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Municipal Waste Combustion Assessment: Technical Basis For Good Combustion Practice

Prepared For
Office of Air Quality Planning and Standards

Prepared By
Air and Energy Engineering Research Laboratory
Research Triangle Park, NC 27711

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MUNICIPAL WASTE COMBUSTION ASSESSMENT: TECHNICAL BASIS FOR GOOD COMBUSTION PRACTICE

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ABSTRACT

The EPA's Office of Air Quality Planning and Standards (OAQPS) is developing emission standards and guidelines for, respectively, new and existing MWCs under the authority of sections 111(b) and 111(d) of the Clean Air Act (CAA). The EPA's Office of Research and Development (ORD) is providing support in developing the technical basis for good combustion practice (GCP), which is included in the regulatory alternatives considered in selecting the proposed standards and guidelines. This report defines GCP and summarizes the approach used to implement GCP into the proposed MWC standards and guidelines. The report identifies the minimum subset of GCP operating parameters that can be continuously monitored to ensure that the goals of GCP are achieved. Finally, the report provides a detailed description of the data and rationale used to establish quantitative operating limits for each of the continuous operating parameters.

FOREWORD

Based upon its analysis of Municipal Waste Combustors (MWCs), the Environmental Protection Agency (EPA) has determined that MWC emissions may reasonably be anticipated to contribute to the endangerment of public health and welfare and warrant further regulation. As a result, EPA's Office of Air Quality Planning and Standards is developing emission standards for new MWCs under Section 111(b) of the Clean Air Act (CAA) and guidelines for existing MWCs under Section 111(d) of the CAA.

In support of these regulatory development efforts, the Air and Energy Engineering Research Laboratory in EPA's Office of Research and Development has conducted an assessment of combustion control practices to minimize air emissions from MWCs. The results of this assessment are documented in the following reports:

Municipal Waste Combustion Assessment: Combustion Control at New Facilities, August 1989 (EPA-600/8-89-057)

Municipal Waste Combustion Assessment: Combustion Control at Existing Facilities, August 1989 (EPA-600/8-89-058)

Municipal Waste Combustion Assessment: Fossil Fuel Co-Firing, July 1989 (EPA-600/8-89-059)

Municipal Waste Combustion Assessment: Waste Co-Firing, July 1989 (EPA-600/8-89-060)

Municipal Waste Combustion Assessment: Fluidized Bed Combustion, July 1989 (EPA-600/8-89-061)

Municipal Waste Combustion Assessment: Medical Waste Combustion Practices at Municipal Waste Combustion Facilities, July 1989 (EPA-600/8-89-062)

Municipal Waste Combustion Assessment: Technical Basis for Good Combustion Practice, August 1989 (EPA-600/8-89-063)

Municipal Waste Combustion, Multi-Pollutant Study, Emission Test Report, Maine Energy Recovery Company, Refuse-Derived Fuel Facility, Biddeford, Maine, Volume I, Summary of Results, July 1989 (EPA-600/8-89-064a)

Municipal Waste Combustion, Multi-Pollutant Study, Emission Test Report, Mass Burn Refractory Incinerator, Montgomery County South, Ohio, Volume I, Summary of Results, August 1989 (EPA-600/8-89-065a)

The 111(b) New Source Performance Standards (NSPS) and the 111(d) Emission Guidelines for new and existing municipal waste combustors (MWCs) include two specific emission control strategies: combustion controls, or good combustion practice (GCP), and add-on flue gas cleaning controls. The specific objectives of this report, "Municipal Waste Combustion Assessment: Technical Basis for Good Combustion Practice," are to identify the combustor design and operating parameters that are necessary components of GCP, to provide the rationale for designating specific components as continuous compliance parameters in the standards and guidelines, and to present the data and supporting rationale used to select operating ranges and limits for the continuous compliance parameters.

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1.0 SUMMARY

The objectives of this report are to define good combustion practices (GCP) as they apply to prevention and control of air pollutant emissions from municipal waste combustors (MWCs), to summarize the approach used to implement GCP in the MWC standards and guidelines, and to provide the rationale and supporting data used to establish numeric GCP operating limits in the regulation. GCP are defined as the MWC system design and operating techniques which, when applied with appropriate flue gas cleaning techniques, are expected to minimize trace organic emissions. The GCP control strategy includes a number of combustor conditions which are applied collectively to achieve this goal. Because of the interrelationship among these conditions, it is possible to provide verification of GCP on a continuous basis by monitoring a select subset of combustor operating parameters.

Based on this rationale, the MWC regulation establishes numeric limits for three specific combustor operating parameters:

- CO in flue gases
- Maximum operating load
- PM control device flue gas temperature

Table 1-1 summarizes the recommended operating limits for each of the three combustor operating parameters. The CO emission limits vary according to combustor technology. The operating load limits apply only to those MWCs that generate steam. All MWCs are subject to the PM control device flue gas temperature limits. These three parameters were selected for inclusion in the regulation for two reasons. First, each can be monitored on a continuous basis to provide verification of good combustion conditions. Secondly, the parameters as a group comprise the minimum set of combustor operating conditions that can be related either directly or indirectly to the GCP components that must be addressed in order to satisfy three broad objectives of GCP:

- Maximize in-furnace destruction of organics
- Minimize particulate matter (PM) carryover out of the furnace
- Minimize low temperature reactions which promote formation of polychlorinated dibenzo-p-dioxins and dibenzofurans (CDD/CDF)

TABLE 1-1. GCP OPERATING STANDARDS FOR MWCs

CO Emission Limits	MWC TECHNOLOGY	ppm at 7% O_2 four-hour block average*
	Mass Burn Waterwall	100
	Mass Burn Refractory Wall	100
	Mass Burn Rotary Waterwall	150
	Modular Starved Air	50
	Modular Excess Air	50
	RDF Spreader Stoker	150
	RDF Co-Fired	150
	Fluidized Bed Combustors	100
Operating Load	MWCs with heat recovery boilers shall not exceed 100 percent of design steam load, four-hour block average.	
Flue Gas Temperature at PM Control Device Inlet	232°C (450°F) maximum, four-hour block average	

* A four-hour block average is defined as the mean value of four one-hour average values in a period which commences and ends at designated times (e.g.,12:00 midnight to 4:00 a.m.)

This report is organized as follows. Section 2 summarizes the potential sources of trace organic emissions from MWCs, identifies the components of GCP, and describes the interrelated roles of the components in the GCP control strategy. Section 3 rationalizes how adherence to the CO, load, and temperature limits ensures continuous achievement of GCP. Section 4 provides the rationale and supporting data used to establish the achievability of the numeric limits for the GCP operating parameters.

2.0 GOOD COMBUSTION PRACTICES

The principles of good combustion have been incorporated to varying degrees to provide the basis for improved efficiency and emissions performance in all types of combustion systems, including MWCs. The application of these principles to MWCs is intended to meet a specific goal: minimization of trace quantities of potentially toxic organic emissions. Organic emissions are products of incomplete combustion which result from the inability of MWCs to achieve ideal combustion conditions. There are three potential sources of organic emissions. First, organics are present in waste feed and can potentially pass through the combustor undestroyed. Secondly, organics can be formed from precursor compounds that evolve in the combustion process. Finally, some organics (specifically CDD/CDF) can form as a result of reactions that occur in low temperature regions of the MWC system. Additional detailed discussion of each of these organic emission sources is included in other reports published by EPA on GCP.[1,2,3]

The GCP control strategy is developed based on the need to minimize the occurrence of all three sources of organic emissions. This is accomplished by identifying a group of combustor design and operating conditions, or components, which will achieve three broad GCP goals:

- Maximize in-furnace destruction of organics
- Minimize PM carryover
- Minimize the occurrence of low temperature CDD/CDF formation reactions

Seven GCP components have been identified which collectively address the three GCP goals. Each component provides a necessary contribution to the GCP control strategy, and each can be directly related to one of the three GCP goals. The following sections describe the role of each component in the overall GCP strategy. Table 2-1 summarizes the objectives of each component.

2.1 Waste Feeding

Combustion stability can be affected significantly by sudden changes in waste composition or feed characteristics (e.g., moisture content, heating value, volatiles content). Excursions in waste feed rates or waste properties can deplete local oxygen levels in the furnace, allowing organics to escape

Table 2-1. GCP COMPONENTS AND OBJECTIVES

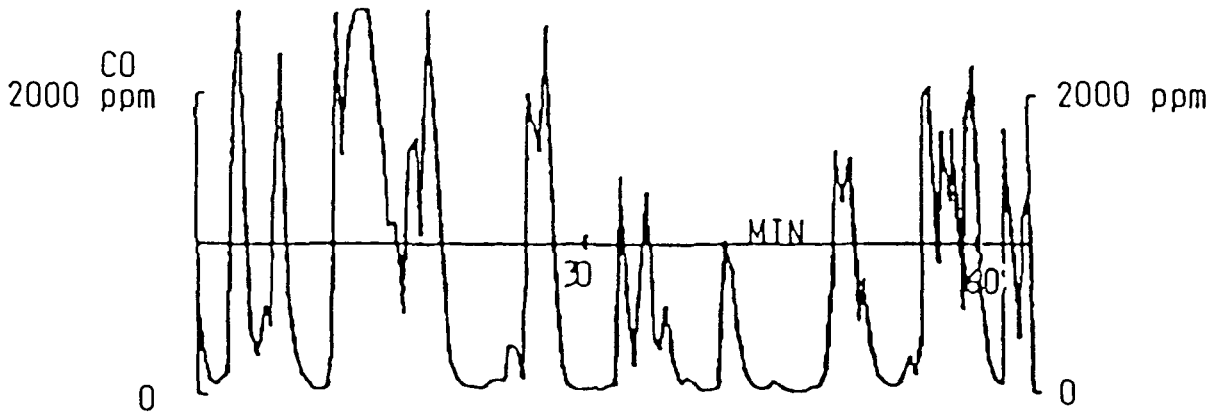
COMPONENT	OBJECTIVE
Waste feed control	o Avoid combustion instabilities
Temperature at fully mixed location	o Ensure destruction of gas-phase organics
	o Maximize particle burnout
Amount and distribution of combustion air	o Provide proper local stoichiometries in waste drying, ignition, and burnout zones
	o Eliminate fuel-rich zones and avoid quenching
	o Provide proper excess air margins
	o Minimize PM entrainment
Mixing	o Ensure availability of oxidant to all organic material within high temperature region
PM carryover	o Minimize escape of organics and metals
Downstream temperature control	o Minimize downstream formation of organics
Monitoring and control	o Ensure that all GCP objectives are continuously met

complete oxidation. Alternately, combustion of low heating value fuel can lead to quenching of combustion reactions, which also allow organics to escape thermal destruction. Both of these conditions are accompanied by elevated concentrations of CO. Therefore, MWCs should be designed and operated in a manner that minimizes occurrence of waste feed excursions. Flue gas CO concentrations can be monitored to provide a continuous indication of proper waste feed conditions. The appropriate design and operating procedures to minimize waste feed excursions vary according to combustor technology, and may include measures such as fuel blending by the crane operator, use of ram feeders, and use of air preheat.

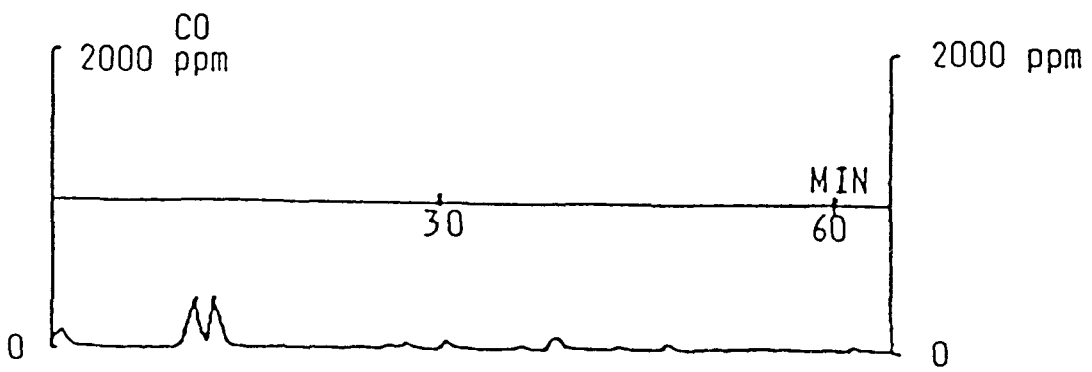
For example, the importance of optimizing waste feed is well demonstrated by two data sets generated at a circulating fluidized bed RDF facility in Sweden, shown in Figure 2-1.[4] The top data set (Figure 2-1a) indicates continuous CO emissions measured in the stack while firing an RDF that was processed with a single-stage shredder. There are frequent CO spikes in excess of 2000 ppmv during a period of just over 1 hour. The second test was conducted while firing RDF which had been processed with two stages of shredding, resulting in a more uniform waste feed with smaller nominal particle size. The change in waste size distribution was the only difference between the two tests. The CO data for the more uniform feed conditions (Figure 2-1b) shows that the majority of spikes are eliminated and combustion conditions are far more stable, resulting in a lower potential for trace organic emissions.

2.2 Adequate Combustion Temperature

The ability of an MWC to achieve combustion temperatures that are adequate to destroy organics is a fundamental requirement of GCP. The occurrence of spatial and temporal temperature variations during normal operating conditions necessitates that MWCs be designed and operated in a manner that will ensure that all combustion products are exposed to the minimum destruction temperature. Residence time is also an important requirement to ensure that burnout of gaseous and solid phase organics occurs in the furnace. Failure to achieve the necessary temperatures and residence times will result in the escape of organics from the furnace, which will lead to elevated concentrations of CO in flue gases.



A. Single-stage shredding.



B. With secondary shredding.

Figure 2-1. Effect of Waste Feed on CO Emissions From a Circulating Fluidized Bed Combustor

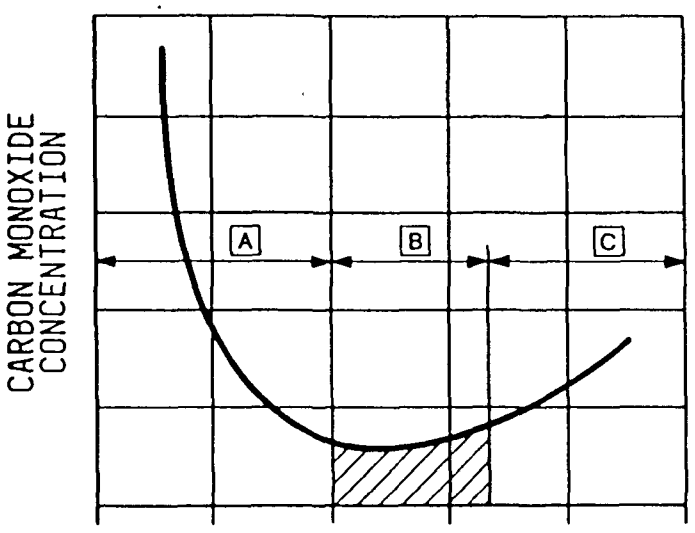
2.3 Amount and Distribution of Combustion Air

The proper amount and distribution of combustion air are essential for efficient combustion. The amount of excess air introduced to the combustor must be sufficiently high to minimize the existence of fuel-rich pockets and sufficiently low to avoid quenching of combustion reactions. The range of excess air levels that will satisfy these objectives varies for each combustor technology. Figure 2-2 illustrates the relationship between excess O_2 and CO emissions. CO emissions typically increase when insufficient O_2 is available to complete combustion, or when excessive amounts of O_2 quench combustion reactions. High excess air levels can also cause excessive PM carryover, which can include adsorbed organics. A key objective of GCP is to ensure that MWCs operate at excess air levels that fall in the trough of this U-shaped curve.

Total combustion air is typically split between primary and secondary supplies. The amount and distribution of primary (underfire) air controls bed burning stoichiometry and waste burnout. Secondary air is used to adjust local stoichiometries to levels needed to achieve complete combustion, to control flame height, and to complete the mixing process (see Section 2.4). Failure to distribute combustion air in the correct proportions to primary and secondary supplies can result in elevated organics and CO emissions and excessive PM carryover. The GCP recommendations for combustion air control must also be applied in a technology-specific manner according to the design objectives of each combustor type. Results from several full scale tests which provide evidence of the effects of the amount and distribution of combustion air on emissions are summarized in Chapter 4.

2.4 Mixing

Mixing of combustion products and air is a key requirement to ensure destruction of organics in the furnace. The most common method used to achieve good mixing in MWCs is properly designed and operated secondary (overfire) air systems. Mixing can also be effected through combustor design measures such as bull noses, baffles, turns, and changes in duct shape or cross-sectional area. Mixing failures are accompanied by spikes or bulk increases in CO emissions. Several full scale tests provide data which



OXYGEN CONCENTRATION

A - INSUFFICIENT AIR $C+\frac{1}{2}O_2 \longrightarrow CO$

B - APPROPRIATE OPERATING REGION

C - "COLD BURNING"

Figure 2-2. Relationship Between Excess O_2 and CO

document the effect of a change in mixing design on CO emissions. These are discussed further in Section 4.1.

2.5 PM Carryover

PM carryover is defined as the amount of entrained particulate matter, both organic and inorganic, which is carried out of a combustor with flue gases. The amount of PM carryover from MWCs can affect the ultimate emission of metals and organic pollutants. In addition, correlations have been established between the amount of PM emitted from MWC boilers and CDD/CDF emission levels in the stack.[5] Therefore, minimization of PM carryover is a necessary requirement of GCP.

Parameters affecting PM carryover include operating load, excess air levels, and primary/secondary air ratios. Combustor specific design features can also influence rates of PM carryover. For example, RDF spreader stokers exhibit higher PM carryover than many other designs due to the use of a semi-suspension firing mode. Conversely, starved air modular MWCs are designed with low air flows and velocities in the primary combustion chamber, and typically exhibit relatively low PM carryover. Operating load limits can be established to minimize PM carryover within the constraints of specific combustor design characteristics. A more extensive discussion of test data correlating PM carryover with emissions of organics is included in Section 4.2.

2.6 Downstream Temperature Control

Several full scale emission testing programs have produced data indicating that, under certain operating conditions, CDD/CDF concentrations in MWC flue gases increase between the combustor exit and the stack.[6,7,8,9] This low temperature CDD/CDF formation has also been investigated in bench scale experiments, and results indicate the existence of formation reactions in a temperature range of approximately 390-750°F (200-400°C).[10,11] This temperature range typically occurs in the flue gas cleaning equipment of many MWCs. Discovery of the low temperature reaction has created the need for inclusion of the third GCP goal: minimization of conditions which promote low temperature CDD/CDF formation. The recommended control strategy is to minimize the retention time of flue gases and particulate concentrations in the temperature window where CDD/CDF formation is maximized. The data leading

to specification of the operating limits that achieve this goal are discussed in detail in Section 4.3.

2.7 Combustion Monitoring and Control

Inclusion of the proper monitoring and control features in the design of the combustion system is a vital part of GCP. A number of combustor operating parameters can be incorporated into the combustion control network, including steam flows, temperatures and pressures, air flows and distributions, combustor operating temperatures, and flue gas oxygen concentrations. Operating parameters are monitored either for purposes of verifying emission performance or to maintain continuous operational stability. Three specific parameters have been identified which must be monitored as GCP regulatory requirements (CO in flue gases, operating load, and PM control device temperature), because they provide direct or indirect verification of good combustion conditions. Additional technology specific operating parameters may be monitored to maintain operational stability and provide the operator with information that can be used to control the combustion process.

3.0 SELECTION OF GCP OPERATING PARAMETERS TO BE CONTINUOUSLY MONITORED

The GCP control strategy is implemented in the MWC regulation by specifying numeric operating limits for selected combustion parameters and requiring that these parameters be monitored on a continuous basis. These parameters are:

- CO in flue gases
- Maximum operating load
- PM control device operating temperature

The parameters selected for continuous compliance are sufficient as a group to provide verification that the three goals of GCP are continuously achieved. These three operating parameters are direct measures of or surrogates for each of the GCP components.

The first goal of GCP, maximization of in-furnace destruction of trace organics, is accomplished by optimizing waste feeding procedures, achieving adequate combustion temperatures, providing the proper amount and distribution of combustion air, and optimizing the mixing process. A failure in any one of these components will be accompanied by spikes or bulk increases in flue gas CO concentrations. Therefore, establishment of a CO emission limit commensurate with GCP ensures that waste feeding, combustion temperature, amount and distribution of air, and mixing are addressed in the regulation.

The second goal of GCP, minimization of PM carryover, is satisfied by maintaining appropriate operating load, combustion air flow rates, and air distributions. For a given combustor design, total air flows are directly related to operating load, because each combustor is designed to maintain a relatively constant excess air level. As load increases above design limits, air flows increase proportionally, and the potential for PM entrainment and carryover increases. Because combustor specific design characteristics which affect PM carryover vary extensively, and typical excess air levels also vary on a combustor specific basis, operating load serves as the best measurable parameter to address PM carryover.

The third goal of GCP, minimization of low temperature CDD/CDF formation downstream from the furnace, can be addressed directly by establishing an operating temperature limit for PM control devices. A detailed discussion of

the rationale and data used to establish specific CO, load and PM control device temperature limits is included in Section 4.

4.0 DETERMINATION OF COMBUSTOR-SPECIFIC CONTINUOUS COMPLIANCE REQUIREMENTS

As discussed in Section 3, the recommended GCP implementation approach is the use of continuous compliance requirements. Three design/operating parameters have been selected to serve as continuous compliance indicators for GCP achievement in MWCs:

1. CO emission limit
2. Load limit
3. Maximum temperature at PM control device inlet

This section describes the impact of each parameter on achieving low trace organic emissions. Data are provided to support the selection of the continuous compliance parameter on a combustor technology-specific basis, and the continuous compliance levels are detailed.

4.1 Carbon Monoxide in Flue Gases

The oxidation of carbon monoxide (CO) to carbon dioxide (CO_2) is the final reaction step in the hydrocarbon oxidation chain. Thus, low bulk CO concentrations in flue gases provide verification of hydrocarbon oxidation, which is one of the goals of good combustion practice. Good combustion is also correlated with low emissions of CDD/CDF and other trace organic compounds.

High emissions of CO in MWCs may be due to a number of conditions, including:

- insufficient bulk oxygen levels resulting from feed and stoichiometry variations
- insufficient temperatures that result in quenching of reactions
- poor air distribution and/or inadequate mixing which results in localized oxygen deficient conditions
- excessive carryover of particulate-bound organics from the furnace into lower temperature regions of the combustion system prior to completion of combustion

Many of these conditions can also contribute to elevated emissions of CDD/CDF. The available emissions data base confirms that good correlations exist between CO and CDD/CDF when CO emissions are high, since high CO generally indicates poor combustion. However, the fact that oxidation of CO to CO_2 is the final reaction step may lead to instances where the cause of the high CO occurs after all the organic species have been destroyed (e.g., furnace residence time is sufficient to destroy all organic species, but too short for complete CO burnout before quenching occurs). The correlation between CO and CDD/CDF is typically not as strong when CO levels are low (i.e., low CO alone is not sufficient to ensure that CDD/CDF is minimized). The absence of a strong correlation between low CO and low CDD/CDF is due to the fact that multiple mechanisms may contribute to CDD/CDF formation, some of which occur independent of the CO oxidation process. Selection of CO as a continuous compliance measure is based on the rationale that maintaining low CO in flue gases provides verification of good overall mixing and combustion stability, both of which are necessary requirements for achieving good combustion. Although low CO is not sufficient to ensure low CDD/CDF, preventing the occurrence of high CO concentrations minimizes the potential for high CDD/CDF emissions from the combustor.

