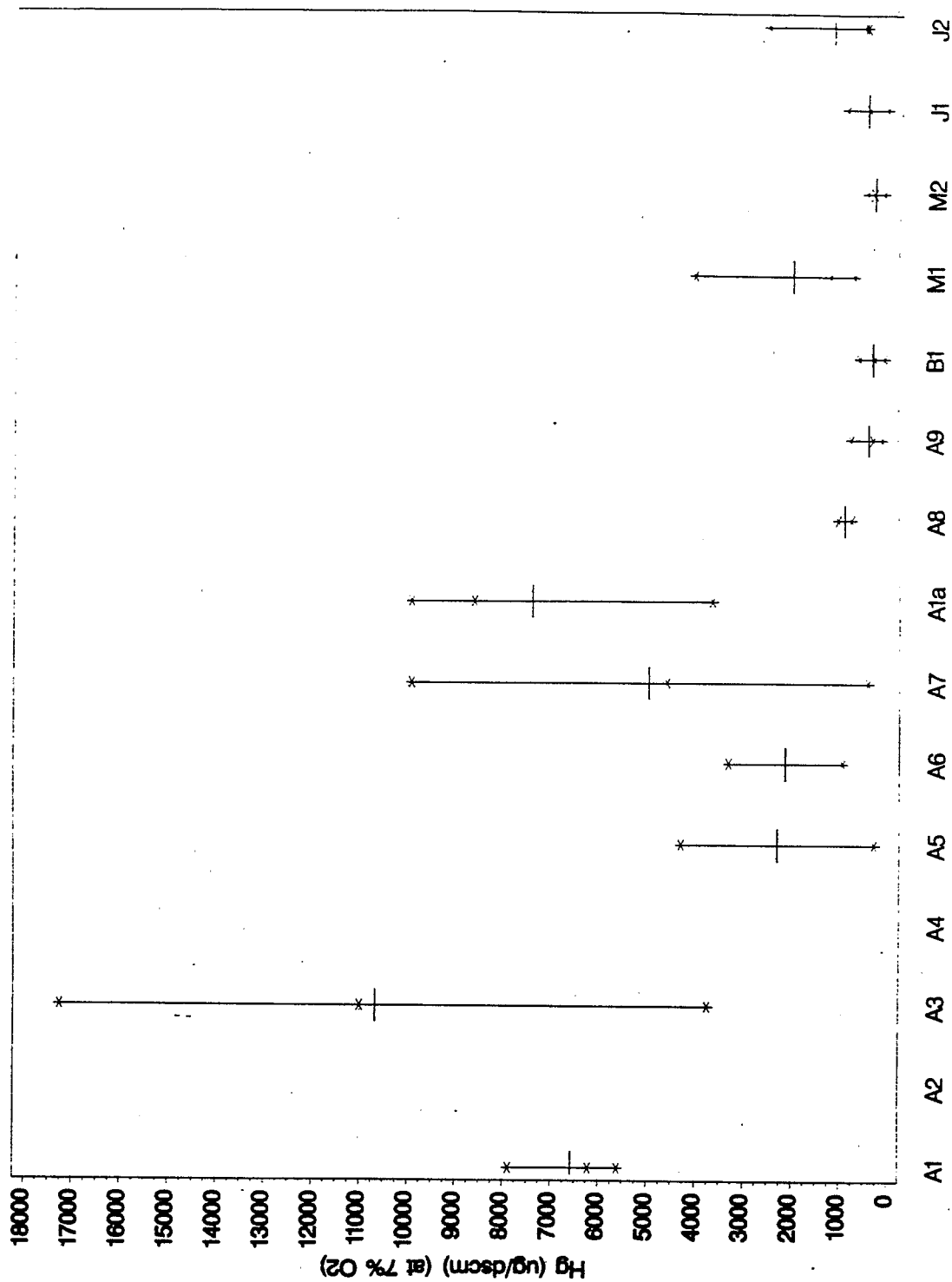


Figure D-5. Schematic plot of post-APCS Hg concentrations.

