

DEVELOPMENT OF GOOD COMBUSTION PRACTICE FOR MUNICIPAL WASTE COMBUSTORS¹

JAMES D. KILGROE

Air and Energy Engineering Research Laboratory
U.S. Environmental Protection Agency
Research Triangle Park, North Carolina

**W. STEVE LANIER AND
T. ROB VON ALTEN**

Energy and Environmental Research Corporation
Durham, North Carolina

ABSTRACT

The U.S. Environmental Protection Agency is developing new air pollution rules for all new and existing municipal waste combustors (MWCs). These rules require all MWCs to use good combustion practice (GCP). The goals of GCP are to maximize furnace destruction of organic pollutants, limit the relative amount of particulate matter (PM) carried out of the combustor with flue gases (PM carryover), and ensure that the PM control device is operated at temperatures which do not result in formation of excessive amounts of chlorinated dibenzo-*p*-dioxins and chlorinated dibenzofurans (CDD/CDF). This paper summarizes the rationale for EPA's GCP strategy. This strategy incorporates the use of three continuous compliance parameters: carbon monoxide (CO) emissions, furnace steam load, and PM control device inlet temperature. Experimental data are provided to show that furnace emission of organics is correlated with CO concentration, the amount of PM carryover (which is related to load), and temperature at the PM control device inlet. The relationships between the GCP compliance parameters and other combustion parameters which are necessary ingredients of good combustion (uniformity of waste feed, the amount and distribution of excess air, combus-

tion temperature and residence time, and mixing of combustion air with thermal decomposition products) are also discussed.

INTRODUCTION

In 1987, EPA completed a comprehensive study of municipal waste combustion which included evaluation of the health and environmental risks associated with MWCs and an assessment of the criteria and hazardous air pollutant emission reduction potential of both combustion process controls and flue gas cleaning technologies [1-5]. Concurrent with the publication of this study EPA announced its intention to propose new rules to control air pollution emissions from MWC facilities [6]. One of the major driving forces behind this announcement was public and scientific concerns related to MWC emissions of trace organics, especially CDD/CDF.

Prior to the announcement of proposed rule making, the Office of Air Quality Planning and Standards (OAQPS) issued operational guidance to EPA's Regional Offices concerning approval of applications for permits for new facilities [7]. These guidelines, which applied to facilities subject to prevention of significant deterioration or nonattainment new source review, specified that all new incinerators use GCP and the appropriate flue gas cleaning technology to ensure adequate control of air pollution emissions. Although the

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criteria for achieving good combustion were not defined in the operational guidance, the Regional Offices were referred to recommendations for good combustion provided in the report, "Municipal Waste Combustion Study: Combustion Control of Organic Emissions" [4].

Shortly after publication of the 1987 recommendations, work was begun to develop GCP recommendations that would be applicable to all existing and new MWC facilities [8, 9]. This work resulted in the formulation of the revised GCP strategy described in this paper. It comprises the technical basis for EPA's rules for GCP at MWC facilities [10–12]. This paper includes a discussion of the origins of organic emissions, the 1987 recommendations, the components of GCP, surrogates for measuring total organics, the strategy for controlling organic emissions, the method of specifying numerical values for continuous parameters, and a summary of EPA rules for GCP.

DISCUSSION

Background

The objective of GCP is to minimize stack emissions of trace organics and the amounts of these organics in collected fly ash. Organic compounds such as CDD/CDF may originate in the waste, but it is unlikely that they will pass through the incinerator or combustor undestroyed [13]. They may also originate in the high temperature regions of the furnace from thermal decomposition products which are not completely oxidized due to insufficient combustion air, mixing, temperature, or residence time [4, 14, 15], or they may originate from reactions on the surface fly ash downstream of the combustion chamber [15–21].

The recommendations contained in the 1987 report on the combustion control of organics (1987 Recommendations) were an attempt to summarize the best combustion practices as applied to modern MWCs [4]. They were intended to be a summary of "current knowledge" and were not intended to be regulatory requirements. The recommendations applied only to mass burn, refuse derived fuel (RDF), and starved air combustors. They were predicated on the belief that optimum combustion within the furnace would minimize stack emission of organics, and they dealt solely with combustion conditions within the furnace. The relative importance of low temperature formation of organics was unknown and none of the 1987 Recommendations dealt explicitly with low temperature (i.e., downstream) formation.

The 1987 Recommendations were classified into three elements: design, operation/control, and verifi-

cation (monitoring). The rationale for these three elements was that:

(a) MWCs must be designed in a manner that allows operation at conditions that minimize organic air emissions.

(b) MWCs must be operated within an envelope dictated by the design of the combustion system, and controls must be in place to prevent operation outside of the established operation envelope.

(c) The performance of the combustion system must be verified by way of compliance testing through continuous monitoring of key operating parameters such as combustion air flow, gas temperature, carbon monoxide (CO) concentrations, and oxygen (O₂) concentrations.