The ability to maintain low CO concentrations in MWC flue gases is dependent on combustor design features and operating practices. A review of emissions data from MWCs confirms that design limitations may make it challenging for some combustor types to achieve CO emission levels that are routinely attained by other units. For example, semi-suspension fired RDF systems may have more difficulty maintaining low CO levels than mass burn units due to the effects of carryover of incompletely combusted materials into low temperature portions of the boiler, and in some cases due to combustion control instabilities which result from fuel feeding characteristics. A number of key combustor design characteristics (e.g., secondary air design) can impact CO emission levels. Based on these considerations it was necessary to establish the achievable CO emission levels on a technology specific basis. However, the achievable CO emission concentrations represent performance levels that correspond to the use of good combustion practices for each MWC design type.

Variations in CO concentrations from a single unit or from units of a similar design are usually caused by differences in operating conditions.

Parametric test data from several MWCs confirm that CO emissions are greatly impacted by combustor operating conditions and that optimization of process operations results in minimization of CO emissions. Fuel properties may also affect the variability of CO emissions from a given MWC. Of particular concern are the waste moisture content and volatility. It may be challenging for a combustor to maintain all the conditions necessary for low CO emissions and good combustion practice when firing extremely wet fuel. Operating problems can also occur with extremely dry, or highly volatile fuels which can ignite quickly and deplete available oxygen in localized portions of the furnace, resulting in unmixed fuel rich pockets. Design and operating measures (e.g., availability and use of air preheat) must be incorporated into the system to accommodate high moisture content and other waste properties caused by seasonal variation. Blending of wastes by crane operators can also help to alleviate some of these types of problems.

The combustion control system provides the link between design and operation of the combustor. The sophistication of the combustion controller can significantly impact the ability of a unit to maintain stable combustion conditions and low CO emission levels. Advances in combustion control hardware and software have evolved so that many new state-of-the-art units now use computerized controllers that automatically adjust multiple combustion control variables to maintain very stable combustion conditions. State-of-the-art combustion controls are considered an available and demonstrated technology which will contribute to optimization of combustion conditions and minimization of emissions. The degree of sophistication in combustion control networks varies greatly for the MWCs included in the emissions data base, and the variations in emissions performance between data sets may, in some cases, be attributed to different combustion control designs or operating philosophies.

4.1.1 CO Emission Data Analysis

The existing CO emissions data base was analyzed to establish an achievable CO emission level for each MWC technology. This analysis includes an examination of several long duration CEM data sets and additional short duration CO emissions measurements gathered during parametric and compliance tests (typically 1-6 hours per test run). The majority of available long term continuous emissions monitoring data can be characterized as representing "normal operating conditions." The majority of the parametric tests provide

an examination of the effects of combustor operating variations on emissions performance. The remaining short term CO data in EPA's emissions data base are from compliance tests, and the majority of these tests represent "best operating conditions."

In some cases, local permit conditions or State regulatory requirements provide little incentive to minimize CO emissions. Thus, normal operation for some MWCs is represented by those operating conditions which result in achievement of current permit and regulatory requirements, and may not necessarily represent optimal operating conditions. Recognition of this difference is important prior to initiation of a data analysis to establish an achievable CO emission level. Application of good combustion practice seeks to optimize the combustion process. The achievable CO emission limit is defined in this analysis by the performance levels that well designed and operated MWCs in a combustor class can achieve on a continuous basis using good combustion practice, and not simply the levels demonstrated by "normal operation."

Parametric test data provide a glimpse of the extent to which operation of the combustor affects short duration CO concentrations. A few of the units for which long term CEM data are available were also involved in parametric testing programs. These data sets provide the basis for concluding that some MWCs can improve CO emissions performance from normal operating levels to levels representing good combustion by making design and operational changes. Special emphasis is given to these data sets in an attempt to characterize the difference between normal operation and optimum combustion conditions.

4.1.1.1 Long Term CEM Data Analysis Procedures

Long term continuously monitored CO data provide the best indication of the process variations experienced during normal operation, and long term continuous data from well designed and operated units provide support for establishing achievable emissions performance. Operators from the majority of MWCs that monitor CO on a continuous basis were contacted, and five sets of data were acquired in addition to one long term data set that was generated by EPA. The six data sets comprise long term data from three RDF facilities, two mass burn waterwall facilities, and one modular starved air MWC. The data were screened to identify episodes of abnormal operation (e.g., start-up and shutdown conditions, etc.) and all data were normalized to 7 percent O_2 and

converted to hourly averages. A decision was made that only those data measured at operating load levels between 80 and 100 percent of design load would be included in the analysis. The data were also subjected to an EPA QA/QC review to verify CEM instrument performance. Results of the data analysis are presented in the following sections.

4.1.1.2 Averaging Time

Process upsets will occur to some extent in all combustion systems. Many of these upsets result in loss of one or more of the operating conditions associated with GCP and, therefore, may be accompanied by spikes in CO concentration. They also represent a significant potential for the formation and release of organic species. Thus, one requirement of good combustion practice is to operate the combustor in a manner that minimizes the frequency and magnitude of CO spikes, both by incorporating practices that minimize their occurrence and by initiating prompt corrective action in the event that upsets and CO spikes do occur. This goal influences the selection of an averaging time for the emission limit. The averaging times considered in this analysis included one-hour, four-hour, and eight-hour averages. Eight-hour and longer duration averaging times were excluded from consideration because they provide the option of simply "averaging out" an extended period of poor operation rather than initiating prompt action to correct the upset.

Some combustor upsets that result in high CO levels may not be correctable immediately (e.g., ram feeder failure will affect the characteristics of the burning waste bed). The time required to move waste through the combustor at normal operating rates should be sufficient to complete any corrective action needed to respond to an upset and reestablish normal CO levels. Any more extensive corrections may necessitate unit shutdown. Since the majority of mass burn waterwall MWCs have a waste retention time on the grate of up to one hour, selection of a one-hour average CO emission limit does not provide adequate time for an operator to make a good faith effort to correct upsets and still achieve an emission limit representative of good combustion practice. Therefore, four hours were selected as an appropriate averaging time. A four-hour average is expected to allow operators to achieve the standard even with occasional upsets, provided that action is taken to correct the upset, yet is sufficiently restrictive to encourage prompt corrective action so that periods of poor operation do not

continue unattended. The four-hour averaging time selected is a block average rather than a rolling average.

4.1.1.3 Categorization of MWC Technologies

Different MWC design types have inherent design and operating limitations which impact their ability to minimize CO emissions by control of the combustion process. The definition of achievable CO concentrations therefore requires that data be evaluated on a technology specific basis. The CO data analysis was organized to establish achievable emission limits for the following specific MWC design types:

- Mass burn combustors
  - Conventional waterwall
  - Refractory wall
  - Rotary waterwall
- Modular combustors
  - Starved air
  - Excess air
- Refuse-derived-fuel (RDF) fired combustors
- Fluidized bed combustors (FBC)

The results of the analysis are presented in the following sections.

4.1.2 Mass Burn Waterwall MWCs

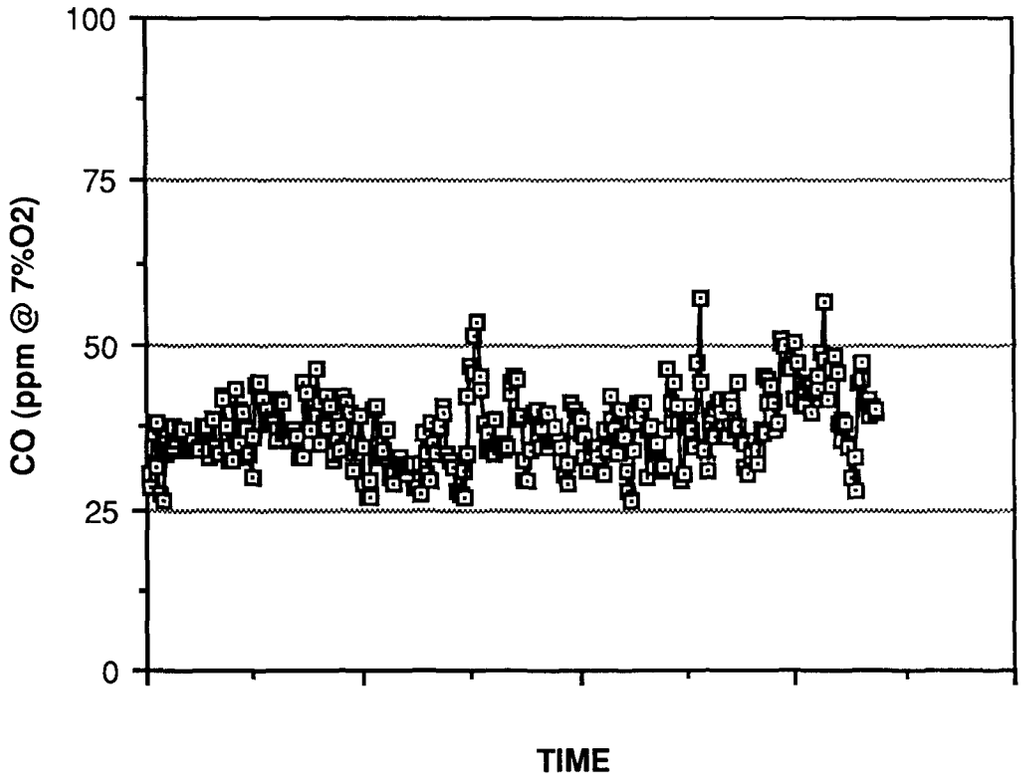
The existing emissions data base from mass burn waterwall MWCs is more extensive than that from any other class of combustor. Two long term CEM data sets were available from the Millbury, MA and Commerce, CA MWCs for use in the analysis. Numerous compliance tests and several parametric data sets are available for mass burn waterwall MWCs, and results of two combustion retrofits at the Quebec City, QE and Hampton, VA facilities provide supporting data to evaluate GCP retrofits to existing units. All of these data contributed to establishment of the achievable CO emission limits. A discussion of the data analysis is provided below.

4.1.2.1 Millbury Long Term CEM Program.

The Millbury, MA MWC comprises three 750 tpd (682 Mg/day) mass burn waterwall combustors. Each unit is equipped with a computerized combustion controller and an individual spray dryer/ESP control device. All three units entered commercial operation in 1987. A 63-day field test program was conducted by EPA in 1988, during which continuous emissions of CO and other pollutants (SO_2, HCl, opacity, etc.) were measured using source-installed continuous monitors and instrumentation provided by EPA.[12] Flue gas CO concentrations were measured using a non-dispersive infrared (NDIR) gas analyzer. Continuous oxygen and CO_2 levels were monitored to provide the basis for normalizing the emissions data to 7 percent O_2 or 12 percent CO_2. Extensive process monitoring was also conducted in the program. During the 63-day monitoring program a total of 42 valid data days were obtained. A valid data day was defined as ≥18 valid hours of monitoring data from all systems concurrently, with a valid hour defined as ≥50 percent data availability.

The Millbury MWCs are balanced draft units, which automatically adjust forced draft and induced draft fan speeds based on steam demand and furnace pressure, respectively. The units typically operate at or near full rated capacity to the maximum extent possible. The primary control loop automatically adjusts combustion air flow to maintain steam setpoints and exhaust gas oxygen concentrations. Grate speeds and ram feed speeds are established manually and maintained automatically. Approximately 40-50 percent of total combustion air is typically supplied by the secondary (overfire) air systems. All of these design and operating practices contribute to the ability of the system to maintain relatively uniform furnace stoichiometry, good mixing, and steady state operation. This is reflected in the ability of the combustor to maintain relatively low, stable CO emissions. Figure 4-1 shows a time plot of all of the four-hour block averages in the long term data set.

A statistical analysis of the Millbury data was initiated to establish an emission limit that would result in various exceedance frequencies for one-hour, four-hour, and eight-hour averaging times. The approach and results of the statistical analysis are included in Appendix A. The results of the statistical analysis of the Millbury data are summarized below:



Note: Each data point represents a 4 hour block

Figure 4-1. Millbury Long Term CO Emissions

ONE EXCEEDANCE PER	CALCULATED CO EMISSION LEVEL (ppm at 7% O_2) 1 HR ROLLING /BLOCK	4 HR ROLLING	4 HR BLOCK	8 HR ROLLING	8 HR BLOCK
100 hrs	51.3	49.8	46.7	48.9	44.3
1 mo	55.4	53.4	51.0	52.3	48.8
3 mo	57.3	55.2	53.0	54.0	50.7
6 mo	58.5	56.2	54.1	54.9	51.9
1 yr	59.6	57.2	55.2	55.8	52.9
10 yr	62.9	60.2	58.4	58.6	56.1

Based on the selection of a four-hour block average for the standard, this analysis indicates that the unit would exceed a CO emission level of 58.4 ppm once every ten years.

4.1.2.2 Millbury Compliance Test Data.

Additional short duration CO emission data are available from testing that was performed by EPA at the Millbury facility in February 1988.[13] Five sample runs were performed at the spray dryer inlet for CDD/CDF concurrent with stack compliance tests, and CO concentrations were measured continuously during each of the sampling runs. CO concentrations are plotted against time in Figure 4-2 for the five runs. Table 4-1 summarizes the mean CO levels for each run. These short term averages are all approximately 5 to 7 hours in duration, and the range of concentrations for the five runs is similar to the emission levels measured during the long term CEM test. All testing was performed on the same combustor (Unit #2).

These results indicate no significant differences between the short and long duration monitored CO data from the Millbury unit. The Millbury MWC was judged to have good combustion practice in place based on its design and operating features, and this judgement is supported by the unit's emission performance. It is probable that the combustion control network contributes to the ability of the unit to maintain operational stability and relatively low, uniform CO emissions.

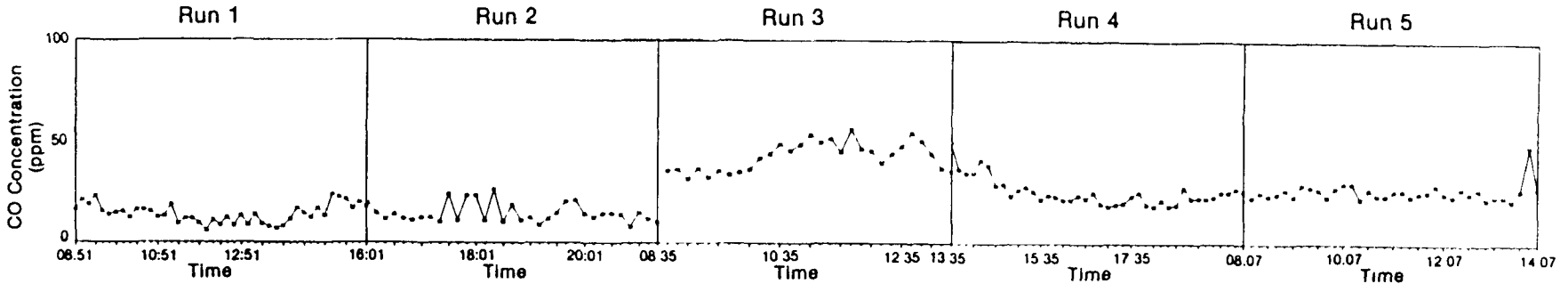


Figure 4-2. Millbury CO Data Plots

Table 4-1. Millbury Compliance Data

RUN NO.	CO (ppm at 7% O2)
1	22
2	24
3	63
4	44
5	36
Average	38

4.1.2.3 Commerce, CA Long Term CEM Data.

Long term CO data were also provided to EPA for the Commerce, CA MWC, a single 350 tpd (318 Mg/day) mass burn waterwall unit.[14] The unit is equipped with the same automatic combustion control system as that at the Millbury, MA plant. Commerce uses selective non-catalytic reduction to control NOx emissions and a spray dryer and baghouse flue gas cleaning system.

Three months of continuous CO emissions data were supplied for Commerce along with the corresponding steam load data. All data were reported as one-hour average values (24 values per day). The data are characterized by significant fluctuations in steam load, and the CO emissions levels appear to be strongly correlated to operating load levels. Figure 4-3 illustrates the relationship between CO emissions and steam load for a one day period when significant fluctuations in steam load occurred. The data indicate that the ability of the Commerce combustor to minimize CO emissions is dependent on the operating load maintained. The unit reportedly experiences load fluctuations due to problems with fuel availability.

Commerce plant personnel reported that extensive problems existed with the CO monitors during the first two months of the period for which the data were supplied, and that the monitors were subjected to certification tests at the beginning of the third month.[15] Based on this information the first two months of data were excluded from this analysis, leaving only one month of valid CO emissions data from the unit.

The variations in CO emissions expressed as four-hour block averages are presented graphically in Figure 4-4. Comparison with Figure 4-3 reveals that the Commerce data are more variable than those from Millbury. The Commerce data were also subjected to a statistical analysis to determine exceedance frequencies for various averaging periods. The results of this analysis are presented below:

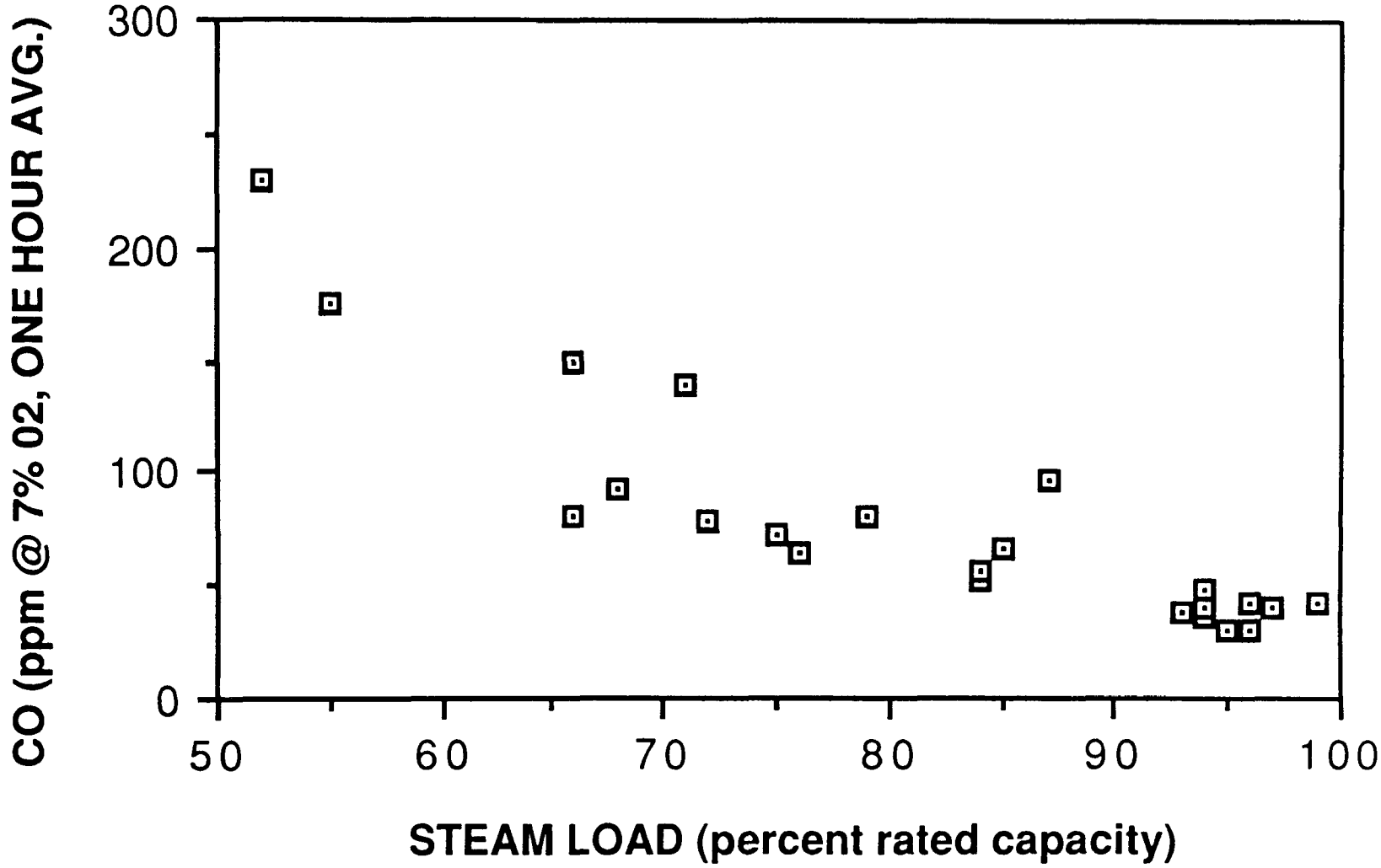
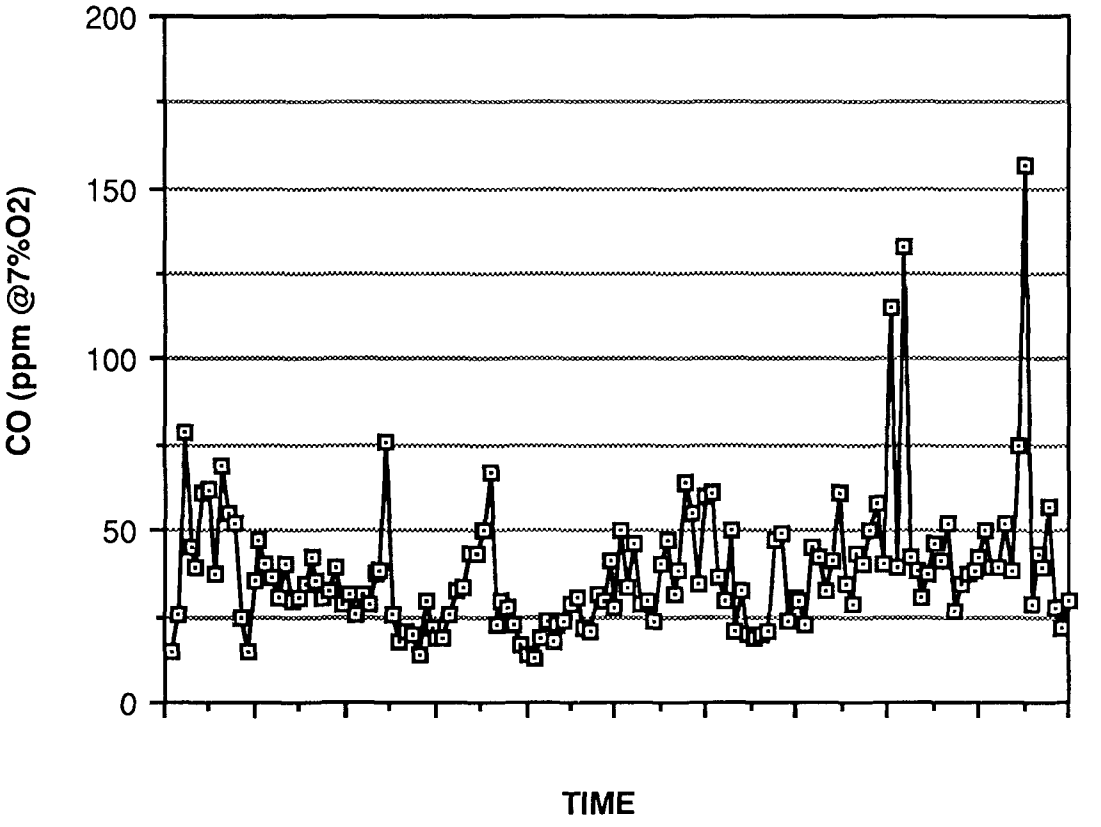


Figure 4-3. Effect of Steam Load on CO Emissions from a Mass Burn Waterwall MWC.