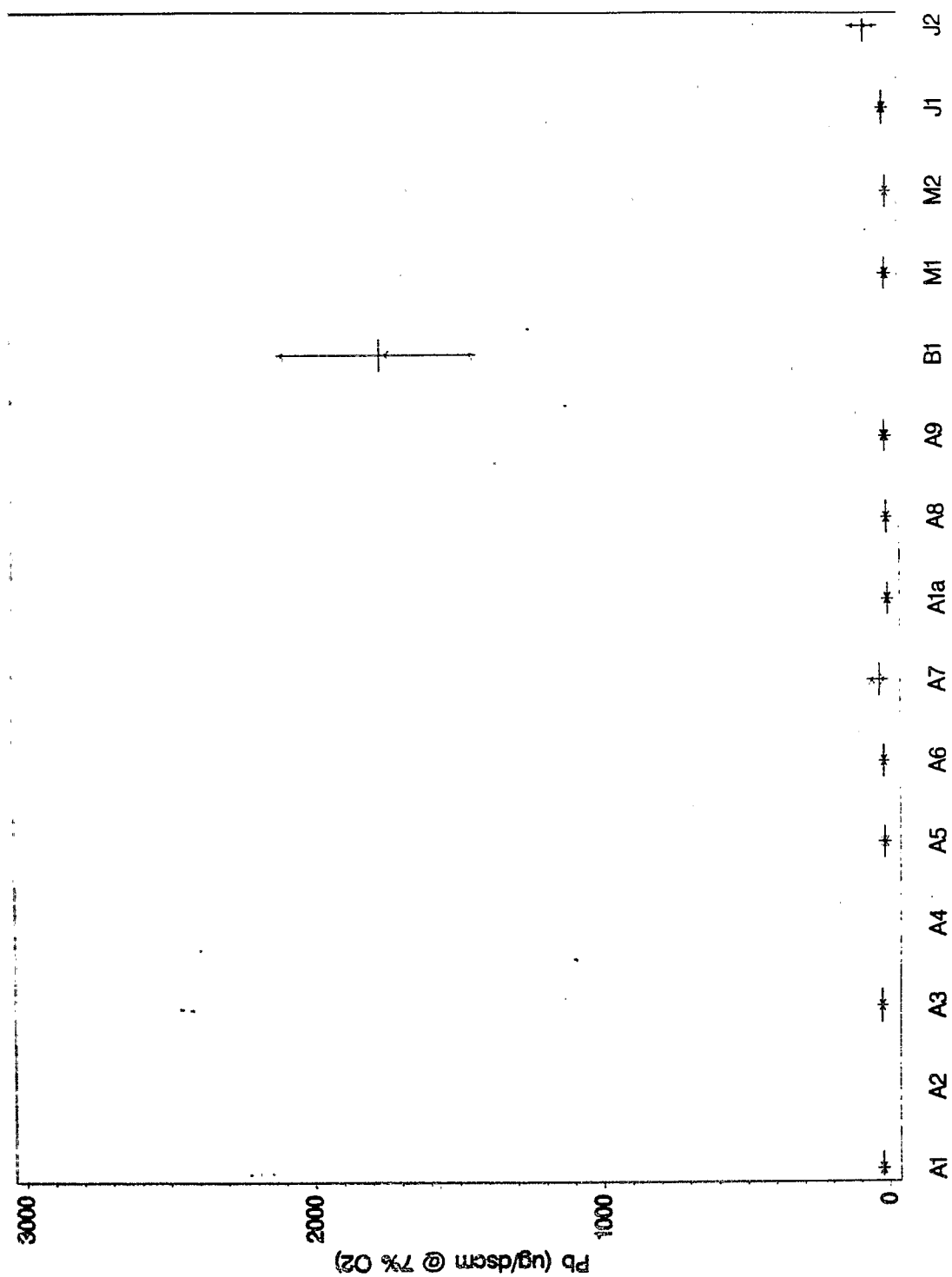


Figure D-6. Schematic plot of post-APCS Pb concentrations.

TECHNICAL REPORT DATA*(Please read Instructions on reverse before completing)*

1. REPORT NO. EPA-453/R-94-044a	2.	3. RECIPIENT'S ACCESSION NO.
4. TITLE AND SUBTITLE Medical Waste Incinerators - Background Information for Proposed Standards and Guidelines: Control Technology Performance Report for New and Existing Facilities		5. REPORT DATE July 1994
		6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S)		8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS Emission Standards Division (Mail Drop 13) Office of Air Quality Planning and Standards U.S. Environmental Protection Agency Research Triangle Park, NC 27711		10. PROGRAM ELEMENT NO.
		11. CONTRACT/GRANT NO. 68-D1-0115
12. SPONSORING AGENCY NAME AND ADDRESS Director Office of Air Quality Planning and Standards Office of Air and Radiation U.S. Environmental Protection Agency Research Triangle Park, NC 27711		13. TYPE OF REPORT AND PERIOD COVERED Final
		14. SPONSORING AGENCY CODE EPA/200/04
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16. ABSTRACT This report describes the various emission control techniques used to control emissions from medical waste incinerators (MWI's), summarizes the emission test data generated during a comprehensive EPA emission test program, and provides an emission test data analysis that quantifies the performance of these techniques. This is one in a series of reports used as background information in developing air emission standards and guidelines for new and existing MWI's.		
17. KEY WORDS AND DOCUMENT ANALYSIS		
a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
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