Design recommendations included: the capability of achieving a minimum temperature of 980°C at fully mixed conditions to ensure thermal destruction of organics; the ability to control the distribution of underfire air as needed because of different combustion air requirements at different locations; the specification of a minimum overfire air capacity to ensure that sufficient overfire air is available for mixing; and requirement that the overfire air system be capable of adequate penetration and coverage of the furnace cross section.

Operating/control recommendations included: the specification of oxygen concentrations in the flue gas as needed to ensure proper levels of combustion air (excess air); a limitation on the range of operating load as needed to maintain minimum combustion intensities and avoid excess waste burning rates; the use of an auxiliary fuel to avoid excess organic emissions during start-up; and the use of auxiliary fuel as a corrective measure for low furnace temperatures or high CO concentrations.

Verification recommendations included continuous monitoring for control of: oxygen concentrations in the flue gas; CO concentrations in the flue gas (no greater than 50 ppm on a 4-hr average); and a minimum combustion gas temperature of 980°C at fully mixed conditions. If a combustor exhibited excessive CO emissions during start-up tests, the use of in-furnace CO profiles was recommended for correcting combustion air distributions.

GCP Components

Recommendations for GCP evolved as the results of additional investigations on the formation, destruction, and control of organics became available. These investigations included: field test projects sponsored by EPA and others [21–35]; laboratory research sponsored by EPA [36–39]; discussions with researchers in the U.S.,

Canada and Europe; and engineering analyses of all available field test data [8–10, 40–43]. The engineering analyses included attempts to validate the 1987 Recommendations by comparing available field test data on organic emissions with the combustion parameters measured during performance and compliance testing of MWCs [8, 9]. These attempts were only partially successful due to the paucity of combustion measurements made during most field test projects. The results of initial work in development of GCP for MWCs are discussed in three previous papers [15, 44, 45].

During the initial work on the development of GCP, it became apparent that waste feed conditions and the low temperature formation of organics must be controlled to limit organic emissions. The 1987 Recommendations were therefore expanded to incorporate components dealing with feed conditions and low temperature formation. GCP requirements were also developed for types of combustors that were not covered by the 1987 Recommendations.

The reformulation of the 1987 Recommendations resulted in the specification of seven GCP components: the Amount and Uniformity of Waste Feed, Combustion Temperature and Residence Time, the Amount and Distribution of Combustion Air, Mixing, PM Carryover, Downstream Temperature, and Combustion Monitoring and Control [10, 15].

Amount and Uniformity of Waste Feed

The rate of waste feed will affect combustion temperature and gas residence times within the furnace. Combustion stability can be affected significantly by sudden changes in waste composition or feeding characteristics. During steady state operation, fuel feed rates and combustion air flows are established to provide local and overall stoichiometries and system temperatures commensurate with operation at normal conditions, usually the design load as determined by steam flow rate.

Variation in waste volatile matter content, moisture content, feed rate, size distribution, or distribution pattern in the furnace will result in rapid changes in combustion air requirements and corresponding changes in local stoichiometry. Surges of highly volatile waste can rapidly deplete local oxygen concentrations, causing formation of fuel-rich gas pockets that may escape the furnace without being adequately oxidized. These conditions are generally accompanied by elevated concentrations of organics and CO. Extreme variations in the waste heating value and moisture content can affect system temperatures as they impact the heat input to the combustor and the total heat capacity of the combustion products, respectively.

The amount and uniformity of waste feed must be controlled to ensure operation at the desired steady state levels and avoid combustion excursions which result in emission of increased amounts of organic pollutants.

Combustion Temperature and Residence Time

Temperature is a consequence of combustion conditions as determined by the waste calorific value, moisture content, ash content, and the combustion gas heat loss rate. Local combustion temperatures are important because they determine the rate of thermal decomposition and the rate of chemical reactions. Low furnace temperatures or inadequate residence times will result in increased furnace emission of organics.

Organics in MWC flue gases may exist as gas-phase compounds or entrained particles. The entrained particles may be sooty particles (condensed products of incomplete combustion) or unburned material such as the skeletal carbon structure of devolatilized paper. Destruction of organics in MWCs occurs by thermal degradation, chemical attack by flame radicals, and by the final oxidization of OH and CO to H₂O and CO₂.

When gas-phase organic compounds at normal combustion temperatures pass through active flame zones containing oxygen they are chemically destroyed within a few milliseconds. Gas-phase organic compounds which do not contact oxygen can be thermally degraded within seconds if temperatures are sufficiently high. Solid-phase organic particles may require long residence times at high temperatures before they are completely destroyed. The time to burn particles depends on the temperature, particle size, and availability of oxygen. Times for burnout increase with increasing particle size and decreasing temperature. Time-temperature requirements for destruction of gas-phase organics may not be sufficient to ensure destruction of solid-phase organics.