Note: Each data point represents a 4 hour block

Figure 4-4. Commerce Long Term CO Emissions.

ONE EXCEEDANCE PER	CALCULATED CO EMISSION LEVEL (ppm at 7% O_2) 1 HR ROLLING /BLOCK	4 HR ROLLING	4 HR BLOCK	8 HR ROLLING	8 HR BLOCK
100 hrs	107.7	80.9	70.0	73.3	59.0
1 mo	128.0	93.5	85.0	83.8	72.8
3 mo	137.8	99.5	91.8	88.7	78.9
6 mo	143.5	103.3	95.8	91.7	82.4
1 yr	149.0	106.4	99.5	98.5	85.6
10 yr	165.6	116.8	110.7	103.0	95.4

The statistical model predicted that the Commerce unit could achieve a CO limit of 110.7 ppm, four-hour block average, with a once in ten years exceedance based on its performance during the one month period of continuous data. Review of the CO time line in Figure 4-4 reveals that this predicted emission level was influenced by several short lived episodes during which a CO spike resulted in a relatively high four-hour average. This type of upset was not experienced by the Millbury unit. A comparison of the Commerce and Millbury units was initiated to determine potential causes for the difference in performance.

The variation in CO emissions performance between the Commerce and Millbury units may be influenced to some extent by differences in unit design and operation. For example, the number and arrangement of secondary air nozzles and the amount of total combustion air supplied as secondary air varies between the two units. Millbury reportedly supplies 50-60 percent of total air through three rows of overfire air nozzles while Commerce typically supplies 20-40 percent of total air as overfire through two rows of nozzles. These differences in design and operation affect mixing characteristics, of which CO concentrations are an indicator. However, the major difference between the two data sets is the apparent stability of the combustion process. The Millbury data are characterized by relatively steady CO concentrations while the Commerce data show much larger fluctuations around the mean CO value. Both units incorporate state-of-the-art automatic combustion control systems which were supplied by the same manufacturer and which provide control of the same combustion parameters. Comparison of the mean one-hour emission levels from Millbury and Commerce confirms that over a long duration (1-2 months in this instance) both units can achieve comparable mean CO emissions (37 and 38 ppm, respectively).

Follow up contacts were initiated with the Commerce plant personnel to investigate potential reasons for the high CO spikes. The periodic episodes of high CO emissions were attributed mainly to problems that are experienced when firing wet refuse.[15,16] The unit was not equipped with air preheat capabilities during the period when the data were generated. Installation of steam coil air preheat will be completed in 1989, and this modification is expected to minimize the occurrence of CO spikes and lead to improved combustion stability. The ability to modify operating procedures in response to changing waste characteristics is an important part of good combustion practice. The absence of air preheat at Commerce is judged to be the primary contributing factor which resulted in the CO spikes. These operating conditions can be minimized by installing air preheat, which is a necessary design requirement of good combustion practice. These design features are in place at the Millbury plant, and there is less evidence of problems associated with wet waste firing based on the CO data available from the CEM study.

Based on a judgement that the CO spikes result from conditions that are preventable, the statistical analysis was repeated for the Commerce data set. Seven additional one-hour averages were deleted from the available data which comprised 524 one-hour averages. Each of these points represented a one-hour average value which was greater than 3 standard deviations above the mean CO concentration, and each point was judged to be due to a preventable upset condition. The values ranged from 130-480 ppm. Calculations with this altered data set indicated an achievable emission level of 76 ppm for a four-hour block averaging period and one exceedance in 10 years. If the upset conditions are limited to those data with CO hourly averages above 200 ppm, only three data points are omitted (202, 232, and 480 ppm) and the achievable emission level is 80 ppm at 7 percent O_2 for a four-hour averaging period with one exceedance in 10 years. These emission concentrations are representative of the achievable CO emission levels when good combustion practices are applied.

4.1.2.4 Long Term Data Analysis Conclusions.

The two data sets provide an example of the distinction between "optimal emissions performance," as demonstrated by Millbury and "normal operation," as demonstrated by Commerce. The Millbury data confirm that mass burn waterwall MWCs can be designed and operated in a manner that results in continuous

achievement of moderately low CO emissions. The data from Commerce indicate that the unit has the ability to achieve long term average CO emissions comparable to those at Millbury. However, periods of combustion instability occurred at Commerce during the measurement period which resulted in occasional high short term average concentrations. These upset conditions are due to conditions which are deemed to be preventable by applying good combustion practices. Therefore, based on the results of the above analysis it is judged that mass burn waterwall MWCs which utilize good combustion practices can achieve a CO emission level of 100 ppm, normalized to 7 percent O_2, four-hour block average.

4.1.2.5 Review of Additional Short Term CO Data.

It is necessary to evaluate additional short term CO data to address the following issues:

(1) How do the CO emission performance data from other mass burn waterwall units compare to the data from the Millbury and Commerce units?

(2) In the event that some units in the population of mass burn waterwall combustors have CO emission performance levels much higher than those demonstrated by Millbury and Commerce, can combustion retrofit measures be specified and implemented which will bring the CO performance of these units into compliance with the recommended emission limit?

The first issue is addressed by review of the available short term data from other facilities in the population. Table 4-2 provides a summary of these data.

All of the CO emissions data in Table 4-2 are short duration test data, generally 1 to 6 hour averages. There are short term CO data available from 15 mass burn waterwall facilities, which represent more than half of the total population using this technology in the U.S. in August 1989. Nearly all of the short term data were gathered during compliance tests under normal steady state operating conditions. With two exceptions these facilities have reported average short term CO concentrations less than 100 ppm at 7 percent O_2. Included among these facilities are Millbury and Commerce, for which long

TABLE 4-2. MASS BURN WATERWALL MWCS - SHORT DURATION TEST EMISSIONS SUMMARY

FACILITY	OPERATING CONDITIONS	CO (ppmv at 7% O2)
Millbury, MA	Normal	38
Pinellas County, FL	Normal	4
Westchester County, NY	Normal, end of campaign	7
	Normal, start of campaign	24
	Low load	21
	High load	36
Saugus, MA	Normal	40
North Andover, MA	Normal	43
Commerce, CA	Normal	16
	Residential/Commercial	50
	Commercial	22
Marion County, OR	Normal	18
Alexandria, VA	Normal	18
Tulsa, OK	Normal	22
Chicago, IL	Normal	215
Hampton, VA	Normal	24
Claremont, NH	Normal	55
Long Beach, CA (SERFF)	Normal	118
Quebec City, Quebec	Low load/good	40
	Design load/good	33
	High load/good	55
	High load	82
	Low temperature	121
	Poor air distribution	204
Portland, ME, North Unit	Normal	41
Portland, ME, South Unit	Normal	75

term CEM data are available. Although individual combustor performance will vary to some extent based on site specific design and operating conditions the available data confirm that the majority of units in the existing population can achieve CO emission levels of 100 ppm, four-hour average, in their current configuration.

The second issue regarding combustion retrofit options is an important one for any mass burn waterwall facility that cannot achieve CO concentrations less than 100 ppm. Combustors that do not currently meet the goals of good combustion practice will be required to implement changes to existing design and/or operating practices in order to minimize emissions. There are three case studies available at this time which provide supporting information and data to relate the effects of combustor design and operating modifications to emission reductions at mass burn waterwall MWCs. Two of the studies (Quebec City, QE and Hampton, VA) involved rather extensive modifications to existing design and operating procedures. The third case study at Commerce, CA provides supporting data concerning the effects of operational changes on CO emissions achievability. The scope and results of each case study are summarized below.

4.1.2.5.1 Quebec City, Quebec Combustion Retrofit Program. The Quebec City MWC facility comprises four 250 tpd (227 Mg/day) mass burn waterwall combustors. All four units have been operating since 1975. The goal of Environment Canada's retrofit program at the Quebec City MWC was to determine the optimum design and operating conditions to minimize air emissions from the unit and to retrofit the system to meet these conditions.[17] A profile of the unmodified design is shown in Figure 4-5a. In their original configuration, each combustor had a vibrating feeder-hopper and a water-cooled chute that fed the waste by gravity. There were three grates (drying, burning, and finishing) in each unit. The grates had a 15° slope and contained vertical drops between each section. The furnaces were membrane waterwall construction with a refractory-lined burning chamber and a mechanically-rapped convective section with superheater and economizer tube sections. Each unit controls PM emissions with a two-field ESP which operated at temperatures between 392-504°F (200-280°C). Bottom ash was discharged from the grates to a wet quench tank and removed with a drag chain.

In 1979 a waterwall arch (shown in Figure 4-5a) was installed above the drying and burning grates. Existing side wall overfire air ports were

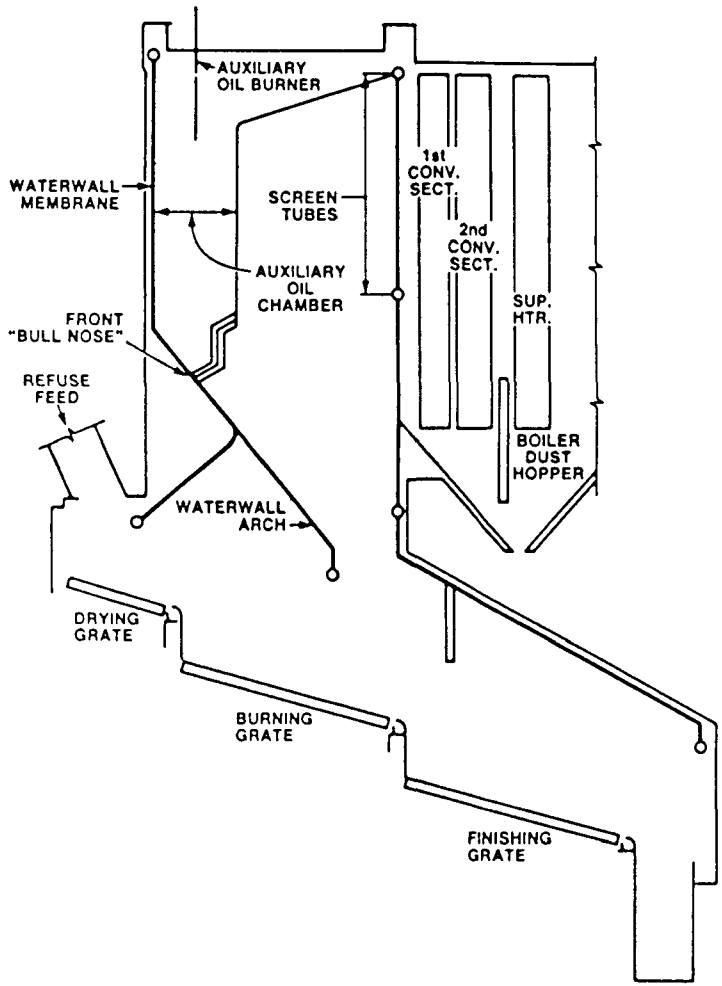


Figure 4-5a. Quebec MWC--Unmodified Design

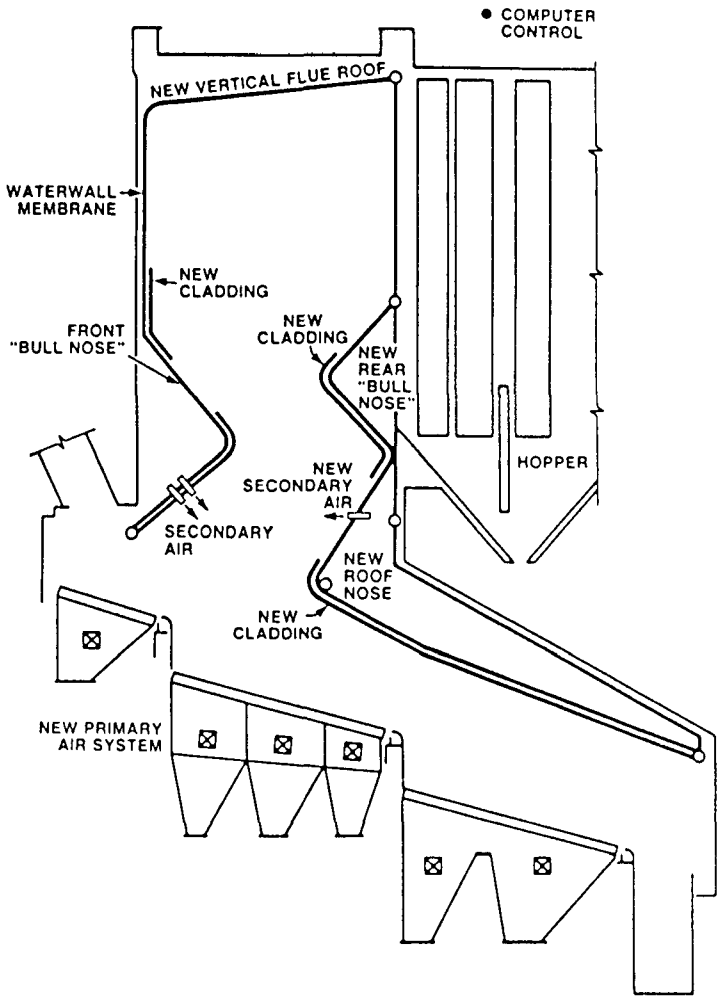


Figure 4-5b. Quebec MWC--Modified Design

abandoned in favor of 20 new ports located on the front wall beneath the waterwall arch. An auxiliary oil burner was located in the upper front furnace; however, it was not used. The underfire air fan supplied approximately 90 percent of the total air flow through five plenums beneath the grates. The control scheme was largely manual, with the exception that total underfire air flows were adjusted automatically to maintain steam flow setpoints.

In 1985 emission testing was conducted on one of the pre-modified boilers. A slipstream arrangement was used to route untreated flue gases from the boiler outlet to a pilot scale dry scrubbing/fabric filter control device in order to examine the performance of the flue gas cleaning technology. Data from this program can be used to characterize the emissions performance of the pre-modified combustor design. Thirteen test runs were evaluated and average CO emissions varied from 198 to 362 ppm corrected to 7 percent O_2.

The first step in the retrofit program was the completion of flow modeling studies to examine the existing furnace flow patterns. The objective of the modeling studies was to select a configuration where furnace geometry and air flows could provide the best mixing of combustion products and adequate retention times in the furnace for good combustion to occur. The following modifications were made to the combustor following analysis of the flow modeling results. A profile of the modified configuration is shown in Figure 4-5b.

A lower bull nose was added on the rear furnace wall to maximize the radiation reflection onto the burning and finishing grates, thus providing improved ash burnout. The bull nose was also designed to pinch the flow of combustion gases from the finishing grate to mix the combustion products and complete the burning process. The upper bull nose reduced gas vortices in the upper portion of the furnace, improving gas distribution and reducing stratification at the inlet to the convective section. New overfire air nozzles were installed to the pinched wall section to improve mixing. Various front-to-rear overfire air ratios were examined and a 1:1 ratio was chosen because it resulted in the optimal vertical mixing and least amount of stratification at the inlet to the convective section. The reconfiguration also prevented high velocities in the upper furnace, which helped to reduce PM carryover.

The underfire air supply was redesigned to include nine separate plenums. The arrangement provided a single plenum under the drying grate, six individual plenums beneath the burning grate, and two plenums beneath the burnout grate. Each of the underfire air supplies is individually controlled to maintain a preset distribution. Total underfire air flows are controlled to maintain steam production rates. The underfire air system supplies 65 percent of total combustion air under normal operating conditions and the overfire air system supplies the remaining 35 percent.

A state-of-the-art automatic combustion controller was installed. The system automatically controls grate speed in response to boiler steam flow with an excess air feedback loop to the grate speed controller. Underfire air flows and distributions are maintained automatically and there are provisions in the control system to vary overfire air flow rates in response to temperature readings in the upper furnace.

Following completion of the modernization program, a parametric testing effort was conducted to evaluate the effects of the retrofit on emission levels. The first phase, characterization testing, investigated the effects of feed rate, excess air rates, combustion temperatures, and overfire/underfire air ratios on emissions of CO and other continuously measured gases. From the results of characterization testing, a series of performance testing conditions were selected for manual sampling of CDD/CDF, and other organic and inorganic pollutants. All sampling was conducted at the ESP exit location. Table 4-3 summarizes the CO emissions measured during each performance condition. These data confirm that changes to design and operation can result in significant reductions in CO emissions.

4.1.2.5.2 Hampton, Virginia Combustion Retrofit Program. The Hampton, VA MWC comprises two 100 tpd (91 Mg/day) mass burn waterwall combustors. The units started up in 1980. Each unit has an individual electrostatic precipitator. The Hampton MWC has been tested for trace organic emissions at least five times, and prior to the completion of a combustion retrofit the units were characterized by relatively high emissions of CDD/CDF and CO.[3] In the 1984 test report average CO emissions reportedly varied from 900 to 1400 ppm, corrected to 7 percent O_2. The units had a history of unstable operation characterized by large fluctuations in excess oxygen and furnace temperature.

TABLE 4-3. SUMMARY OF EMISSIONS FROM QUEBEC CITY MWC PERFORMANCE TESTS

TEST NO.	OPERATING LOAD	COMBUSTION CONDITIONS	CO (ppm at 7% O_2)
PT1	Low	Poor	99
PT2	Low	Good	20
PT3	Design	Poor	89
PT4	Design	Poor	86
PT5	Design	Good	21
PT6	Design	Good	29
PT7	High	Good	46
PT9	High	Good	50
PT10	Low	Good	28
PT11	Low	Good	31
PT12	Design	Good	35
PT13	High	Good	82
PT14	Design	Poor	165
PT15	Design	Poor	202

Following the completion of the 1984 emissions test, the plant operators initiated a retrofit program to modify the design and operation of the units.[18] This was not only due to concerns related to emissions, but also due to the need for corrective action to address operating problems that were plaguing the boilers. These problems were mainly related to chloride corrosion. The original cast iron grate bars were replaced with high alloy chrome-nickel grates and the life of the grates was extended from 4-6 months to 2-3 years. High alloy blocks were retrofitted on the lower side walls of the furnace, replacing existing silicon carbide refractory, and resulting in improved heat transfer and reduced clinker formation. Steam coil air preheaters were also added to the units for operation during periods of wet waste firing.

The major improvements that were made to reduce emissions were primarily related to combustion airflows and distributions. First, it was determined that the forced draft fan supplying the overfire air was providing less than half its design capacity. The fan blades were modified and the discharge duct size was increased, making the flow more aerodynamic. These modifications restored the overfire air supply to its original design capacity (45 percent of total air). The plant personnel also realized that mixing was not optimized, so they began to evaluate the size and orientation of the overfire air nozzles. There are four rows of overfire air nozzles (two rows on each of the front and rear walls). The orientation of the lower two rows was changed based on visual observations made in the furnace. The angle of the front row was raised from -45° (from the horizontal) to -22.5°. The angle of the rear wall nozzle row was changed from -20° (from the horizontal) to 0° (horizontal). Now the overfire air jets converge at a point approximately five feet (1.5 meters) above the grate rather than directly on the grate.

Modifications were also made to the operation and combustion control system. The grate speeds, which were automatically controlled, were switched to manual, which allowed the speed to be varied from 0-80 percent rather than 40-80 percent. This provided more flexibility to deal with varying waste characteristics (particularly wet waste), and resulted in improved burnout. A 15 point CO profile was performed at the economizer outlet and it was determined that CO was highest when active burning occurred on the lower burnout grate sections. An oxygen trim loop was installed which modulates the distribution of air to the burnout grate based on the O_2 content of the flue

gases. Setpoints are maintained between 7-9 percent O_2 and the proper burnout of waste on the grates is maintained.

Lastly, the existing economizer was replaced with new tube banks which drop the flue gas temperature to 425°F (218°C) before entering the ESP. Previously the ESP operated at approximately 550°F (288°C), where the potential for CDD/CDF formation was relatively high. Installation of the new economizer has reduced total fuel consumption on an hourly basis, but this has been offset by increased system availability, which has actually increased overall steam output and waste throughput. The most recent emission test performed at Hampton resulted in CO stack concentrations of 24 ppmv. The modifications were successful in reducing CO emission concentrations by more than an order of magnitude.

4.1.2.5.3 Commerce, California Overfire Air Optimization Tests. Results from a combustion optimization study conducted at the Commerce, CA MWC provide data correlating emissions of CO and NO_x with changes in overfire air firing rate and excess air operating levels.[19] The study was initiated in an attempt to define the optimal levels for these operating variables. Gaseous emission and unit operating characteristics were monitored and observed continuously, providing a set of criteria for determining optimal operating conditions. Sixteen separate test runs were performed which included three overfire/underfire air ratios (30/70, 40/60, and 50/50) and three excess O_2 setpoints (5.5%, 7.0%, and 8.5%). The test matrix is presented in Table 4-4. The thermal de-NO_x control system was shut off during the tests in order to examine the effects of the operational changes on NO_x emissions. Some of the major conclusions in the study were:

- CO emissions were less than 39 ppm (corrected to 7% O_2) for all O_2 levels when operating at 40 and 50 percent overfire air. At 30 percent overfire air, CO levels ranged from 39 to 140 ppm (corrected to 7% O_2). This relationship is illustrated in Figure 4-6.

- At 40 and 50 percent overfire air CO increases slightly with excess air.

TABLE 4-4. TEST MATRIX FOR COMMERCE, CA MWC COMBUSTION OPTIMIZATION PROGRAM

TARGET OFA	FURNACE O2 SET POINT (wet)		
	5.5%	7.0%	8.0%
30%	3, 15	1, 2, 4	8
40%	5	6, 9	7, 16**
50%	12*	11	10, 13, 14**

Numbers in table designate individual test runs.