Amount and Distribution of Combustion Air

The proper amount and distribution of combustion air are essential for efficient combustion. The total amount of air needed for complete combustion at a given waste burning rate includes a stoichiometric requirement and an excess air requirement. The stoichiometric air requirement is the average amount needed to completely oxidize all the waste thermal decomposition products. Excess air can be considered to be an additional amount to account for: (a) short term variations in waste feed properties; and (b) the inability to exactly match combustion air requirements with combustion air supplies at all locations. In refractory walled incinerators, high levels of excess air are used to limit grate

temperatures and control slagging. Excess air levels may also be controlled to limit NO_x emissions.

It is also important to distribute combustion air to under- and overfire locations where it is needed to satisfy local combustion requirements. The distribution of primary (underfire) air is essential in maintaining bed burning stoichiometry and good waste (char) burnout. Optimal conditions for primary air control will depend on the combustor technology. For example, in conventional mass burn waterwall units, primary air control is achieved by the use of multiple underfire air plenums, each with separate controls. The distribution of underfire air to each grate section is varied to accomplish drying, burning, or burnout. In starved air combustors, sub-stoichiometric amounts of underfire air are provided in the primary combustor to avoid clinker formation and limit particulate emissions. RDF combustors can be designed to meet the underfire air requirement by the use of multiple underfire air zones or by controlling the manner in which RDF is distributed on the grate.

In many types of combustors, secondary or overfire air is needed to adjust local stoichiometries to complete oxidization of bed thermal decomposition products which are fuel-rich. Overfire air is also important in controlling combustion of the fuel bed. In burning fuel beds the local volatilization rate and bed burning rate are dependent on the local underfire air rate. An increase in underfire air rate to supply air to the overfire region, as needed to complete combustion, may result in increased bed burning rates, increased volatilization rates, and increased entrainment of particulates. Addition of combustion air above the fuel bed avoids these problems, provides combustion air to oxidize organics, and provides flexibility in controlling the combustion process.

Mixing

Intimate mixing of fuel and air is widely recognized as a requirement for complete combustion. Poor mixing produces local stoichiometries which prohibit complete destruction of organics even at equilibrium conditions. Combustion processes typically exhibit a high degree of mixing associated with the turbulence of the thermally expanding products of combustion. In modern MWCs this inherent mixing is abetted by one or more techniques, including the use of: (a) jets of combustion air, recirculated flue gas or steam; and (b) furnace geometry or configuration. Many designs use both configuration and jets to achieve good mixing.

Furnace geometry or configuration can be used to direct combustion gas flows and enhance mixing of combustion air and thermal decomposition products.

Common design techniques for enhancing mixing are the use of cross-sectional area changes, flow baffles, and wall-turns. Some designs incorporate two combustion chambers. Changes in cross-sectional flow areas and flow direction between the chambers enhance mixing effects. Other designs use baffles or bull noses to improve mixing.

Overfire air jets are one of the most common techniques used to enhance mixing. Recirculated flue gas, used primarily to control NO_x emissions, is occasionally used. Steam jets are almost never used. Important design considerations associated with jets are the number and location of jets and jet momentum. It is important to get good jet penetration (momentum) and lateral coverage (number of jets) at the injection cross-section. Most conventional waterwall mass burn combustors use overfire air jets on both the front and rear walls. In these designs there is an arch over the burnout grate. This arch reflects radiant heat back into the refuse bed and directs combustion products from the burnout grate back to the middle portion of the furnace (entrance to the upper furnace), where they can mix with gases from the burning and drying grates. Overfire air jets are typically placed at the entrance to the upper furnace, where they are most effective in adjusting lower furnace stoichiometries and mixing with thermal decomposition products from the lower furnace.

MWC manufacturers typically rely on experience and flow modeling to achieve good mixing. Poor mixing generally results in high emission of trace organics and CO. Good mixing is a function of many design and operating variables. While the principles of good mixing can be defined, there is currently no known combination of design and operating parameters which can guarantee a priori good mixing. However, CO can be used as an indirect measure to ensure that satisfactory mixing is being achieved in MWCs.

PM Carryover

Particulate matter carried out of the furnace with flue gases (PM carryover) can result in formation of CDD/CDF and other chloro-organics downstream of the combustor. Limiting PM carryover will help to limit downstream formation of organics.

The results of field tests have shown that CDD/CDF and other organics are formed as flue gases and fly ash pass through the combustion system and flue gas cleaning equipment [10, 21, 30, 32–35]. Low temperature formation, called de novo synthesis, is believed to involve reactions on the surface of fly ash at temperatures ranging from approximately 150°C to 450°C [16–18, 21]. The rate of formation depends on the flue gas composition (oxygen and water content), fly ash

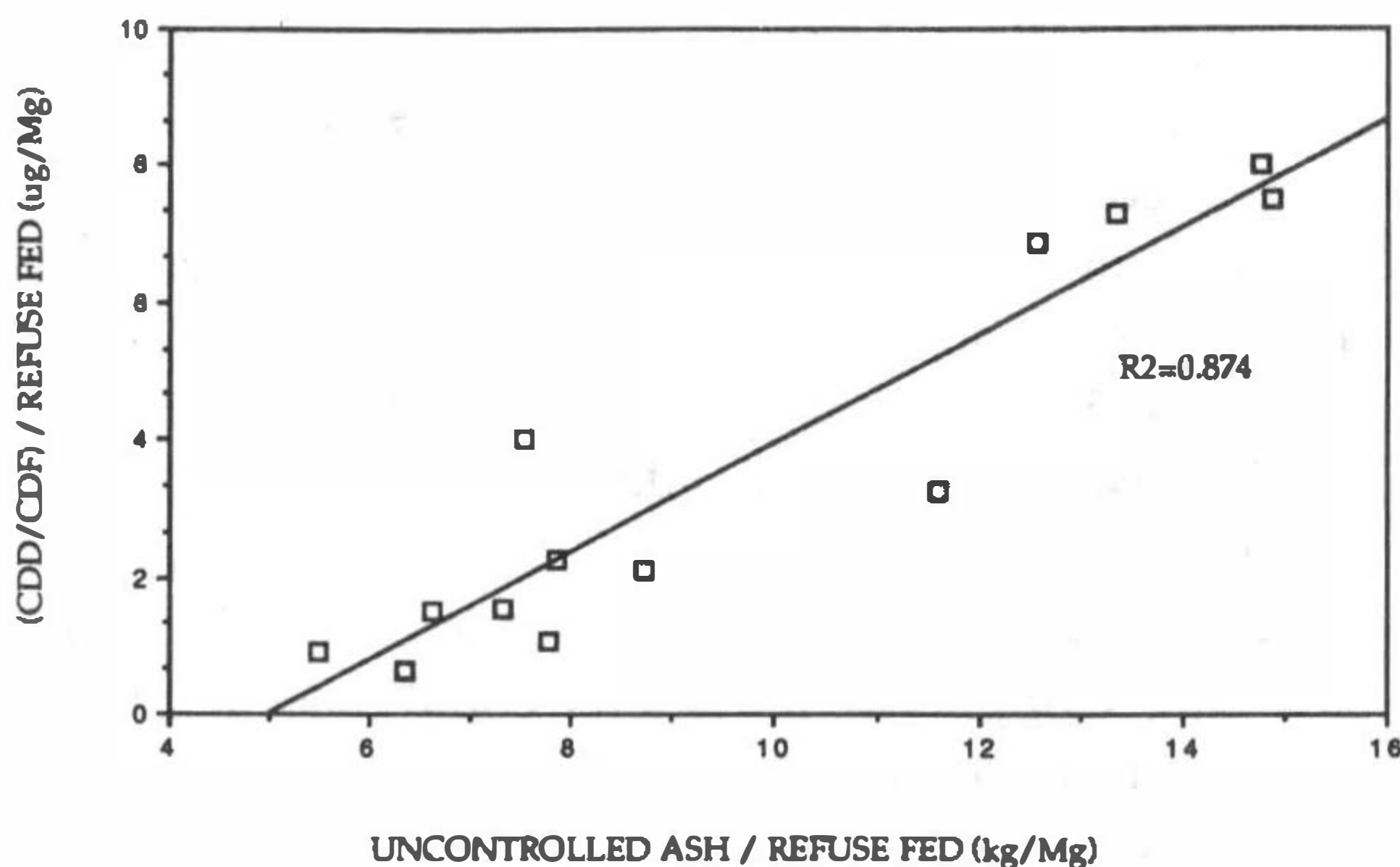


FIG. 1 CDD/CDF VS PM CARRYOVER
(Quebec City — Mass Burn Incinerator [10])

composition (carbon and metal content), and temperature. Increased amounts of fly ash result in increased reaction sites for the formation of organics. Figure 1 shows the strong correlation between the amount of PM carried out of a mass burn waterwall combustor and stack emission of CDD/CDF.

PM carryover is dependent on combustion conditions, waste properties, and combustor type. Fundamentally, the tendency of a particle to be entrained in an upward flowing gas stream is a function of the particle size, shape, and density and the gas velocity around the particle. The entrainment of particles will increase with increased flue gas flow rates and specifically increased underfire air flow rates. Thus PM entrainment tends to increase with decreasing waste particle size, increasing waste burning rates (load), increasing excess air rates, and increasing underfire air rates. Conventional mass burn combustors have higher PM entrainment rates than starved air combustors because of the lower relative amount of air supplied as underfire air. RDF spreader stokers tend to have higher rates of particle entrainment due to the semi-suspension mode of combustion employed and because RDF contains more small light particles.