*Actual setpoint 6.0%

**Actual setpoint 8.0%

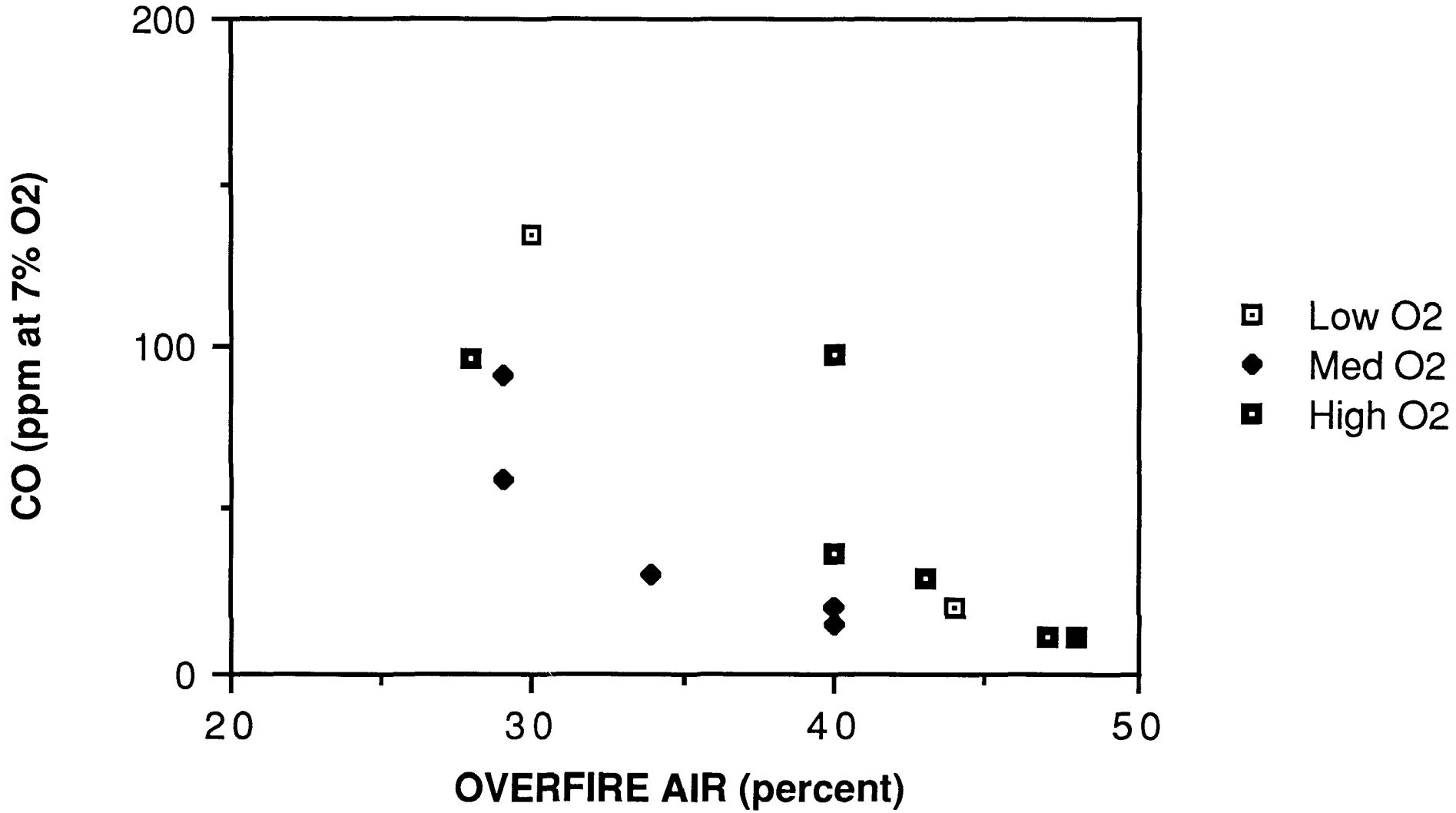


Figure 4-6. Effect of Overfire Air on CO Emissions from a Mass Burn Waterwall MWC

- At 30 percent overfire air, a parabolic curve of CO versus O_2 was demonstrated, with CO increasing sharply at both low and high O_2 levels.

The authors concluded that there is a threshold level above which mixing and completion of combustion at the overfire air injection location are optimized. Visual observations confirmed that flame height in the furnace was also lower during operation at high overfire air levels. The study confirms the ability of MWCs to minimize CO emissions by making changes to combustor operating conditions.

4.1.2.5.4 Conclusions. The Quebec City and Hampton combustion retrofit studies provide conclusive evidence of the ability for existing mass burn waterwall MWCs to minimize CO emissions through changes in combustor design and operating practices. It is doubtful that there are many existing mass burn waterwall units that will require design changes as extensive as those implemented at the Quebec unit. In addition, it is difficult to assess the contribution that each individual design change made to the overall improvement in emissions performance by the combustion system. However, results of these programs provide strong support for the judgement that combustors can retrofit successfully to reduce CO emission limits. The results of the combustion optimization study at the Commerce MWC also provide evidence that it is possible to implement operational changes that result in improved emissions performance with little or no resultant capital expenditures. The testing programs provide support for the achievability of 100 ppm CO, four-hour average, by way of applying good combustion practices.

4.1.3 Modular Starved Air MWCs

The available CO emissions data base for modular starved air MWCs consists of one set of long term continuous data, two parametric tests, and one compliance test. The long term data demonstrated that modular starved air combustors can achieve CO emissions less than 10 ppm over extended periods of time at normal steady state operating conditions. These findings were verified by data gathered during one parametric test and one compliance test. However, due to the occurrence of periodic combustor upsets during the course of normal operation, an emission limit of 50 ppm, four hour average, was

determined to be continuously achievable for new and existing modular starved air units. The test results used to reach this conclusion are summarized below.

4.1.3.1 Oswego County, NY Long Term CEM Data.

The Oswego, NY MWC plant comprises four starved air combustors, each rated at 50 tpd (45 Mg/day). Each unit is equipped with a separate waste heat boiler and electrostatic precipitator (ESP) controls. Individual O_2 and CO monitors are in place at each of the four units.

Process and emissions data were obtained for a 60 day period from March 17 to May 15, 1989, which reportedly represents a period of normal operation.[20] All four units were in operation to some extent during this period, although normal operation consists of three units on line and one on standby. The units normally operate at 80 to 90 percent of rated capacity. Emissions and process data are measured at 3 minute intervals.

Carbon monoxide emissions data from all four units were relatively consistent over the 60 day period. In general, during steady-state operating conditions, the CO concentrations were 0 to 2 ppm. A number of spikes were traced to CO instrument calibration, which occurred automatically every eight hours. These values usually varied from 10 to 50 ppm for one 3 minute reading, depending on the timing between the calibration procedure and data recording. The consistent frequency of these readings permitted them to be identified as calibration values.

There were also periodic episodes when CO spikes occurred during normal steady state process conditions. In most cases these were isolated instances for one or two readings (3-6 minutes) which could be traced to abnormal operating conditions (e.g., low secondary chamber temperatures). These upsets were usually corrected in less than an hour by taking specific action such as turning on auxiliary fuel burners.

In a few instances the duration of a CO spike extended for periods of several hours, resulting in one-hour and four-hour average CO concentrations of 100 ppm or greater. Review of process data (secondary temperature, steam flow, flue gas flow rate, etc.) provided no indication that the spikes are a direct result of process variations. Therefore, two potential sources of the

high CO levels are suggested. First, some of the high CO levels may result from incorrect instrument readings. Plant personnel identified several specific time periods during which problems were experienced with one or more of the emission monitors.[20] There may have been additional periods of monitor malfunction that were not specifically identified. The unexplained CO excursions were confined almost exclusively to Unit #2. Alternately, the high CO may have been a result of combustor operating procedures which could not be pinpointed by review of available process data. For example, several episodes of high CO occurred with regularity between midnight and 8:00 a.m. Although the process data do not provide an explanation of why the higher emissions were occurring, it is possible that the pattern reflects the operating procedures employed during that 8-hour shift. Additional periods of high CO were experienced during combustor start-up and shutdown conditions as expected. Data gathered during start-up and shutdown were excluded from the analysis.

Despite the occasional occurrence of flue gas CO concentrations as high as 100 ppmv, nearly all of the data measured during normal operating conditions were less than 10 ppm, resulting in extremely low one-hour and four-hour average values. The data represent "best combustion conditions" during the majority of time that the units are in operation.

4.1.3.2 Oswego County, NY Parametric Test.

The emission performance of one of the Oswego units has also been verified independently in a parametric emissions test sponsored by New York State Energy Research and Development Authority (NYSERDA).[21] The program included four testing conditions carried out at beginning and end of campaign cycle and at varying secondary combustion chamber temperatures. Table 4-5 summarizes the results of the CO data for each test run. The data clearly confirm the ability of the unit to operate in a consistent fashion which minimizes CO emissions. The data suggest a slight degradation in CO oxidation at lower secondary chamber operating temperatures. However, the consistently low CO emissions confirm that the unit achieves good mixing and adequate residence time at the temperatures necessary to complete CO burnout, and that the low CO emissions obtained in the long term CEM study are representative of normal operating conditions. The data indicate that burnout of CO continues in the high temperature portion of the boiler, reducing CO concentrations between the boiler inlet and outlet sampling locations.

TABLE 4-5. OSWEGO COUNTY, NY PARAMETRIC TEST RESULTS

TEST CONDITION	RUN	SECONDARY CHAMBER TEMPERATURE (°F)	(°C)	CO (ppm @ 7% O2) BOILER INLET	BOILER OUTLET
Start of Campaign	1	1875	1024	NA	0
	2	1851	1011	3	1
	3	1837	1003	4	0
	Avg	1854	1012		0
Mid-Range Secondary Temperature	4	1752	956	NA	0
	5	1741	949	4	1
	6	1738	948	3	5
	Avg	1744	951		2
End of Campaign	7	1817	992	18	2
	8	1822	994	4	4
	9	1834	1002	20	3
	Avg	1824	995	14	3
Low Secondary Temperature	10	1634	890	21	6
	11	1627	886	20	6
	12	1617	881	18	3
	Avg	1626	885	20	5

One important finding in the parametric testing program was that periodic high, short duration CO spikes coincided with activation of the ash ram in the primary combustion chamber. It was assumed by the author of the report that the cause of the CO spike was flashing of unburned refuse as it was pushed off the hearth into the ash discharge. This may have also caused the periodic short lived CO spikes that were observed in the long term continuously monitored data.

4.1.3.3 Prince Edward Island (PEI) Parametric Test.

An earlier parametric test was conducted at the Charlottetown, PEI facility by Environment Canada in 1984.[6] The plant includes three 36 tpd (33 Mg/day) units with a single waste heat boiler and no add-on pollution control equipment. The primary goal of the program was to study the relationship between combustion conditions and emissions. The available CO and CDD/CDF data are summarized in Table 4-6. Although the CO emissions data measured at PEI are relatively low, they are significantly higher than the Oswego data. Because the two units are of a similar design, it was assumed that the higher values reflected a difference in combustor operating procedures.

4.1.3.4 Red Wing, MN Compliance Test.

The Red Wing, MN MWC includes two 36 tpd (33 Mg/day) units with a waste heat boiler and ESP controls. The unit was tested for a host of pollutants in September 1986.[22] Average CO concentrations for three runs were less than 2 ppm. Limited process data are available for the units. Average primary chamber temperatures ranged from 1400-1590°F (760-866°C) and mean secondary chamber temperatures ranged from 1750-1960°F (954-1071°C).

4.1.3.5 Conclusions.

The available data from the Oswego, PEI, and Red Wing facilities confirm the ability of modular starved air MWCs to achieve very low CO emissions. However, PEI had a significantly higher mean CO concentration than the other units. The Red Wing and PEI combustors use the same combustor design. Thus, it is judged that PEI is not limited by its design from achieving CO emissions on the order of those demonstrated by the Oswego and Red Wing units, and the slightly higher emissions must be attributed to differences in combustor

TABLE 4-6. PEI PARAMETRIC TEST RESULTS

CONDITION	RUN	SECONDARY CHAMBER TEMPERATURE (°F)	(°C)	STACK EMISSIONS* CO (ppmv)	O2 (%)
Normal	2	1834	1001	59	12.3
	3	1832	1000	68	12.3
	4	1839	1004	78	12.2
	Avg	1835	1002	68	12.3
Long Cycle	5	1830	999	47	12.6
	6	1837	1003	48	12.6
	7	1788	976	29	12.3
	Avg	1818	992	41	12.5
High Secondary Temperature	8	2055	1124	47	9.9
	9	2079	1137	15	9.5
	10	2095	1146	39	9.6
	Avg	2076	1136	34	9.7
Low Secondary Temperature	11	1617	881	40	13.6
	12	1656	902	74	13.6
	13	1656	902	45	13.2
	Avg	1643	895	53	13.5

*CO emissions corrected to 7 percent O2.
O2 percentages as measured.

operating procedures, feed characteristics, or both. Contacts were made by telephone with the unit supplier to discuss operating practices which can affect CO emission levels, and one suggestion was that slag buildup around secondary air ports or in the breeching between the primary and secondary chambers can often disrupt air flow and mixing patterns to the extent that higher CO levels result.[23] This effect is implied by the data from the Oswego parametric test in which higher CO concentrations are observed at the boiler inlet during the end of campaign test runs than at the beginning of campaign. If mean CO emissions increase during the end of an operating campaign due to slagging problems it may be necessary to increase the number of scheduled shutdowns to perform maintenance and cleaning in order to maintain low CO concentrations in flue gas.

Based on the available emissions data, a CO emission limit of 50 ppm, four-hour block average, corrected to 7 percent O_2, is judged to be achievable for modular starved air MWCs. It is expected that all new units can achieve this limit by incorporating the proper mixing design and residence time in the secondary combustion chamber. The majority of existing modular starved air units are expected to be able to achieve the limit by optimizing process operations. In a very few cases the emission limit may force combustors to modify existing designs to satisfy the criteria of good combustion practice.

4.1.4 RDF Spreader Stoker MWCs

The CO concentrations from RDF spreader stokers are historically higher than from other MWC design types.[24] This is partially a result of some inherent design features unique to RDF spreader stokers. For example, semi-suspension firing results in a higher percentage of particulate matter carryover from the furnace. Particle bound organic matter can be swept out of the primary combustion zone prior to completion of the combustion process, resulting in increased CO concentrations. The design of the combustion control system also influences combustion stability and CO emissions. RDF spreader stokers typically use fuel input rate as the primary operating variable to control steam flows, while mass burn combustors automatically adjust the rate of primary combustion air supplied to the burning waste bed. Both combustion control modes attempt to maintain uniform heat release rates by adjusting overall furnace stoichiometry. However, RDF units are subject to more rapid changes in fuel properties and heat release rates due to semi-suspension feeding, and many RDF units do not have control features which can

respond to these changes in stoichiometry by automatically adjusting air flow rates. Thus, excess oxygen levels in RDF units experience wider variations than mass burn waterwall MWCs, and greater difficulties are encountered in maintaining stable combustion conditions and low CO concentrations. Secondly, RDF units are generally designed to operate at lower excess oxygen levels than mass burn waterwall units (3-9 percent O_2, dry basis, in flue gases, versus 6-12 percent O_2 for mass burn).[1] Lower O_2 availability provides a greater potential for the existence of starved air pockets of gas in the combustion process, which can lead to elevated CO levels.

Two sets of long term data were available for inclusion in this analysis from RDF combustors located in Hartford, CT and Orrington, ME. Both data sets are characterized as representing "normal operating conditions", which include significant fluctuations in oxygen and CO concentrations. Recent data from a parametric testing program at the Mid-Connecticut (Mid-Conn) RDF fired plant in Hartford, CT provide evidence that, despite differences in the design of RDF combustors which may result in high CO, emissions can be reduced significantly by modifying combustor operating conditions. These results, along with other limited compliance data from two new facilities, comprise the supporting data for the proposed CO emission limit for RDF fired combustors. A discussion of the available data is provided below.

4.1.4.1 Mid-Connecticut Long Term CEM Data.

The Mid-Connecticut (Mid-Conn) RDF facility includes a waste processing plant and three spreader stoker boilers with a combined capacity of 2000 tpd (1818 Mg/day). The units have the ability to fire 100% coal in addition to RDF. Emissions control is achieved by spray dryers and fabric filters. Three months of continuous emissions and processing data were submitted to EPA for each of the three units (#11, #12, and #13).[25] An initial screening of the data revealed that the three month period was characterized by frequent unit start-up and shutdown. Normal operating procedures at the plant include two units on line while the third is down for maintenance. However, the longest periods of continuous operation for each of the boilers were 9 days, 22 hours for Unit #11, 11 days, 20 hours for Unit #12, and 5 days, 23 hours for Unit #13. Periodic problems with instrumentation resulted in exclusion of additional data from these periods. Periods of 100 percent coal firing were also excluded. The remaining data were included in a statistical analysis for purposes of determining exceedance frequencies. Results from the statistical

analysis are presented below for Units #12 and #13. The analysis predicted the level at which one exceedance per ten years would occur was 338 ppm for Unit #12 and 333 ppm for Unit #13. Figures 4-7, 4-8, and 4-9 illustrate the variation in CO with time for each of the three units.

UNIT 12 — CALCULATED CO EMISSION LEVEL (ppm at 7% O_2)

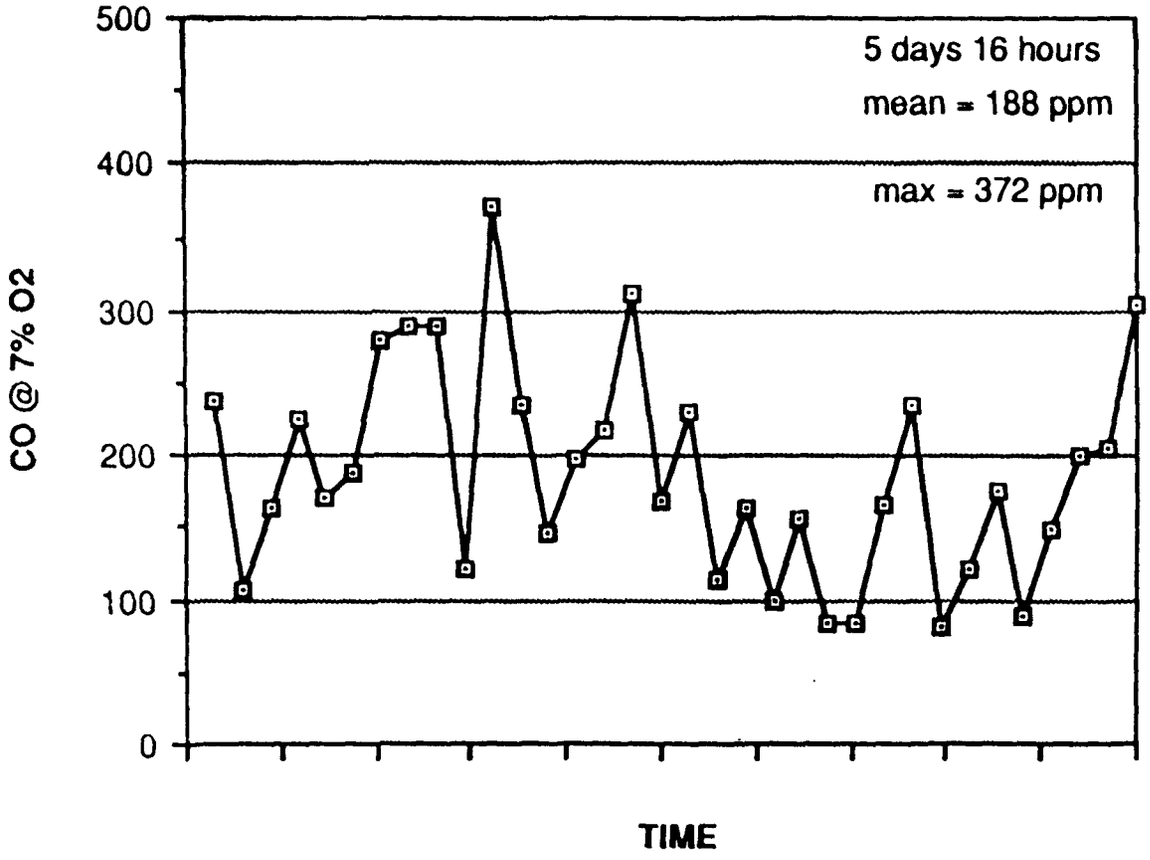
ONE EXCEEDANCE PER	1 HR ROLLING /BLOCK	4 HR ROLLING	4 HR BLOCK	8 HR ROLLING	8 HR BLOCK
100 hrs	299	211	211	253	217
1 mo	338	297	276	279	251
3 mo	357	311	292	292	267
6 mo	368	319	302	299	276
1 yr	379	328	311	306	294
10 yr	411	352	338	328	308

UNIT 13 — CALCULATED CO EMISSION LEVEL (ppm at 7% O_2)

ONE EXCEEDANCE PER	1 HR ROLLING /BLOCK	4 HR ROLLING	4 HR BLOCK	8 HR ROLLING	8 HR BLOCK
100 hrs	332	283	265	247	232
1 mo	368	340	290	258	247
3 mo	385	314	302	263	253
6 mo	395	320	308	266	256
1 yr	404	326	314	269	260
10 yr	433	343	333	278	270

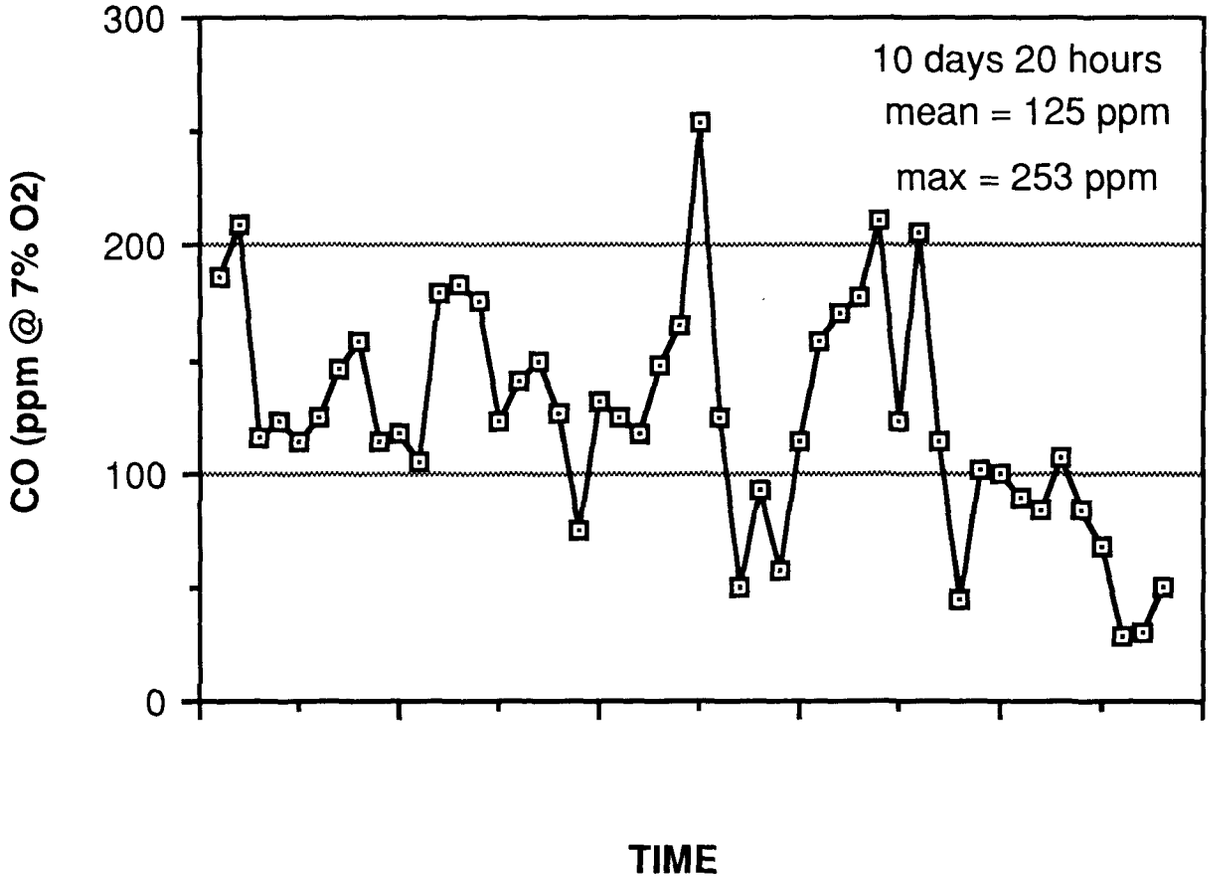
4.1.4.2 Penobscot, ME Long Term CEM Data.