Downstream Temperature

The rate of downstream CDD/CDF formation in MWC systems is highly dependent on temperature. Control of the time/temperature history of flue gas and PM leaving the furnace is an important component in limiting the amount of organics in emitted stack gases and collected fly ash.

Laboratory experiments have shown that de novo synthesis of CDD/CDF occurs at temperatures ranging from approximately 200–450°C [15–18]. Maximum formation rates are observed at approximately 300°C [16–18]. The results of field tests lead to the conclusion

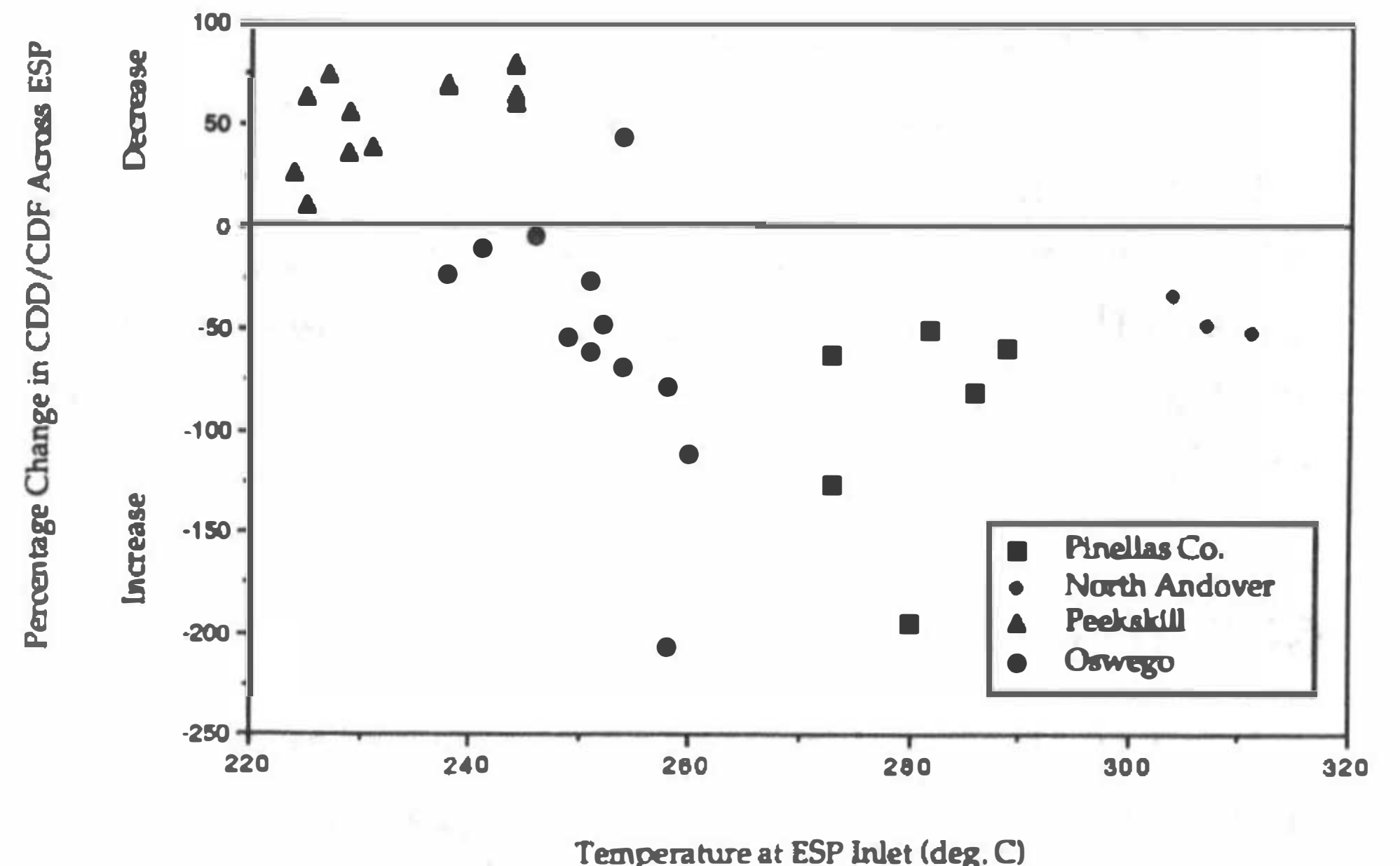


FIG. 2 CHANGE IN CDD/CDF AT INLET AND OUTLET OF ESP WITH INLET TEMPERATURE [10]

that particulate control devices which hold large amounts of collected fly ash can act as chemical reactors which generate CDD/CDF and other trace organics. Tests on mass burn waterwall and starved air modular combustors have shown lower flue gas concentrations of CDD/CDF at the electrostatic precipitator (ESP) inlet than at the outlet (formation within the ESP) for temperatures greater than approximately 230°C (see Fig. 2) [10, 15]. Tests on a mass refractory combustor have shown CDD/CDF formation in an ESP at temperatures as low as 150°C [21]. Pilot scale combustor tests have also shown that CDD/CDF can be formed in fabric filters (FFs) [20]. It is therefore important to avoid PM control device operation at temperatures that result in high CDD/CDF formation rates.

Combustion Monitoring and Control

The last GCP component, combustion monitoring and control, provides a means of integrating system design and operation to provide for achievement of GCP on a continuous basis. The relationships between waste feed rate and the amount and distribution of combustion air that are needed to provide a given heat release rate (load) while maintaining efficient combustion with minimal emission of organics are complex. Organic emissions can increase substantially during periods of upset or “off-spec” operation, and operation under these conditions should be minimized. MWCs must be operated according to design specifications, and controls must be incorporated into the system design to respond to changes in steam load, temperatures, O₂ concentrations, and CO concentrations that result in changing waste properties. MWCs must also be capable of starting up, shutting down, and changing load from one level to another while maintaining satisfactory combustion conditions.

To adequately control combustion conditions to minimize emission of organics, MWCs should be capable of continuously monitoring and controlling: waste feed rates, combustion air flow rates, steam load, temperatures in the furnace, the temperature at the entrance to the PM control device, flue gas concentrations of O₂, and flue gas concentrations of CO.

GCP Application Strategy

Early in the development of new rules for controlling air pollution emissions from MWC facilities, EPA decided to control MWC organic emissions, MWC metal emissions, and MWC acid gas emissions. The total concentrations of CDD/CDF were selected as an indicator (surrogate) for measuring the control of MWC organics. MWC organics were to be controlled by the use of GCP and appropriate flue gas cleaning techniques.

The strategy for implementing GCP as a method of regulating organic emissions was based on a number of considerations:

(a) The implementing strategy should ensure the control of all organic emissions. It should not focus solely on CDD/CDF.

(b) The control of emissions should be verifiable on a continuous basis.

(c) Performance requirements are preferable to design or operating specifications.

(d) Implementation (monitoring and control) costs should be reasonable.

GCP was implemented to achieve two basic objectives: to maximize furnace destruction and to minimize downstream formation of organics. Maximizing furnace destruction of organics would also ensure that trace organics in the feed are destroyed.

After a careful review of the components of GCP, it was concluded that the two major technical objectives of GCP could be achieved by continuously monitoring and controlling: (a) the flue gas concentration of CO; (b) steam load (a surrogate for PM carryover); and (c) temperature at the inlet of the PM control device. These three variables were therefore selected as "continuous compliance parameters" to demonstrate continuous control of "MWC organic" emissions.

The use of CO as a single indicator for furnace destruction is not consistent with the 1987 Recommendations, in that O₂ concentrations, combustion temperature, load ranges, and the use of an auxiliary fuel are not prescribed. There are several reasons for this difference. A major reason was the desire to avoid the specification of design and operating conditions whenever possible. Performance standards are preferable to equipment operating specifications. A second reason

was the inability to define the limits or ranges of conditions for all combustion parameters for all the various types of combustors employed in the U.S. For example, combustion temperatures and flue gas oxygen concentrations are important indicators of combustion conditions which should be measured at MWC facilities. While these parameters should be measured at all facilities, they should be used by the operators for monitoring and control of the combustion process. Their use as a GCP compliance parameter could place improper limitations on combustor operation and result in problems such as slag buildup. CO and total hydrocarbon (THC) concentrations in flue gas are more appropriate indicators of combustion conditions which result in the furnace destruction of organics.

Furnace Destruction of Organics

Gas-phase CDD/CDF and other organics are believed to be thermally destroyed in active combustion zones at temperatures ranging from 730°C to 980°C [4]. However, measurements made at high temperatures (590–980°C) in MWC furnaces have shown the presence of significant quantities of CDD/CDF (250–5000 ng/dscm) [21, 34, 35]. Depending on operating conditions, the CDD/CDF and other organics in combustion products may either increase or decrease as the combustion products pass through heat extraction and flue gas cleaning equipment. Combustion conditions which maximize the furnace destruction of organics will minimize organics leaving the combustor and reduce the potential for downstream formation of CDD/CDF.

Ideally, verifying the furnace destruction of organics on a continuous basis would involve a technique for monitoring the total amount of organics leaving the furnace. Since no such technique exists for continuously monitoring total organics, it was decided to continuously monitor the furnace flue gas CO concentration. Field and laboratory experiments have shown that low concentrations of CO are associated with low concentrations of organics in flue gases, and high concentrations are associated with high concentrations of organics [29, 31]. While CO is not a direct measure of total organics, it is a good indicator of the combustion conditions which characterize combustion efficiency. An alternative approach would have been to monitor total (gas-phase) hydrocarbons with a continuous emission monitor. However, field tests had shown CO to be a more sensitive indicator of combustion conditions, and it was therefore selected as an indicator to characterize furnace destruction of organics [15].