Five months of continuous CEM data from the Penobscot Energy Recovery Company (PERC) RDF fired facility were submitted to EPA for inclusion in this analysis.[26] The PERC plant, located in Orrington, ME, utilizes two 360-tpd (327 Mg/day) spreader stoker boilers with spray dryer/baghouse controls. The boilers are capable of burning 100 percent oil in addition to RDF. The carbon monoxide monitor is located in the stack, which serves both boilers. The units have a CO emission limit in their operating permit of 400 ppmv, corrected to 12% CO_2, four-hour rolling average. A statistical analysis was performed on a representative segment of the data. The results are presented below:



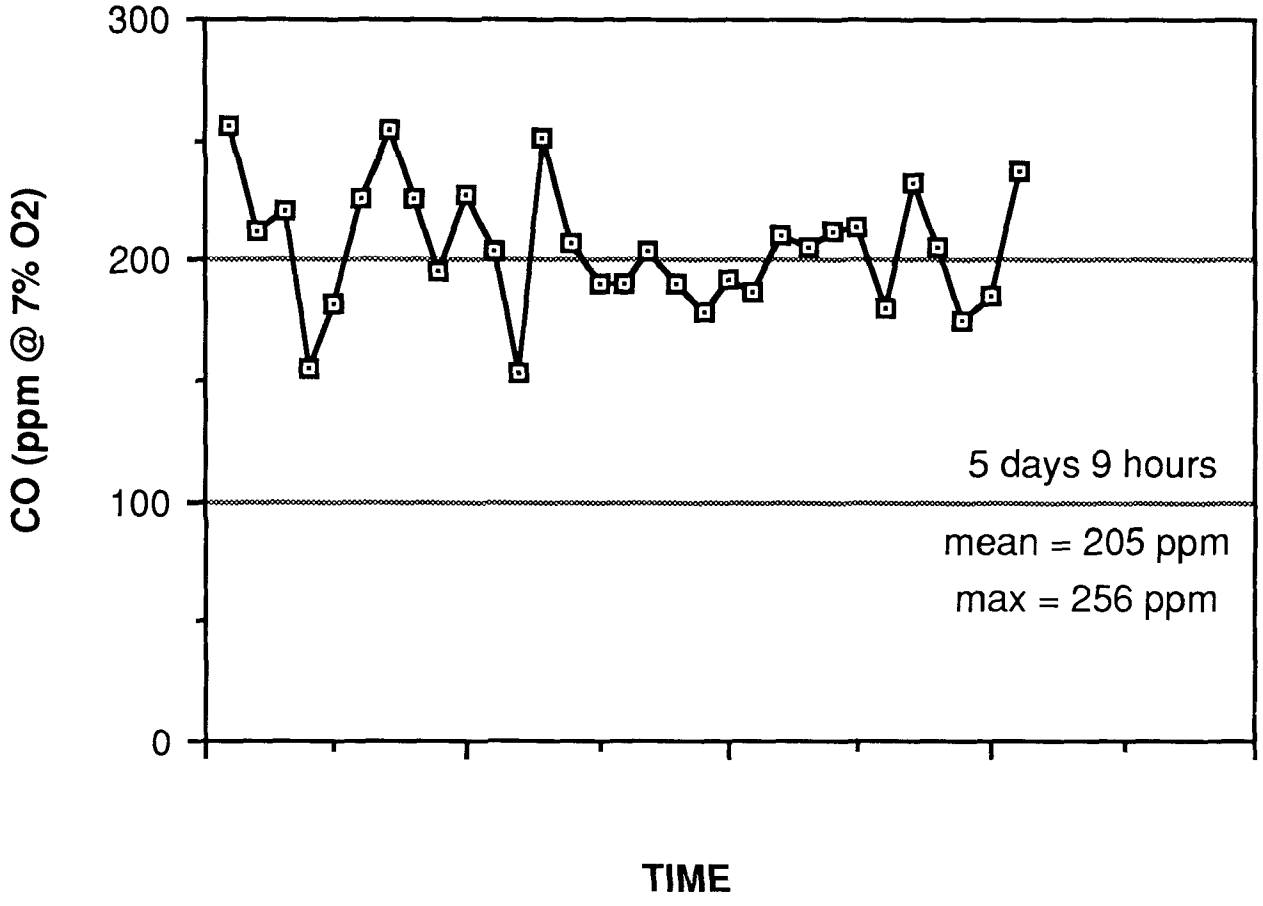
Note: Each data point represents a 4 hour block average

Figure 4-7. Mid-Connecticut Long Term CO emissions - Unit 11



Note: Each data point represents 4 hour block average

Figure 4-8. Mid-Connecticut Long term CO Emissions - Unit 12



Note: Each data point represents 4 hour block average

Figure 4-9. Mid-Connecticut Long Term CO Emissions - Unit 13

ONE EXCEEDANCE PER	CALCULATED CO EMISSION LEVEL (ppm at 7% O_2) 1 HR ROLLING /BLOCK	4 HR ROLLING	4 HR BLOCK	8 HR ROLLING	8 HR BLOCK
100 hrs	293	265	233	253	206
1 mo	339	303	278	287	251
3 mo	361	321	298	304	271
6 mo	374	332	310	313	283
1 yr	386	342	321	322	293
10 yr	423	373	355	350	325

The predicted concentration that would result in one exceedance every ten years was 355 ppm, four-hour block average. The data are plotted for a two week period in Figure 4-10.

4.1.4.3 RDF Compliance Test Results.

Numerous compliance tests have been performed on new RDF boilers that have come on-line in the past two years. Short term data are available from the following plants: Mid-Conn; PERC; Maine Energy Recovery Company (MERC) in Biddeford, ME; and Red Wing, MN. [27,28,29,30] The test results are summarized for each of the facilities below.

Facility	Mean CO Concentration (ppm @ 7% O_2)
Mid-Conn	198
PERC	191
MERC	81
Red Wing	99

By comparison, the mean four hour block concentrations from the continuous Mid-Conn data were 188, 125, and 205 ppm (see Figures 4-7, 4-8, and 4-9), and the mean four hour block concentration from the long term PERC data was 144 ppm. Although the short term compliance data may not necessarily reflect the variations in CO concentration that occur over longer operating periods, the short term mean concentrations do not vary significantly from the long term

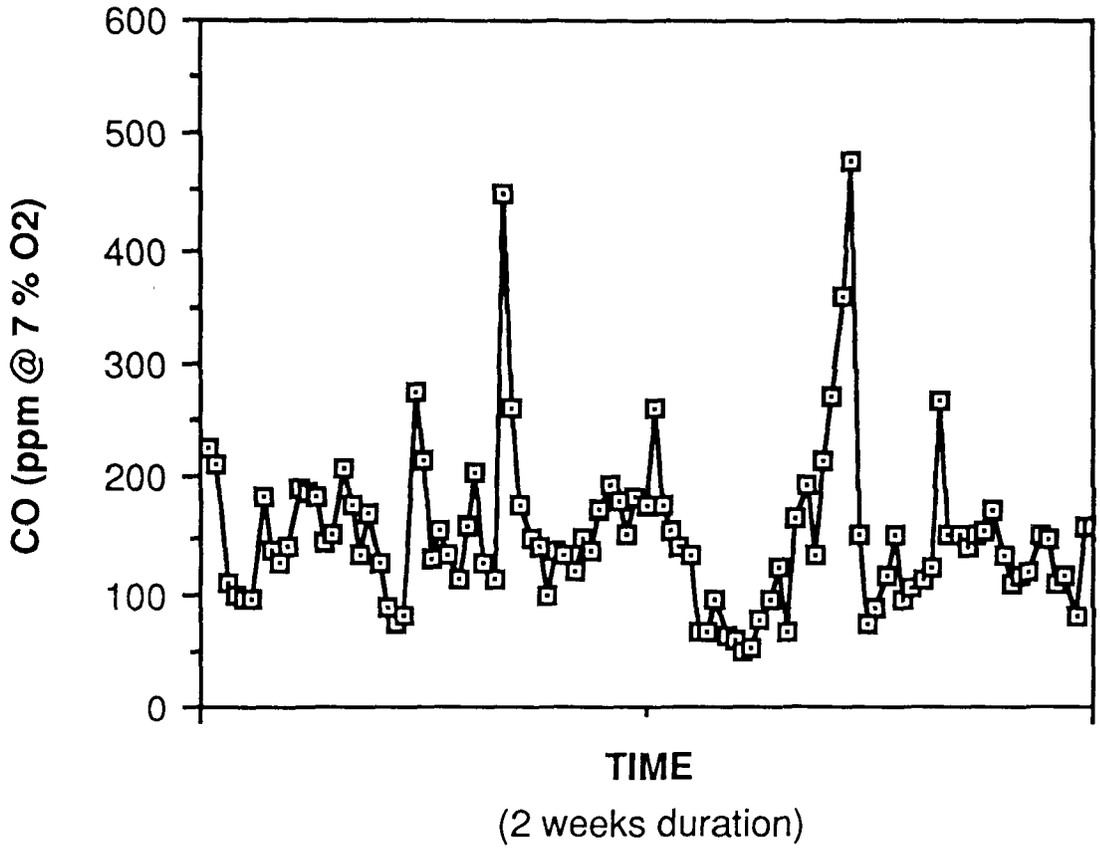


Figure 4-10. Penobscot Long Term CO Emissions

mean values. Based on this finding, it is judged that long term data from MERC or Red Wing would likely provide lower predicted exceedance levels than those from Mid-Conn or PERC.

4.1.4.4 Mid-Connecticut Parametric Test.

An extensive set of combustor operating conditions were investigated in a parametric testing program that was conducted on Unit #11 at the Mid-Conn facility in late 1988 and early 1989.[31] The goals of the program were to determine the design and operating practices which influenced emissions of organic, metals, acid gases, and criteria pollutants. Simultaneous characterization of combustor and flue gas cleaning device performance were examined. Carbon monoxide was monitored continuously during all test conditions.

Table 4-7 summarizes the test conditions examined in the program and the mean CO concentrations that were measured during each test. The data are organized based on four operating load levels (low, intermediate, normal, and high). The units have rated capacities of 231,000 lb/hr (105,000 kg/hr) of steam. However, normal steam flow conditions during the performance tests ranged from 209,000 to 223,000 lb/hr (95,000 to 101,400 kg/hr), and high load conditions were only 1 to 2 percent above rated capacity [234,000 to 235,000 lb/hr (106,400 to 106,800 kg/hr)]. The test conditions were characterized as good, poor, and very poor by target CO levels (<100 ppm, 200 to 400 ppm, and >400 ppm, respectively). These conditions were established primarily by varying combustion air distributions.

Although the test data cannot be used to characterize the long term performance of the combustor, they provide important evidence of the effect of operating conditions on CO emissions. For example, the units are equipped with two separate overfire air systems; there are three elevations of tangential overfire air (TOFA) which are normally used when burning RDF, and rows of conventional overfire air nozzles on the boiler walls, which are used when firing coal. Various combinations of TOFA and wall air were examined in the study. A pressure setting of 35 inches of water (8715 Pa) for the wall air was determined to be the optimal pressure for minimizing CO emissions in the characterization tests, which were performed prior to the performance tests. Tests PT3 (normal load) and PT5 (intermediate load) were conducted with one bank of TOFA in service and 35 inches of wall air. It is clear that

TABLE 4-7 . MID-CONNECTICUT PERFORMANCE TEST SUMMARY

PT#	STEAM LOAD 1000 lb/hr (1000 kg/hr)	OPERATING CONDITION*	CO (ppm @ 7% O2)	O2 (%)	% OFA	TOFA**	OFA PRESSURES, in. H20 (Pa)	
							RW OFA	FD FAN
13	157 (71.4)	Low/Good	199	10.1	47	2	--	10 (2490)
14	163 (74.1)	Low/Good	75	9.6	49	2	--	10 (2490)
2	193 (87.7)	Int/Good	131	9.1	52	2	--	<15 (<3735)
5	184 (83.6)	Int/Very Poor	901	8.7	36	1	35 (8715)	15 (3735)
10	192 (87.3)	Int/Good	101	9.2	52	2	--	<15 (<3735)
3	215 (97.7)	Norm/Poor	358	6.8	44	1	35 (8715)	15 (3735)
4	217 (98.6)	Norm/Poor	219	7.6	54	3	--	15 (3735)
7	223 (101.4)	Norm/Poor	340	7.2	51	3	--	13 (3237)
8	212 (96.4)	Norm/Good	93	7.5	48	2	35 (8715)	13 (3237)
9	209 (95.0)	Norm/Good	96	7.5	51	2	35 (8715)	13 (3237)
11	211 (95.9)	Norm/Good	71	7.9	52	2	35 (8715)	15 (3735)
6	234 (106.4)	High/Poor	402	8.0	57	2	--	16 (3984)
12	235 (106.8)	High/Good	109	6.5	53	2	35 (8715)	17 (4233)

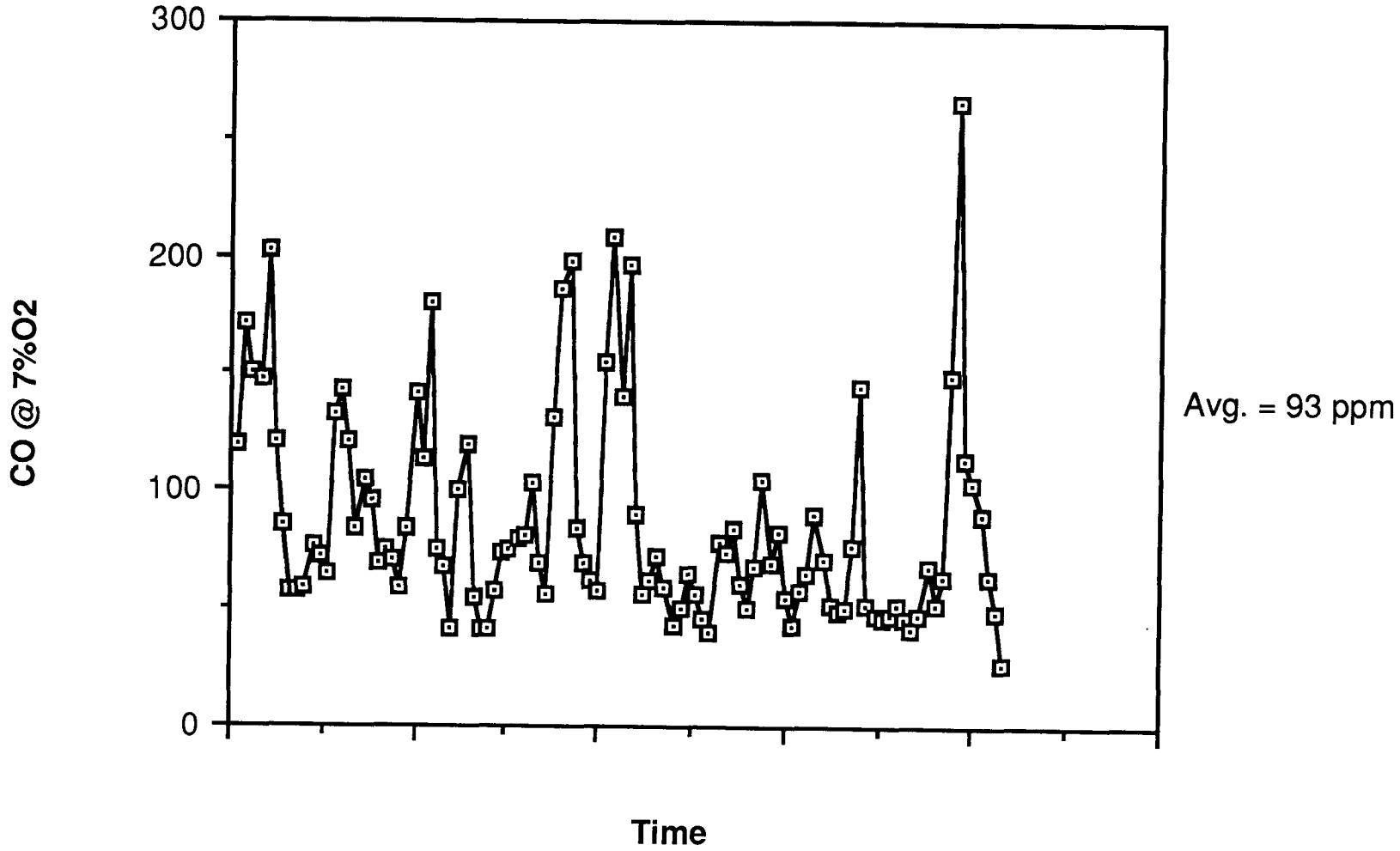
* Opeerating Conditions defined based on operating load and CO emission levels (see text, pp. 4-42)
** Elevations in service

this is an undesirable operating condition based on the CO levels (358 and 901 ppm, respectively). A single bank of TOFA does not provide sufficient mixing in the upper furnace to control CO emissions. Two additional tests were performed with all three banks of TOFA in service, PT4 and PT7 (both normal load). Neither test included wall air, and average CO emissions were 219 ppm and 340 ppm.

The remaining nine test conditions were conducted with two banks of TOFA in service, which is a normal combustion air distribution for the unit. All four operating loads were examined. Two tests were performed at low load conditions. No wall-fired combustion air was used in either case. Mean CO levels were 199 ppm during PT13 and 75 ppm during PT14. At intermediate load, the CO levels were 131 ppm during PT2 and 101 ppm during PT10, without wall-fired air.

At normal load conditions, triplicate runs were conducted with two banks of TOFA and 35 inches (8715 Pa) of wall-fired air (PT8, 9, and 11). Mean CO levels were less than 100 ppm for all tests, with a three-run average concentration of 87 ppm. Time plots are provided for each of the runs in Figures 4-11, 4-12, and 4-13. The data include periodic CO spikes which generally last for several minutes duration, with magnitudes on the order of 300-650 ppm at 7 percent O_2. Figure 4-14 shows the relationship between flue gas oxygen levels and CO concentrations for PT9. The figure clearly shows that when bulk O_2 levels in flue gases are maintained between 6 and 12 percent, the CO concentrations are below 150 ppm, corrected to 7 percent O_2. The CO spikes are entirely associated with operating conditions for which O_2 levels are below 6 percent or above 12 percent. One of the requirements of good combustion practice is to maintain operating conditions (excess O_2 levels) in a range which results in low CO emissions. This combustor, and many other existing RDF units, are lacking the control features which provide this ability, or are simply not operated in a manner which achieves this goal. It is suggested by these data that if control setpoints were established which would prevent operation outside of an acceptable range of excess O_2 levels, that CO emissions would be significantly reduced.

Additional support for the benefit of good operation on CO emission levels is provided by review of data measured during high load conditions. Two tests (PT6 and PT12) were conducted at high load, both while firing two banks of TOFA. However, wall-fired air was added during PT12, and average CO



Note: Each data point represents 3 minutes

Figure 4-11. Mid-Connecticut CO Emissions - PT8

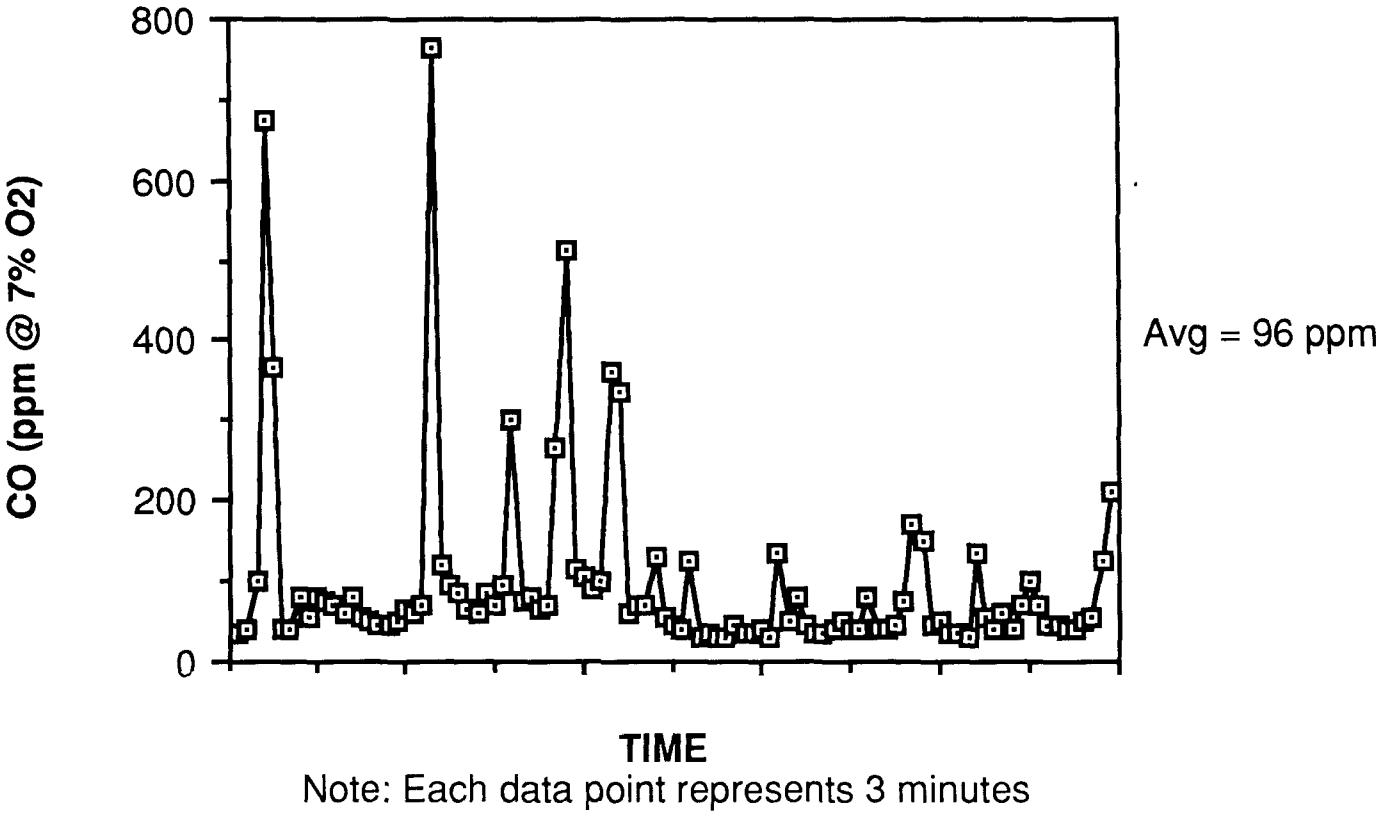
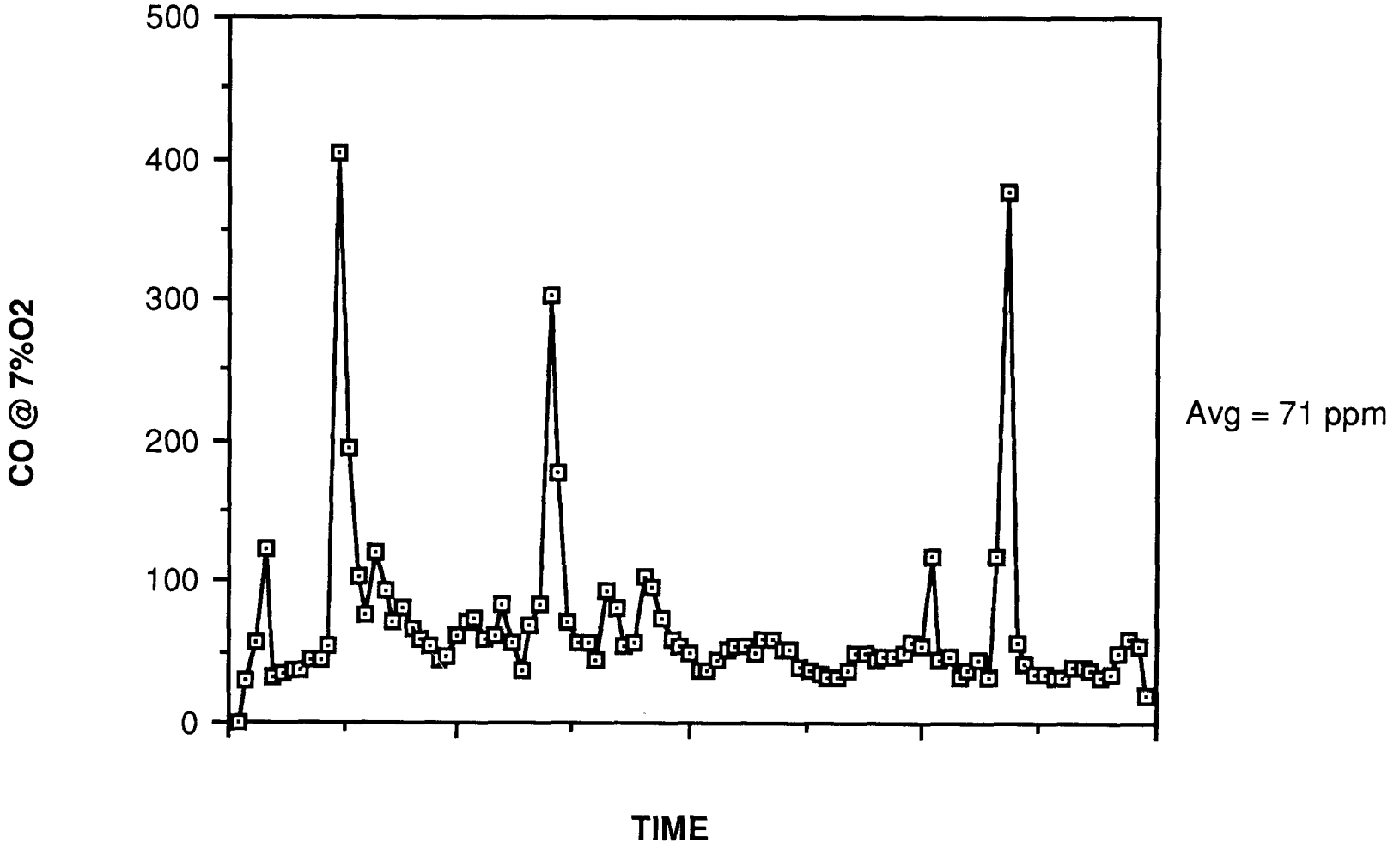