The adequacy of CO for demonstrating combustion efficiency in destroying organics was evaluated by con-

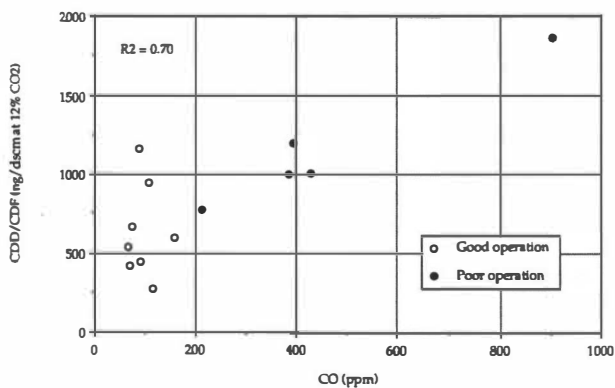


FIG. 3 CDD/CDF VS CO IN FLUE GAS AT SPRAY DRYER INLET (Mid-Connecticut RDF Combustion Facility [29])

sidering the effects of a failure to satisfy each of the GCP components dealing with furnace destruction of organics. From theoretical analyses and combustion test results it can be concluded that CO emissions will increase if:

(a) Excess amounts of waste are fed to the combustor or excessive variations in waste uniformity cause combustion upsets. Combustion tests at the Quebec City mass burn incinerator and the Mid-Connecticut RDF combustion facility exhibited increased CO emissions at high loads (high burn rates) [26, 29, 31]. Variations in waste feed conditions were found to be major causes of high CO emissions at fluidized bed combustion and RDF spreader stoker facilities [9, 46].

(b) Combustion temperatures are too low or combustion gas residence times at high temperatures are too short. Combustion tests at the Quebec City facility exhibited higher CO emissions at low combustion temperatures than for normal combustion temperatures [31].

(c) An improper amount of combustion air is used or there is poor distribution of combustion air. Tests with poor combustion air distribution resulted in higher than normal CO concentrations during combustion tests at the Quebec City and Mid-Connecticut facilities [26–29, 31].

(d) Waste thermal decomposition products and combustion air are improperly mixed in the high temperature regions of the furnace. CO concentrations during tests at the Mid-Connecticut facility were very sensitive to overfire air mixing conditions [26, 29].

The effectiveness of CO as an indicator for the furnace destruction of organics can be illustrated by the results of tests at the Mid-Connecticut RDF combustion facility. The correlation between average CO and CDD/CDF concentrations at the spray dryer inlet (furnace emissions) for 13 tests is shown in Fig. 3. These

13 tests represent a matrix of operating conditions designed to produce a wide range of good ($\text{CO} \leq 200$ ppm) and poor ($\text{CO} > 200$ ppm) combustion conditions. The primary combustion variables were load, under-to-overfire air ratio, and overfire air distribution. The CO concentration at the spray dryer inlet provided the best single parameter correlation for CDD and CDF concentrations at the same location. It provided the second best correlations (after THC concentration) for chlorophenols, chlorobenzenes, and polycyclic aromatic hydrocarbons [29]. Multiple regression analyses using monitoring variables (combustion gas properties) indicated that two to four of the following variables best explained variations in flue gas concentrations of organics: CO concentrations, THC concentrations, NO_x concentrations, furnace temperature, and Cl concentrations (CDF only). Multiple regression analyses using combustion control variables indicated that the following control variables best explained variations in organic concentrations: total undergrate air flow, rear wall overfire air flow, total overfire air flow, steam flow rate (load), and RDF moisture content [29]. These and other tests provide ample evidence that flue gas concentration of CO is a good indicator of the furnace destruction of organics [15].

Downstream Formation of Organics

CDD/CDF and other organics can be formed downstream of the furnace by de novo synthesis reactions on the surface of fly ash. The amount formed is believed to be proportional to the amount of fly ash and the time individual particles reside at temperatures ranging from about 150°C to 450°C .

The results of tests at the Quebec City Urban Community Center Incinerator and other facilities have shown that CDD/CDF concentrations in the flue gas are strongly correlated with the amount of fly ash entrained in the combustor flue gases (see Fig. 1). The relative amount of fly ash in the flue gas depends on the type of combustion technology and specific combustion parameters such as under-to-overfire air ratio and total volumetric flow of flue gases. Excessive amounts of fly ash, relative to normal conditions, are entrained if the rate of waste burned exceeds the design capacity of the combustor. Higher volumetric flue gas flow rates and increased fly ash entrainment result from operation above the design load. Since there are no commercially available systems for measuring the amounts of entrained fly ash or validated techniques for continuously measuring flue gas flow rates, it was concluded that boiler load, as measured by steam flow rate, could be used to avoid operation at conditions that are associated with excessive PM carryover.