Figure 4-12. Mid-Connecticut CO Emissions - PT9



Note: Each data point represents 3 minutes

Figure 4-13. Mid-Connecticut CO Emissions - PT11

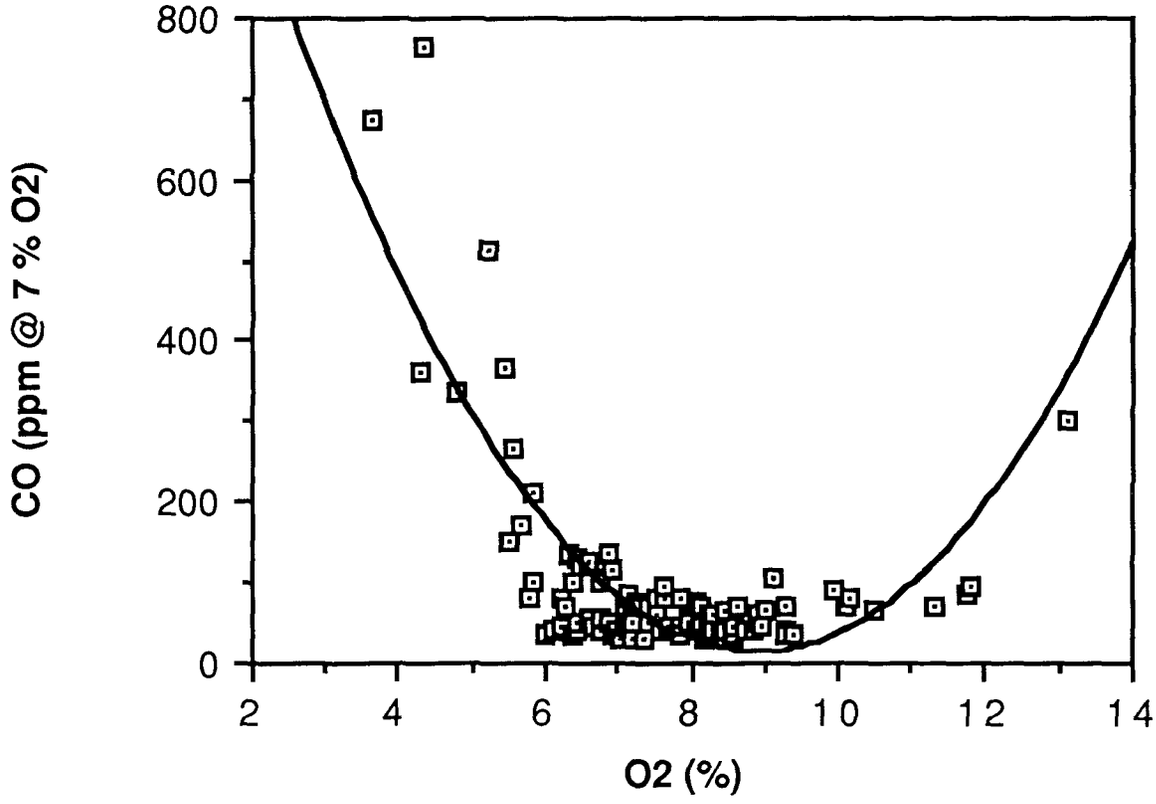


Figure 4-14. CO Versus O_2 - Mid-Connecticut PT9

emissions were reduced significantly, from 402 ppm during PT6 to 109 ppm. Thus, the use of wall-fired secondary air appears to be the optimal operating condition for minimizing CO emissions. This is currently not part of normal operating practice at the Mid-Conn units, and the long term CEM data which were discussed previously do not reflect this mode of operation.

4.1.4.5 Conclusions.

It is concluded that by establishing the proper controls to maintain excess air levels within a prescribed range, and by incorporating some key changes in combustion air distribution, that the Mid-Conn units can greatly reduce CO emissions from current normal operating levels. These recommended changes in operation (or design, if necessary) are consistent with achievement of the goals of good combustion practice. The recommended design and operating practices can be implemented for new RDF units from the initial design stages. Modification to current operating practices, and possibly design changes, will be necessary for many existing RDF units to achieve comparable CO emission limits. However, these changes are judged to be necessary as a part of the application of good combustion practices. The average CO concentrations that resulted from "good operating conditions" during the Mid-Conn performance tests ranged from 71 ppm at normal load (PT11) to 199 ppm at low load (PT13). The average steam flow rate during PT13 was 68 percent of rated capacity and included no rear wall air. The data from "best operating conditions", which are characterized by two rows of TOFA and 35 inches of rear wall air, ranged from 71-109 ppm. Based on these data, it is judged that 150 ppmv, four-hour block average, is an achievable CO emission limit for new and existing RDF boilers, and that the performance level is representative of good combustion.

4.1.5 Mass Burn Refractory Wall MWCs

There are currently no long term data available from mass burn refractory wall MWCs that can be used to establish an achievable CO emission limit. Short term data are available from one parametric testing program and several compliance tests. However, the majority of data were gathered at units that do not satisfy key requirements of good combustion practice, and are therefore not useful in establishing an achievable CO emission level. There are limited data available from two units that are comparable to the performance data routinely measured at well designed and operated mass burn

waterwall MWCs. Based on engineering judgement and these limited data it was concluded that well designed and operated mass burn refractory wall MWCs should be capable of achieving the same CO emission limits as mass burn waterwall units. The following sections provide a discussion of the available data and rationale used to reach this conclusion.

4.1.5.1 Dayton, OH Parametric Test.

A parametric emissions test was conducted by EPA at the South Dayton, OH municipal incinerator to investigate the effects of ESP temperature and sorbent use on the control of trace organic and acid gas emissions. The plant comprises three 300 tpd (273 Mg/day) refractory wall combustors with rotary kilns. There is no energy recovery capability currently in place at any of the units. Flue gas temperature reduction is accomplished by water quench chambers and emissions control is achieved by three-field ESPs. Six test conditions were examined in the program as shown in Table 4-8.[32] Triplicate testing runs were conducted at each test condition.

As shown by the test matrix, conditions 1 through 5 represent normal combustor operating conditions with a mixing chamber temperature setpoint of 1800°F (982°C). Despite attempts to maintain consistent combustor operating conditions for the first five test conditions, average CO concentrations experienced more than an order of magnitude variation (single run average concentrations ranged from 17 ppm during Run 1 to 369 ppm during Run 16). The data indicate that the unit was able to maintain the lowest CO concentrations when furnace limestone injection was shut off (conditions 1 and 2).

The specific reasons for the wide variation in CO emissions are not clear at this time, but are probably due to poor mixing and an overall lack of combustion control. For example, the unit was operated solely on induced draft, which is manually set and automatically adjusted to maintain negative pressure setpoints in the furnace. There was no primary air supplied through the existing forced draft fan. Multiple points of air inleakage are present throughout the system at access doors, ports, and at both the entrance and discharge of the rotary kiln. Temperature setpoints in the ignition chamber (upstream of the kiln) and the mixing chamber (downstream of the kiln) are maintained by adjusting refuse feed rates, the speed of the reciprocating feed grates and to a lesser extent, the kiln speed. There is no secondary air injection with the exception of side wall ports in the ignition chamber.

TABLE 4-8. SOUTH DAYTON MWC PARAMETRIC TEST - SUMMARY OF CO EMISSION CONCENTRATIONS

CONDITION	ESP INLET TEMPERATURE SETPOINT	MIXING CHAMBER TEMPERATURE TARGET	SORBENT INJECTION	CO EMISSIONS (ppm at 7% O2) RUN	
1	575°F (302°C)	Normal - 1800°F (982°C)	off	1	17
				2	42
				3	34
				Avg	31
2	400°F (204°C)	Normal	off	4	37
				5	52
				6	35
				Avg	41
3	400°F (204°C)	Normal	Limestone Furnace Injection	10	303
				11	206
				12	181
				Avg	230
4	300°F (149°C)	Normal	Limestone Furnace Injection	13	140
				14	154
				15	108
				Avg	134
5	300°F (149°C)	Normal	In-Duct Hydrated Lime Injection	16	369
				17	38
				18	31
				Avg	146
6	575°F (302°C)	Low - 1500°F (816°C)	Limestone Furnace Injection	7	118
				8	347
				9	412
				Avg	292

The facility fails to satisfy a key requirement of GCP (good mixing at adequate temperature) with its current design. The absence of good combustion air distribution and control results in relatively high fluctuations in O_2 and CO concentrations. Although the units can clearly achieve the necessary temperatures to destroy trace organics, failure to provide good mixing at the necessary temperature results in poor CO oxidation. It is probable that the units could make the necessary modifications in design and operation to correct these problems.

4.1.5.2 Mass Burn Refractory Compliance Test Results.

The McKay Bay MWC, located in Tampa, FL comprises four 250 tpd (227 Mg/day) units that began operating in 1985. The units are equipped with waste heat boilers and ESP controls. Compliance tests were performed in 1986 and average CO emissions were 32-35 ppm for each of the four units.[24] Limited information is available describing the process control data during the tests. The units reportedly operate on a manual control scheme to maintain O_2 levels in flue gases between 8-12 percent, dry basis. This range of excess oxygen is lower than concentrations reported for most non-heat recovery refractory wall MWCs and it corresponds to the range established for good combustion practice recommendations. The very low CO levels indicate that the units have the ability to achieve good mixing at adequate furnace temperatures. It is not possible to speculate on the stability of the combustion process over long term operating periods. However, the units are equipped with steam air preheaters which provide the ability to address operating problems that may be encountered with wet waste. These operating provisions, which are rarely found at refractory wall MWCs, are necessary to ensure good combustion practice.

Additional compliance test results are available from three old refractory wall incinerators (Philadelphia Northwest and East Central plants and Grosse Point/Clinton, Michigan plant).[24,33] None of these plants satisfies the design and operating requirements of GCP, and the data are not useful for establishing emission levels representing good combustion practice. Both of the Philadelphia plants were permanently closed in 1988. Short term average CO emissions from the plants ranged from a low value of 51 ppm at Philadelphia East Central #2 to a high of 821 ppm at Philadelphia Northwest #2. Emissions from the Grosse Point/Clinton MWC were reported to be 376 ppm.

4.1.5.3 Conclusions.

The McKay Bay data provide some evidence that new refractory wall combustors can be designed and operated to achieve CO emissions in the range typically reported for well designed and operated mass burn waterwall units. Although basic differences in furnace design exist between waterwall and refractory wall mass burn systems, the principles that control CO burnout (good mixing at adequate temperature) can be incorporated into the design of new units in both combustor classes. Thus, no design limitations are expected to prevent new refractory wall combustors from achieving CO emission levels comparable to those from mass burn waterwall units, provided that the refractory wall units incorporate good combustion practice. This requirement may force some manufacturers to consider inclusion of additional design features such as automatic combustion controls to provide for combustion stability or to consider modifying mixing designs. However, by designing the combustor to satisfy a basic goal of GCP, good mixing at adequate temperature, refractory wall combustors are expected to attain CO emission performance levels similar to those of mass burn waterwall MWCs.

The population of existing refractory wall MWCs includes incinerator units that vary in age from more than 30 to less than 5 years. Nearly all of these units will require retrofits to improve operating performance to a level representing good combustion practice. A discussion of potential combustion retrofit strategies is included for refractory wall combustors in a separate report published by EPA.[34] In this report it was estimated that existing refractory wall MWCs could reduce CO emissions to 150 ppm, four-hour average, by retrofitting to meet good combustion practice requirements. This estimate was made prior to the completion of the South Dayton parametric test. Results from that testing program indicate that the estimate was overly conservative because the unit achieved very low CO levels for many test runs despite lacking some key components of good combustion practice. It is therefore judged that implementation of the necessary design and operating modifications to satisfy good combustion practice would result in the ability of the units to achieve CO emission levels comparable to new and existing mass burn waterwall MWCs. It was concluded that the mass burn waterwall CO emission levels (100 ppm corrected to 7 percent O_2, four-hour block average) are also achievable for new and existing mass burn refractory wall MWCs that apply good combustion practices.

4.1.6 Mass Burn Rotary Waterwall MWCs

Limited emissions data are available to characterize the CO emission performance of mass burn rotary waterwall MWCs, partly due to the few number of operating facilities in the existing population. However, the units are sufficiently distinct in their design from conventional mass burn waterwall combustors that a technology specific performance analysis is warranted. For example, rotary waterwall combustors are typically designed to operate at excess air levels near 50 percent, which is a value more commonly associated with RDF spreader stokers than conventional mass burn waterwall MWCs.[1] Grate burning waterwall units are typically designed to operate at 80-100 percent excess air. Lower excess air levels reduce the availability of oxygen to complete the combustion process, which can lead to higher CO emissions. The available data from a new mass burn rotary waterwall MWC confirm that CO performance levels are also more typical of RDF spreader stokers than conventional mass burn waterwall MWCs. The data support establishment of an achievable CO emission limit equal to that of RDF spreader stokers, 150 ppm at 7 percent O_2, four-hour block average. A discussion of the data is presented below.

4.1.6.1 Dutchess County, NY Compliance Test. The Dutchess County MWC is designed to burn 510 tpd (464 Mg/day) of MSW in two rotary waterwall combustors. Each combustor has its own boiler and flue gas cleaning system, a dry sorbent injection system and a baghouse. Both units were tested for CO as part of an initial compliance requirement in February 1988.[35]

The permitted CO emission rate is 13 lb/hr for each unit. Both units exceeded the permitted limit during the initial compliance test. Average emissions were 13.9 lb/hr (161 ppm at 7 percent O_2) for Unit #1 and 13.8 lb/hr (156 ppm at 7 percent O_2) for Unit #2. Both values are average emission rates for three one-hour tests.

Two specific design changes were reportedly made to the units which were intended to improve combustion conditions and lower CO emissions.[35] First, the axial seals, which are used to seal the combustor windbox sections, were redesigned and replaced. Second, a deflector plate was installed to spread the bottom ash evenly across the afterburning grate. Following completion of these modifications, the units were retested in May 1988. Average CO

concentrations for the units were reported to be 144 ppm and 127 ppm, both corrected to 7 percent O_2.

A plot of the CO data from the retest is included for both units in Figures 4-15a and 4-15b. The data include three individual one-hour runs per unit. Two of the hourly runs include CO spikes which exceeded 600 ppm at 7 percent O_2. Review of the 5-minute average O_2 concentration confirms that the CO spikes occurred at low O_2 conditions. High heating value fuel can cause a rapid release of volatiles which depletes local O_2 concentrations and results in the occurrence of oxygen starved, fuel rich gas pockets. If these fuel rich gases escape the furnace unmixed, high CO spikes will occur. The flue gas O_2 levels at the Dutchess County plant are controlled manually. The absence of an automatic O_2 control loop which can respond to low flue gas O_2 concentrations probably contributes to the high CO levels. The new rotary waterwall designs are expected to incorporate this control feature, which should lead to more stable CO performance.

4.1.6.2 Conclusions

The CO data available for mass burn rotary waterwall MWCs are insufficient to firmly establish a long term achievable emission limit. However, it is judged that the units can maintain relatively low CO levels by providing good control of excess air levels and a good mixing design, both of which are necessary requirements of good combustion practice. Based on the similarity between rotary waterwall MWCs and RDF spreader stokers with regard to typical excess O_2 design and operating levels, it is judged that rotary waterwall units can achieve the same long term CO emissions as RDF spreader stokers, 150 ppm at 7 percent O_2, four-hour block average.

4.1.7 Modular Excess Air MWCs

There are currently no long term continuous CO emissions data available for excess air modular MWCs. The available data base does include short term data gathered at the Pittsfield, MA facility during a parametric testing program and data measured during compliance testing at the Pope/Douglas County, MN MWC. An extensive set of data from Pittsfield confirmed that the unit was capable of achieving CO concentrations comparable to those from well designed and operated modular starved air MWCs. Based on the similarities in design, operation, and emissions performance between excess air and starved

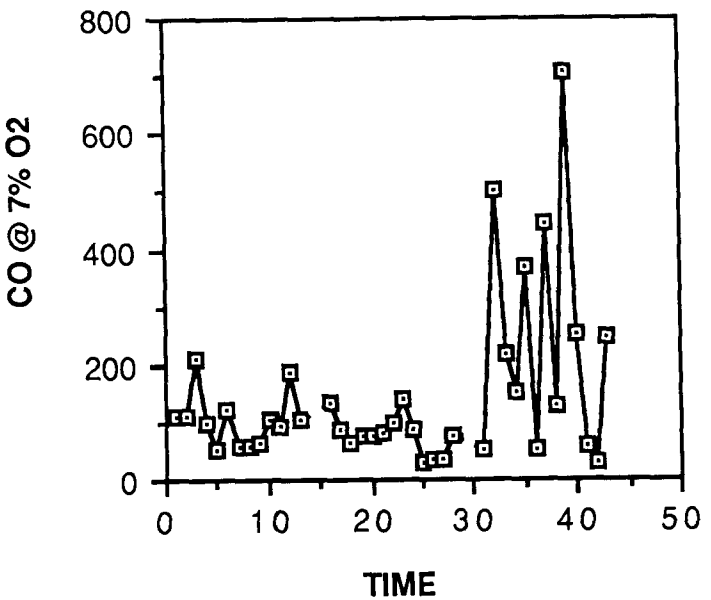


Figure 4-15a. Dutchess County CO Emissions - Unit 1

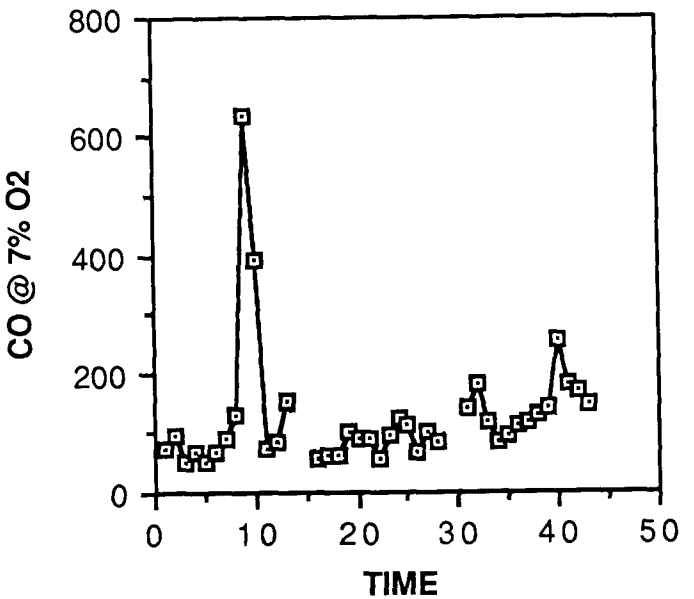


Figure 4-15b. Dutchess County CO Emissions - Unit 2

air modular MWCs, identical CO emission levels were recommended for the two technologies. The test results used to establish this conclusion are summarized below.

4.1.7.1 Pittsfield, MA Parametric Test. The Pittsfield MWC comprises three units, each rated at 120 tpd (109 Mg/day), with two waste heat boilers and electrified gravel bed filter controls. Table 4-9 summarizes average CO emission results from the Pittsfield, MA parametric test on a run-by-run basis.[7] The units were tested while operating at temperatures varying from 1300-1800°F (704-982°C), and while firing a number of waste fuels with different characteristics. Two units operated during the test and the third was maintained on standby. The key operating variable used to control combustion temperature was the feed input rate. Varying amounts of combustion air and recirculated air were also used to a lesser extent to vary operating temperatures.

The data in Table 4-9 clearly confirm that the Pittsfield MWC is capable of maintaining CO emissions below 20 ppm while operating at design conditions. Only when the unit was operated at very low temperatures did the CO concentrations show a noticeable increase above baseline levels.

4.1.7.2 Pope/Douglas County, MN Compliance Test.

The Pope/Douglas County facility includes two modular excess air units, each rated at 38 tpd (35 Mg/day). Compliance tests were performed in July 1987. One hour carbon monoxide samples were measured and ranged from 20-40 ppm at 7 percent O_2 during normal operating conditions.[36]

4.1.7.3 Conclusions.

The short duration test results from the Pittsfield and Pope/Douglas MWCs are not sufficient by themselves to firmly establish a continuous CO emission limit for modular excess air MWCs. However, the data demonstrate that excess air modular units and starved air modular units have demonstrated similar levels of CO emission performance. The two technologies are extremely similar in their design in that both typically include multiple refractory lined combustion chambers into which waste is fed and burned in a primary chamber and the off gases are mixed with air and burned out in a separate

TABLE 4-9. PITTSFIELD, MA PARAMETRIC TEST RESULTS

TESTING CONDITION	RUN	TERTIARY DUCT	BOILER OUTLET	
		CO* (ppmv)	O_2 (%)	CO* (ppmv)
1300°F - MSW	11	152	13.5	111
	22	251	14.8	187
1400°F - MSW	28	43	12.1	21
1550°F - MSW	10	8	12.0	13
	16	11	10.8	13
1550°F - MSW + H_2O	15	8	10.8	12
	21	25	12.3	16
1800°F - MSW	9	5	8.7	7
	14	3	10.1	16
1800°F - MSW, low O_2	23	3	8.3	8
	26	12	8.0	10
1800°F - MSW + PVC	18	7	9.5	7
	25	4	10.1	8
1800°F - PVC free	12	0	9.4	5
	17	2	10.3	13
1800°F - PVC free + PVC	13	4	10.8	20
	19	7	11.2	8
1800°F - PVC free + H_2O	24	11	10.0	3
	29	6	10.6	10

*CO presented corrected to 7 percent O_2.

secondary chamber. The major distinction between the two technologies is the stoichiometry in the primary chamber. This oxidation of CO to CO_2 is achieved by both combustor types in the secondary combustion chamber, so the distinction in the primary chamber stoichiometry is not significant in determining the extent to which the units can achieve low CO levels. Therefore, the similarity between starved air and excess air modular MWCs in design and in emissions performance provides the rationale that both combustor types can achieve CO emission levels of 50 ppm at 7 percent O_2, four-hour block average.

4.1.8 Fluidized Bed Combustors

The use of FBC units in the MWC industry is not widely practiced in the U.S. at this time. There are currently only two operating facilities, both of which use bubbling bed technology, in Duluth, MN and La Crosse, WI. Two facilities are in the advanced planning or construction stage and several others are in the feasibility study or early planning stage. The available CO performance data are limited to short term emission compliance tests from the Duluth and La Crosse units, and short term data from a circulating fluidized bed unit located in Sundsvall, Sweden. The majority of the data are comparable to or lower than short term CO concentrations typically measured at well designed and operated mass burn waterwall MWCs. These results led to the conclusion that well designed and operated FBC units could achieve a continuous CO emission limit of 100 ppm, corrected to 7 percent O_2, four-hour average. A discussion of the data used to reach this conclusion is presented below.

4.1.8.1 Western Lake Superior Sanitary District (WLSSD), Duluth, MN.

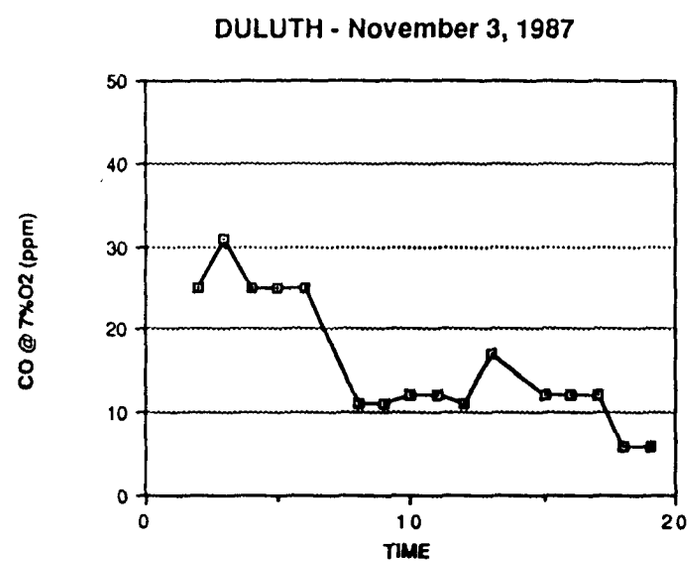
The WLSSD facility consists of two identical bubbling bed FBCs with individual waste heat boilers. Each combustor is capable of firing 120 tpd (109 Mg/day) of fluff-RDF and 345 tpd (314 Mg/day) of sewage sludge (18 percent solids); thus, RDF represents approximately 26 percent of the total waste input at full load. A detailed description of the facility design and operating conditions is provided in a separate FBC technology report which is published as part of EPA's MWC Technology Assessment.[37]

An emissions performance test was conducted on Unit 2 in November 1987.[38] During these tests, RDF was fired at 4.7 ton/hr (4.3 Mg/hr) and sewage sludge was injected at 14.4 ton/hr (13.1 Mg/hr). Available CO data are summarized in Figure 4-16. Four separate test runs were performed on consecutive days. Each test run was four hours in duration. Average four-hour block CO concentrations for the four runs were 16 ppm, 56 ppm, 5 ppm, and 7 ppm, all corrected to 7 percent O_2. The 56 ppm mean value included two measured values of 346 and 369 ppm. The cause of the CO excursions are not identified. The available data from the unit confirm the ability of the system to achieve good CO burnout. With the exception of the one run, all four-hour block averages are below the CO values typically measured at mass burn waterwall MWCs.

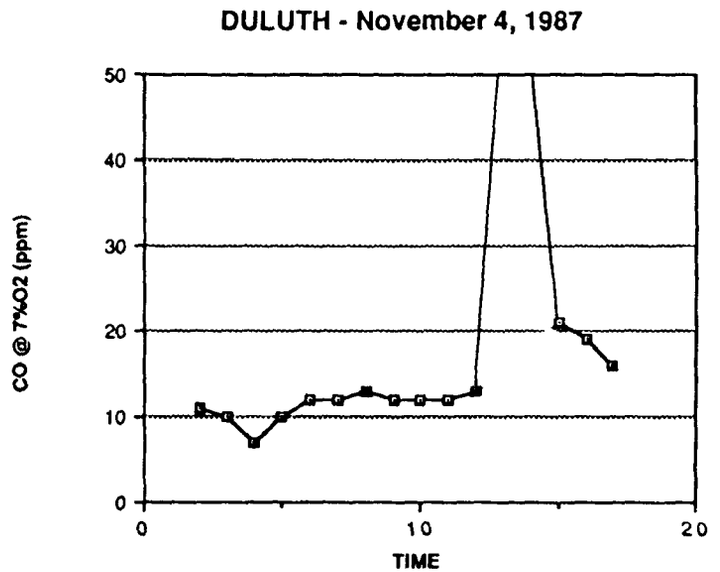
4.1.8.2 Northern States Power French Island Facility, La Crosse, WI.

The NSP French Island Generating Facility in La Crosse, Wisconsin, comprises two bubbling bed FBCs which were retrofitted to existing boilers in 1981 (Unit 2) and 1987 (Unit 1). NSP began co-firing RDF and wood chips in the two units (previously fueled with coal) in November 1987. Each of the FBC units has capacity to fire about 12 ton/hr (10.9 Mg/hr) of RDF and 11 ton/hr (10.0 ton/hr) of wood chips; with the current operation pattern (16 hr/day, 5 day/wk), the daily capacity of each unit is about 185 tpd (168 Mg/day) of RDF and 175 tpd (159 Mg/day) of wood waste (approximately 51 percent RDF by weight). The facility operating permit limits the RDF to a maximum of 50 percent of the heat input.

An emissions performance test was conducted on Unit 1 in May 1988.[39] During the test, the unit heat input was evenly distributed between RDF and wood chips. Sampling was conducted in the stack, downstream of the gravel bed electro-scrubber. Average CO emissions from the unit were 296 ppm, corrected to 7 percent O_2. It is probable that design constraints resulting from the retrofit of the boiler limit the ability of the unit to achieve good CO burnout. Less than 9 feet (2.7 meters) of furnace height separates the top of the bed from the entrance to the first convective section. This relatively short freeboard limits the time at which combustion gases emitted from the bed are subjected to high temperatures. By contrast, the WLSSD freeboard is approximately 30 feet (9.1 meters) high. It is probable that CO oxidation reactions are quenched when the combustion products reached the convective



Note: Each data point represents 15 minutes



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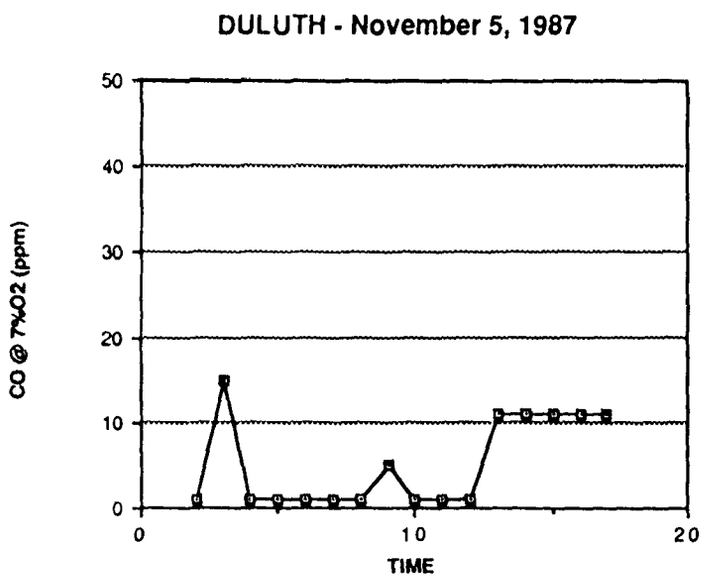

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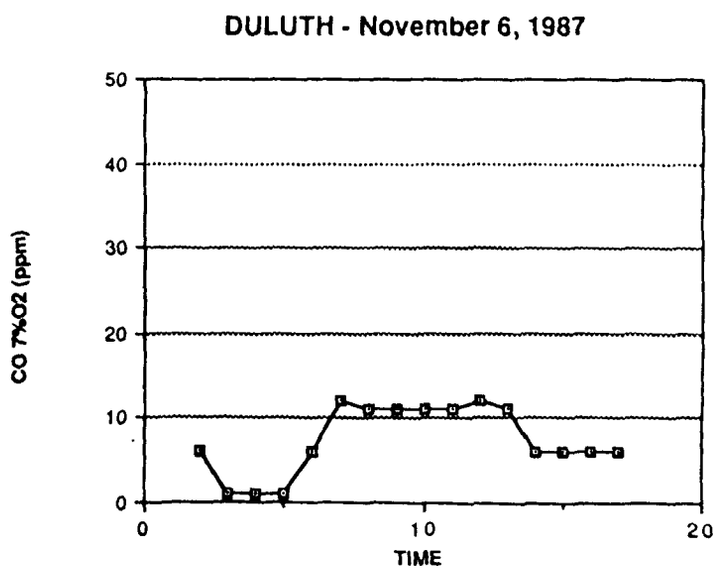

Note: Each data point represents 15 minutes

Figure 4-16. Fluidized Bed Combustor - CO Emissions

sections of the boiler, resulting in incomplete CO oxidation. This condition is unique to the French Island boilers and is not expected to be encountered in units that are designed to fire RDF in the future. The data were not considered in determining the achievable CO emission limit for FBC units.

4.1.8.3 Sundsvall, Sweden CFB Test Program.

The Sundsvall CFB is a 20 MW boiler manufactured by Gotaverken. The unit is equipped with an ESP and a baghouse in series. Results from 17 performance tests at the unit were supplied to EPA by Gotaverken during which multi-pollutant emissions testing was performed at various operating loads.[37] The tests ranged from 1-3 hours duration. Average CO emissions in the stack ranged from 5-59 ppm, corrected to 7 percent O_2. Documentation describing process operating conditions for the tests is very limited. However, the data indicate that CFB units are capable of achieving low CO levels over short operating periods.

4.1.8.4 Conclusions.

The CO data available from FBC units are very limited. However, the short term data from one bubbling bed unit and one CFB unit provide evidence that the units can be designed and operated to achieve low CO concentrations. The achievable CO emission limit is established for FBC units largely by use of these limited data and by using engineering judgement. The short term CO data are comparable to data from other units for which long term continuous data are available (mass burn waterwall MWCs). It is judged that by providing the necessary design, operation and control measures associated with good combustion practices, FBC units can achieve CO levels of 100 ppm, corrected to 7 percent O_2, four-hour block average, on a continuous basis.

4.2 Operating Load

A large number of combustor operating parameters, including furnace temperature, mixing, and combustion air flow rate, are impacted by operating load levels. Because these parameters have a direct effect on pollutant emission levels, it is necessary to maintain an appropriate operating load range as part of good combustion practice. Low load operation is limited by minimum temperature and mixing constraints. For example, as waste feed rates are reduced, it is necessary to make corresponding reductions in combustion

air flow rates to maintain stoichiometry and furnace temperature. As load continues to drop furnace temperature also decreases (Figure 4-17), and as air flows are reduced, a point is reached at which the overfire air system does not provide adequate mixing. The combined deterioration in mixing performance and temperature will lead to increased CO and organic emissions.

Low load operating limits are incorporated indirectly in GCP by way of the CO emission limits. Figure 4-18 illustrates the relationship between steam load and CO flue gas concentrations for a mass burn waterwall unit. As the operating load is reduced, the temperature and mixing characteristics diminish, resulting in increased flue gas CO concentrations. This relationship applies in all MWCs. Therefore, the existence of a CO emission limit precludes the need for a lower operating load limit.

At operating loads above design ratings the furnace may be overcharged, volumetric flow rates are increased, solid and gas residence times are reduced, and increased amounts of unburned gas and solid organic materials may be carried out of the furnace prior to completing combustion. Recent research on CDD/CDF formation mechanism indicates that emissions of CDD/CDF are correlated with the amount of particulate matter carryover from the furnace. Figure 4-19 illustrates the relationship between PM carryover and CDD/CDF in the stack for a mass burn waterwall combustor and an RDF spreader stoker.[40] The amount of PM carryover will vary based on a number of parameters, including fuel properties and feeding method, excess air levels, and primary/secondary air ratios. No direct method exists to continuously monitor PM carryover. Therefore, a maximum operating load level in effect provides a surrogate limit to address control of PM carryover.

Maximum design loads are established based on calculated volumetric heat release rates and on established boiler design codes and standards. An upper load limit is established for MWCs to prevent operation at loads that exceed design criteria. Limited data are available to characterize the effect of high load operation on emissions. However, a fundamental requirement of good combustion practice is that combustors be operated within limits established by design criteria. This requirement provides the basis for establishing a maximum operating limit of 100 percent of design steam flow.

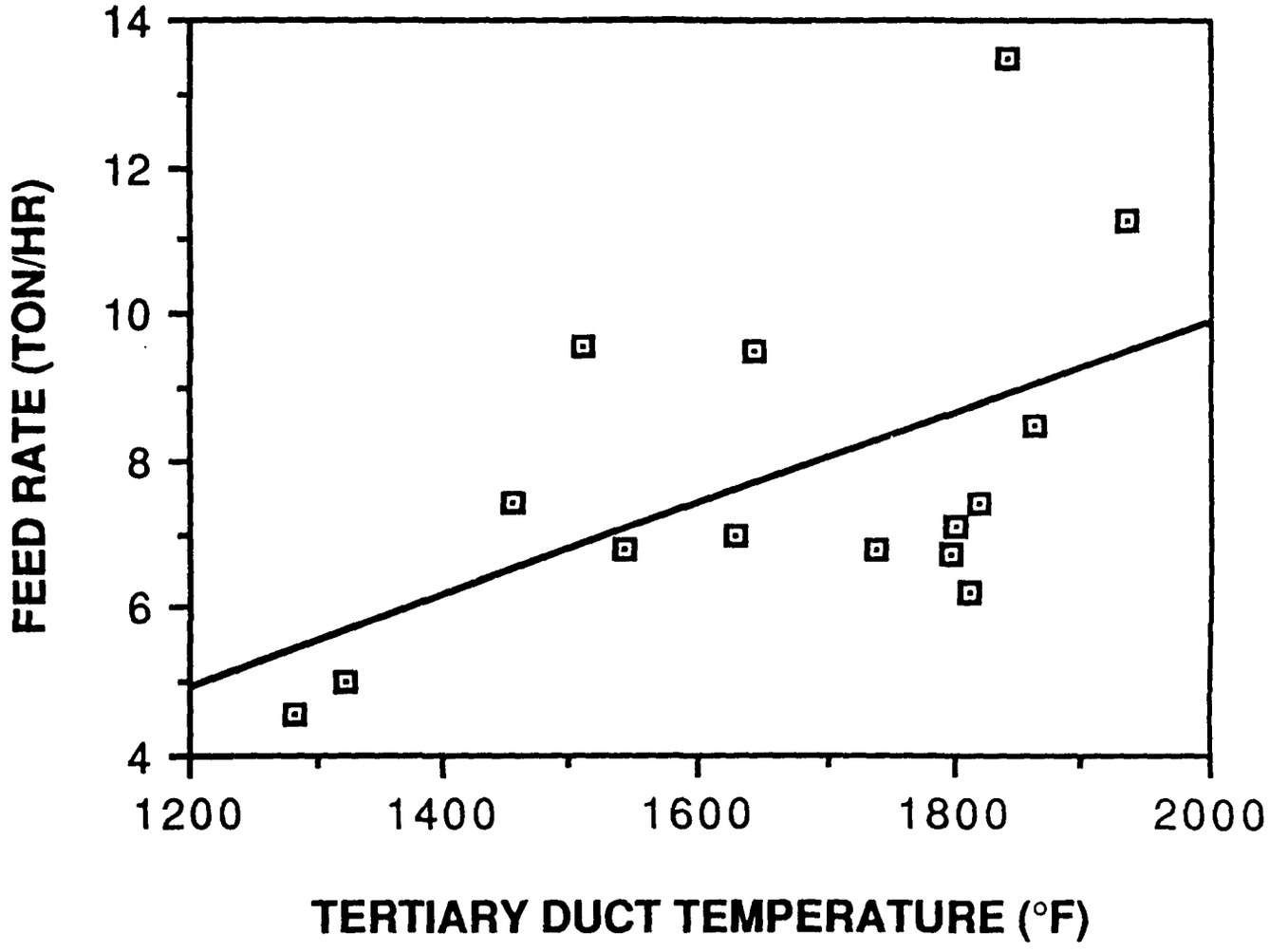

Figure 4-17. Effect of Feed Rate on Temperature for a Modular Excess Air MWC

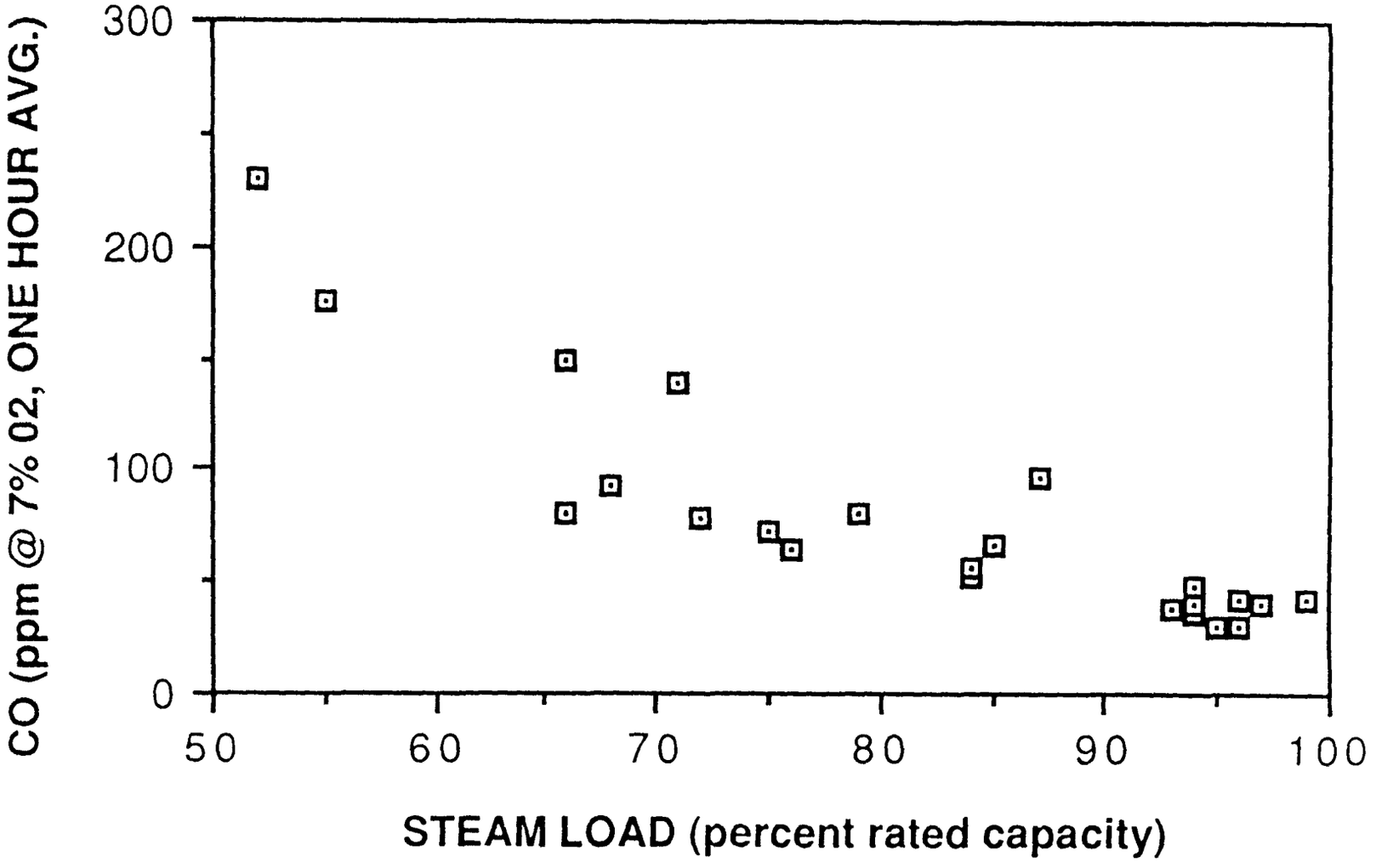

Figure 4-18. Effect of Operating Load on CO Emissions from a Mass Burn Waterwall MWC

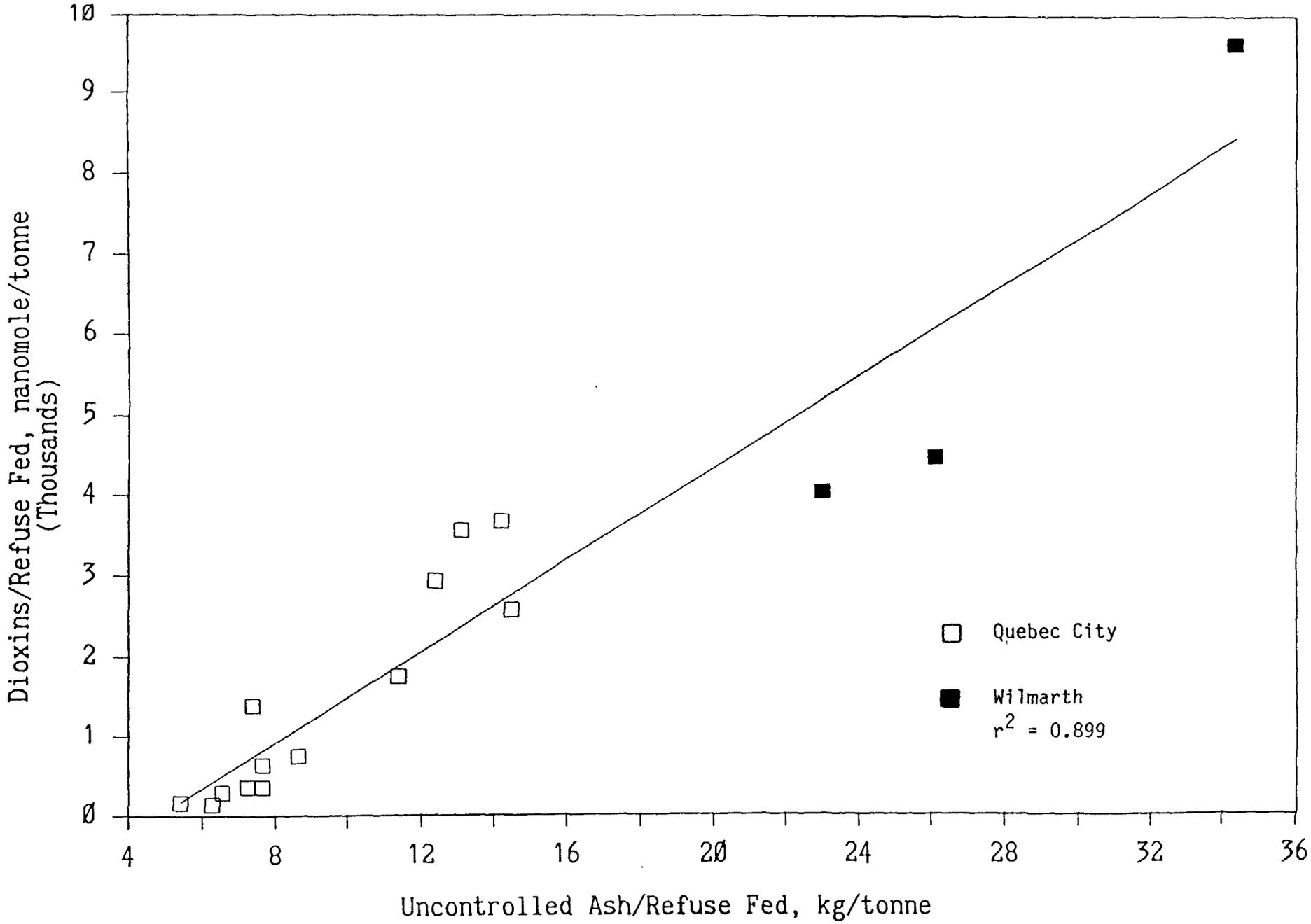

Figure 4-19. Relationship Between PM Carryover and CDD/CDF Emissions

The operating load limit can be verified in heat recovery units by continuously monitoring steam production rates. All MWCs that generate steam are expected to continuously monitor steam flow rates and/or pressures and temperatures. Steam flow or pressure setpoints are maintained automatically by adjusting combustion air flows and feed rates. No convenient continuous verification method exists for facilities that do not produce steam. Thus, the operating load can be measured only at the following MWC design types:

- mass burn waterwall boilers
- RDF spreader stoker boilers
- rotary waterwall boilers
- RDF co-fired boilers
- FBC boilers
- CFB boilers
- mass burn refractory and modular combustors with waste heat boilers

Normal steam production rates are subject to slight variation from setpoints despite the automatic controls in place at most MWCs. Therefore, it is necessary to include an averaging time with the operating limit to allow for initiation of corrective action in the event of upset conditions. A four-hour block average is selected because it is of short enough duration to encourage prompt corrective action to be taken in the event of an upset condition, and it is consistent with other data averaging periods in the combustor operating standards.

4.3 Downstream Temperature Control

Recent research findings indicate that CDD/CDF formation can occur on fly ash particles in the presence of excess oxygen at temperatures in the range of 392-752°F (200-400°C), with maximum formation rates occurring near 572°F (300°C).[10,11] A number of variables, including oxygen content, fly ash carbon content, catalysts, moisture, residence time, etc., appear to influence the rate of the formation reactions. The effects of these parameters on CDD/CDF formation have been measured in the laboratory in controlled experiments. In addition, multi-point emission testing results from full scale MWCs provide further evidence of the occurrence of low temperature CDD/CDF formation.[6,7,8,9] The full scale data suggest that the particulate matter (PM) control device operating temperature plays a key role in

determining the extent to which CDD/CDF is either generated and released to the atmosphere or captured on fly ash and removed in the control device.

Figure 4-20 illustrates the relationship between PM control device temperature and CDD/CDF capture efficiency for four MWCs. Each unit is equipped with ESP controls. The mean ESP operating temperatures range from 435°F (224°C) to 590°F (310°C). The temperature values are averaged over the duration of the sampling runs, which varied in duration from three to six hours. The data clearly show that negative removal efficiencies were measured (CDD/CDF concentrations increased through the ESP) during runs with ESP temperature greater than 500°F (260°C). At ESP operating temperatures between 450 and 500°F (232 and 260°C), both positive and negative removal efficiencies were observed. When the ESP operating temperatures were maintained below 232°C (450°F), positive CDD/CDF removal efficiencies were measured for all runs.

Based on the data in Figure 4-20, it is recommended that all MWCs maintain flue gas temperatures below 450°F (232°C) at the inlet of particulate control devices in order to minimize the potential for occurrence of CDD/CDF formation, and that the flue gas temperature be monitored continuously at this location. The operating temperature limits will not totally eliminate CDD/CDF formation; the formation temperature window will be shifted to upstream portions of the system. However, the temperature limit will help to minimize the CDD/CDF formation reaction process by avoiding increased residence times such as would occur in the ESP or fabric filter at temperatures where formation of CDD/CDF has been observed. In fact, the available data indicate that operating a PM control device at temperatures below 450°F (232°C) can provide removal of CDD/CDF.[41]

Although several MWCs currently operate ESPs at temperatures below 450°F (232°C), there is little information available on long term performance of low temperature operation. In general, ESP corrosion concerns should not exist provided that gas temperatures are maintained above 350°F (177°C).[42] Normal PM control device operating temperatures will typically be lower than 300°F (149°F) for those MWCs equipped with acid gas controls. The 450°F (232°C) limit is appropriate for systems that do not use acid gas controls because it provides a 100°F (56°C) operating window above the temperatures where corrosion concerns may exist, thus allowing for temperature fluctuations which result during a normal operating campaign cycle.

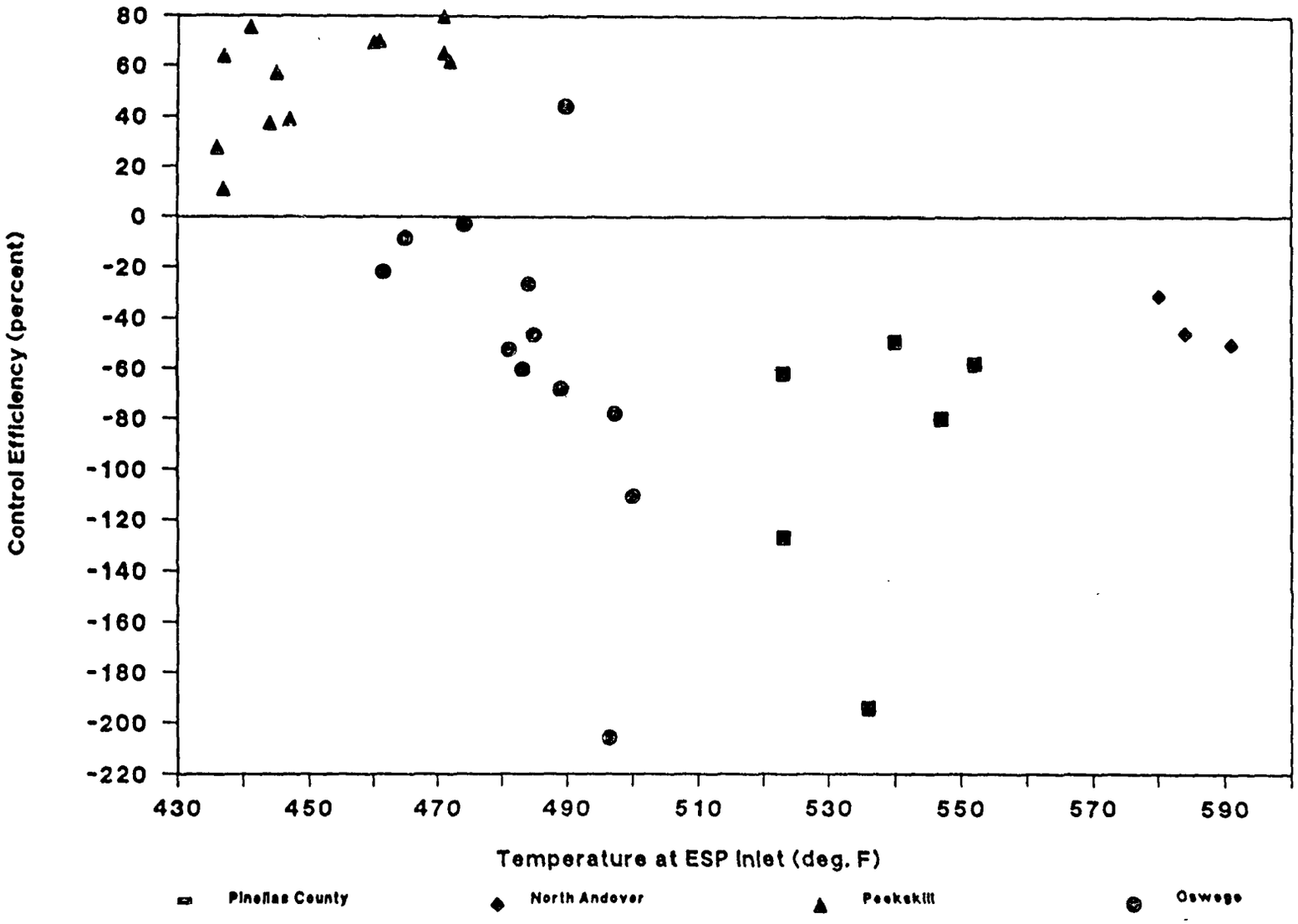

Figure 4-20. **CDD/CDF Removal Efficiency as a Function of ESP Inlet Temperature**

Continuous achievement of the temperature limit will pose no problem for new MWCs because the temperature limit can be incorporated into the design of the system, and in most cases the design will include acid gas controls. Existing MWCs equipped with water spray chambers or lime slurry spray dryers can maintain the PM control device inlet temperature by establishing adequate temperature setpoints in the existing control system. However, a number of existing MWCs without acid gas controls are designed with economizer outlet temperatures above the recommended temperature limit. Design retrofits would be required for many of these existing units to achieve the temperature limit.

An averaging time must be included with any limit due to the fluctuations that occur in economizer exit gas temperature during normal operating conditions. Changes in operating load, use of air preheat and cleanliness of heat transfer surfaces will result in economizer exit gas temperature variations over a normal campaign cycle. As fly ash adheres to boiler tubes the system heat transfer characteristics diminishes, resulting in less heat removed by the boiler and slightly higher flue gas exit temperatures. Periodic sootblowing removes fly ash from heat transfer surfaces. A four-hour block average is recommended because it is short enough in duration to encourage relatively prompt response action in order to meet the operating requirement. Therefore, an operating temperature limit of 450°F (232°C) maximum, four-hour block average, at the PM control device inlet is achievable for all MWCs. The four-hour block average is also consistent with other averaging times for parameters included in the combustion operating standards.

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APPENDIX A

EXPECTED EXCEEDANCE LEVELS FOR CO DATA FROM MUNICIPAL WASTE COMBUSTION FACILITIES

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EPA Contract 68-02-4269

1. Introduction

The purpose of this analysis is to estimate levels which will be exceeded at given rates (in the long run) by CO emissions at selected municipal waste incineration facilities. In each case the basic data (provided by EER) consists of hourly averages and it is desired to consider a variety of exceedance rates including 1/10 yrs, 1/yr, 1% for hourly, 4-hourly and 8-hourly "rolling" and "block" averages. The three facilities considered are:

(1) Wheelabrator Resource Recovery Facility, Millbury, MA (here referred to as "Millbury")
(2) Mid-Connecticut Resource Recovery Facility (here referred to as "Mid-Conn")
(3) Penobscot Energy Recovery Company, Penobscot, ME (referred to as "Penobscot")

The most complete analysis has been carried out for the Millbury data (1). For cases (2) and (3) sample calculations have been done for small sections of the data, which nevertheless demonstrate the general conclusions.

Since the desired exceedance rates (1% or less) are small, direct estimates of the corresponding levels by counting exceedances will be unreliable and indeed virtually impossible for 1/yr rates when the available data extends over 2 months. Hence the approach taken is to model the data as a "stationary, normal process" and to calculate the exceedance rates theoretically from this estimated model. The calculations use the mean, variance and "lag correlations" estimated from the data. It should perhaps be pointed out that previous similar studies for SO_2 emissions have used the more special so-called "AR-1" models. The advantage of so doing lies only in that estimation of one parameter (the lag 1 serial correlation) determines all the

other correlations required, thus providing a neat computation. In the cases dealt with here, the simple AR-1 model does not fit the data well, but the correlations needed are readily estimated individually.

A number of data points are either missing or regarded as aberrant for various indicated reasons. A special program has been written so that the estimates do not involve these data points, for the complete Millbury analysis.

The Millbury results are presented in Section 2, and Section 3 contains the sample results obtained for Penobscot and Mid-Conn. The methods used for the calculation are detailed in Section 4 of this Appendix.

2. Millbury Data

Hourly CO averages were reported for a 9-week period involving potentially 1512 data points. Missing and aberrant values were coded as zeros (by EER, who supplied the data) and a special program was written to obtain serial correlations using the zeros only to preserve the time sequencing and not otherwise in the calculations. The values of the mean (μ), variance (σ) and lag correlations r_1, r_2 ... r_7, were calculated (technically, estimated) from the data giving

$\mu = 37.112$ $\sigma^2 = 37.176$ ($\sigma = 6.0972$)

$r_1 = .78036$
$r_2 = .70094$
$r_3 = .15510$
$r_4 = .59370$
$r_5 = .52109$
$r_6 = .45512$
$r_7 = .41337$

The standard deviations σ_1, σ_4, σ_8 of each 1-, 4- or 8-hour average were calculated by Eqn A.2 using the above correlation giving

$\sigma_1 = 6.0972$ $\sigma_4 = 5.4527$ $\sigma_8 = 5.0791$

Using these values, the levels corresponding to exceedance rates ranging from 1 in 100 hrs to 1 in 10 yrs were calculated from Eqn A for 1-, 4-, and 8-hour (both "rolling" and "block") averaging, giving the values in Table A-1.

A point should be made clear concerning the relationship between the rolling and block averages. It is commonly supposed that for a given level the expected "rolling rates" should exceed the block rates for the reason that one high average will tend to be followed by another. However the argument is not relevant since also low averages tend to be followed by further low averages, reducing the rolling rate in a compensatory manner. In fact, for a given level, the <u>percentage</u> of expected exceedances is precisely the same for rolling and block averages. The differences in the table arise since the exceedance rates are reported not as percentages but as 1/100 hr, 1/month, etc. and there are e.g., four times as many rolling as block 4-hour averages in any given period. For example there are the same number of 4-hour block averages in a year as there are rolling averages in 3 months so that the same level 55.2 in Table 1 gives a 4-hour rolling rate of 1 per 3 months and 4-hour block rate of 1 per year. In both cases this corresponds to the percentage

$$\frac{100}{3 \times 30 \times 24} = \frac{100}{(12 \times 30 \times 24)/4}$$

assuming 30 day months for simplicity.

As a consequence, it may be regarded as better to report levels for exceedance rates expressed as percentages, so that the "rolling" and "block" levels would coincide. For example the level for a 4-hour average at a 1% rate would be 49.8 for both rolling and block averages. The figure 46.7 corresponds to a percentage exceedance rate of 4% (1/25) since there are 25 4-hour blocks in 100 hours.

3. Penobscot and Mid-Conn Data

As noted, short periods (approximately 6 days) were analyzed for Penobscot and Mid-Conn data. Tables A-2, A-3, and A-4 summarize the results obtained.

TABLE A-1.

Estimated levels corresponding to stated expected exceedance rates for 1-, 4-, 8-hour (rolling and block), Millbury CO data
$\mu = 37.112$, $\sigma_1 = 6.0972$

EXPECTED EXCEEDANCE RATE	1-HOUR ROLLING /BLOCK	4-HOUR ROLLING	4-HOUR BLOCK	8-HOUR ROLLING	8-HOUR BLOCK
1/100 hr	51.3	49.8	46.7	48.9	44.3
1/mo	55.4	53.4	51.0	52.3	48.8
1/3 mo	57.3	55.2	53.0	54.0	50.7
1/6 mo	58.5	56.2	54.1	54.9	51.9
1/yr	59.6	57.2	55.2	55.8	52.9
1/10 yr	62.9	60.2	58.4	58.6	56.1

TABLE A-2.

Estimated levels corresponding to stated expected exceedance rates for 1-, 4-, 8-hour (rolling and block), Penobscot CO data
$\mu = 134.57$, $\sigma_1 = 68.1863$

EXPECTED EXCEEDANCE RATE	1-HOUR ROLLING /BLOCK	4-HOUR ROLLING	4-HOUR BLOCK	8-HOUR ROLLING	8-HOUR BLOCK
1/100 hr	293	265	233	253	206
1/mo	339	303	278	287	251
1/3 mo	361	321	298	304	271
1/6 mo	374	332	310	313	283
1/yr	386	342	321	322	293
1/10 yr	423	373	355	350	325

TABLE A-3.
Estimated levels corresponding to stated expected exceedance rates for 1-, 4-, 8-hour (rolling and block), Mid-Conn Unit 12 CO data
μ = 161.75, σ_1 = 58.908

EXPECTED EXCEEDANCE RATE	1-HOUR ROLLING /BLOCK	4-HOUR ROLLING	4-HOUR BLOCK	8-HOUR ROLLING	8-HOUR BLOCK
1/100 hr	299	211	211	253	217
1/mo	338	297	276	279	251
1/3 mo	357	311	292	292	267
1/6 mo	368	319	302	299	276
1/yr	379	328	311	306	294
1/10 yr	411	352	338	328	308

TABLE A-4.

Estimated levels corresponding to stated expected exceedance rates for 1-, 4-, 8-hour (rolling and block), Mid-Conn Unit 13 CO data
$\mu = 209.79$, $\sigma_1 = 52.715$

EXPECTED EXCEEDANCE RATE	1-HOUR ROLLING /BLOCK	4-HOUR ROLLING	4-HOUR BLOCK	8-HOUR ROLLING	8-HOUR BLOCK
1/100 hr	332	283	265	247	232
1/mo	368	340	290	258	247
1/3 mo	385	314	302	263	253
1/6 mo	395	320	308	266	256
1/yr	404	326	314	269	260
1/10 yr	433	343	333	278	270

4. Model and Calculations

Let X_n denote the measured average CO for hour n, n=1, 2.... Assume X_n is a stationary normal series with mean μ, variance σ^2 and log correlation $r_j = \text{corr}_n (X_1, X_{1+j})$. Write

$$X_n = \frac{1}{n} \sum_1^n X_i = \text{average of } X_1 \ldots X_n$$

σ^2 = var of X_n ($\sigma_1 = \sigma$)

z_α = $(1-\alpha)$ percentile of standard normal distribution (e.g., $z_{.05}$=1.65, $z_{.01}$ = 2.33)

X_n = desired exceedance rate for averages of length n = 1, 4, 8 hrs (e.g., α_n = .01 for rate of 1/100 hrs, rolling basis)

C_n = level giving the exceedance rate of α_n

The purpose of the analysis is to express C_n in terms of α_n, μ, σ^2 and the correlations r_j. Now

α_n = expected number of exceedances of C_n per unit time by X_n

$$= P\{X_n > C_n\} = 1 - \Phi \frac{C_n - \mu}{\sigma_n}$$

where Φ is the standard normal distribution function. Hence, $(C_n - \mu)/\sigma_n = z_{\alpha n}$ or

$$C_n = \mu + \sigma_n z_{\alpha n} \qquad \text{(A.1)}$$

To complete the calculation σ_n is expressed in terms of σ and the lag correlation as follows:

$$\sigma_n^2 = \text{var} \frac{1}{n} \sum_1^n X_i$$

$$= \frac{\sigma^2}{n} + \frac{2\sigma^2}{n^2} \sum_{j=1}^n (n-j) r_j$$

$$= \frac{\sigma^2}{n} 1 + \frac{2}{n} \sum_{j=1}^n (n-j) r_j \qquad \text{(A.2)}$$

The procedure used to calculate the entries in the tables is to

(a) estimate μ, σ^2, r_j, $1 \le j \le 7$ from each data set

(b) thus estimate σ_n^2 by (4.2) for n=1, 4, 8

(c) use the estimates in (4.1) for each desired C_n for n=1, 4, 8

The specific numerical calculations for σ_n^2 were as follows:

Millbury Data

$\mu = 37.112$ $\sigma^2 = 37.176$

Estimated lag correlations:

j	1	2	3	4	5	6	7
r_j	.78036	.70094	.65510	.59370	.52109	.45512	.4133

n = 4: $$1 + \frac{2}{4} \sum_{j=1}^{4} (4-j) r_j = 3.11903, \quad \sigma_4^2 = 29.731$$

n = 8: $$1 + \frac{2}{8} \sum_{j=1}^{8} (4-j) r_j = 5.5513, \quad \sigma_8^2 = 25.797$$

$\sigma_1 = 6.097$, $\sigma_4 = 5.453$, $\sigma_8 = 5.079$

Penobscot Data

$\mu = 134.566$ $\sigma^2 = 4{,}649$

Estimated lag correlations:

j	1	2	3	4	5	6	7
r_j	.6261	.5448	.4747	.4011	.4066	.3174	.4018

$\sigma_1 = 68.19$, $\sigma_4 = 56.24$, $\sigma_8 = 50.97$

Mid-Conn Data, Unit 12

$\mu = 161.745$ $\sigma_1^2 = 3,470$

Estimated lag correlations

j	1	2	3	4	5	6	7
r_j	.4659	.4478	.3790	.2952	.1925	.1704	.2224

$\sigma_1 = 58.91$, $\sigma_4 = 45.02$, $\sigma_8 = 39.19$

Mid-Conn Data, Unit 13

$\mu = 209.786$ $\sigma^2 = 2778$

Estimated lag correlations

j	1	2	3	4	5	6	7
r_j	.2647	.1150	-.1562	-.4269	-.1793	-.2135	-.1364

$\sigma_1 = 52.71$, $\sigma_4 = 31.56$, $\sigma_8 = 1601$

The listed exceedance rates correspond to the quartiles $z_{\alpha n}$ as follows:

	Exceedance rate: one per					
Type of Avg:	100 hr	1 mo	3 mos	6 mo	1 yr	10 yr
8 hr rolling	2.3263	2.9955	3.3160	3.5050	3.6853	4.2351
4 hr block	1.7507	2.5440	2.9068	3.1171	3.3160	3.9126
8 hr block	1.4051	2.2918	2.6826	2.9068	3.1171	3.7419

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16. ABSTRACT

The EPA's Office of Air Quality Planning and Standards (OAQPS) is developing emission standards and guidelines for, respectively, new and existing MWCs under the authority of sections 111(b) and 111(d) of the Clean Air Act (CAA). The EPA's Office of Research and Development (ORD) is providing support in developing the technical basis for good combustion practice (GCP), which is included in the regulatory alternatives considered in selecting the proposed standards and guidelines. This report defines GCP and summarizes the approach used to implement GCP into the proposed MWC standards and guidelines. The report identifies the minimum subset of GCP operating parameters that can be continuously monitored to ensure that the goals of GCP are achieved. Finally, the report provides a detailed description of the data and rationale used to establish quantitative operating limits for each of the continuous operating parameters.

17. KEY WORDS AND DOCUMENT ANALYSIS

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