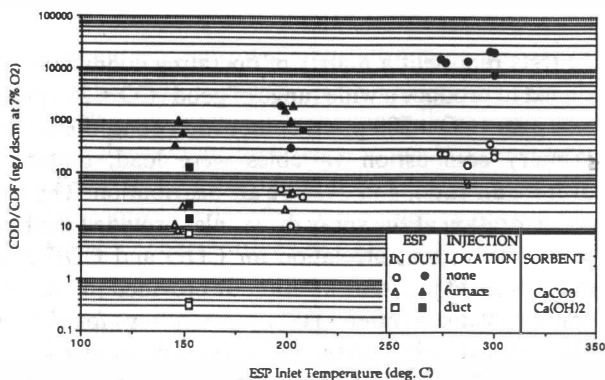


FIG. 4 CDD/CDF VS ESP INLET TEMPERATURE (Montgomery County South Incinerator)

Flue gas cleaning devices for the dry collection of PM, such as ESPs, retain large amounts of fly ash that can serve as a source of reactions which form CDD/CDF and other organics. A large fraction of the CDD/CDF entering an ESP is probably associated with fly ash that can be collected. However accumulated fly ash within the ESP can serve as a source for the de novo synthesis of CDD/CDF. Newly formed CDD/CDF can remain with the collected fly ash, it can be re-entrained along with the associated fly ash, or it can be desorbed into the flue gas stream as a vapor. The amount formed within the PM device will depend primarily on the rate at which fly ash and organic precursors enter the device, the flue gas composition (O_2 and water vapor), the length of time fly ash is retained (amount accumulated), and the temperature. If other factors are relatively constant, then the temperature at which the PM control device is operated will play a dominant role in determining the CDD/CDF collection, formation, and stack emission rate. At inlet temperatures near 300°C , formation rates will dominate and CDD/CDF outlet concentrations will generally exceed CDD/CDF inlet concentrations. At some lower temperatures, the inlet and outlet concentrations will approach a balance and, as the inlet temperature is further reduced, formation rates will become negligible or cease.

In tests conducted by EPA to investigate the effects of ESP inlet temperature on CDD/CDF collection, formation, and emission rates, it was found that measurable rates of formation (net increases of CDD/CDF concentrations across the ESP) occur at temperatures as low as 150°C (see Fig. 4) [21]. High rates of formation occur at 300°C and intermediate rates occur at 200°C . In tests at other facilities, it has been found that net capture and formation rates balance at approximately 230°C [i.e., the mechanisms which control formation

and stack emission of CDD/CDF are not dominated by PM control operating temperature (see Fig. 2)]. Although the rates of downstream formation are dependent on the design and operating conditions at each facility, it can be generally concluded that limiting the PM control device to 230°C or less will avoid temperatures which maximize formation rates of CDD/CDF.

Numerical Values for Continuous Compliance Parameters

Recommendations on numerical values for the GCP continuous compliance parameters were developed, and the resulting values were published along with other proposed rules for MWC facilities on December 20, 1989 [10, 11]. These proposed rules were applicable to new and existing MWCs regardless of size.

The proposed requirements were applicable to nine specific types of combustors: waterwall mass burn, refractory mass burn, rotary waterwall, starved air modular, excess air modular, RDF spreader stoker, bubbling fluidized bed, circulating fluidized bed, and coal/RDF co-fired combustors. The proposed emission limits for these combustors ranged from 50 to 150 ppm (at 7% O_2), depending on the combustor type. All emission limits were to be based on a 4-hr block averaging time, and the emission limits for a given type of combustor were the same for new and existing units. These CO emission limits and associated averaging times were based on EPA field test experience and on an evaluation of short and long term emission data sets from commercially operating MWCs [10]. The proposed rules also prohibited operation in excess of 100% of the maximum MWC unit load (1-hr average) and limited the temperature at the inlet to the PM control device to a maximum of 230°C (4-hr average). The proposed rules for load and downstream temperature were the same for all types of combustors and for both new and existing combustors. MWCs which do not generate steam were exempt from the load requirement.

The proposed rules also required certification of chief facility operator and shift supervisors by the American Society of Mechanical Engineers (ASME). The development and use of a training manual specific to each site was also required [11].

Based on public comments and further evaluations of technical achievability and likely cost impacts, revisions were made to the proposed rules and final rules were promulgated on February 11, 1991 [12, 47]. The promulgated rules applied only to large new units, large existing units, and very large existing plants. Although rules had been proposed for small new plants and small existing plants, rules for small new units were not promulgated because of provisions in the November

TABLE 1 MWC RULES FOR GOOD COMBUSTION PRACTICE

Parameter/MWC Technology	Requirement			
	Existing		New	
CO Emissions	Limit,ppm	Avg Time,hr	Limit,ppm	Avg Time,hr
-Mass Burn Waterwall	100	4	100	4
-Mass Burn Refractory	100	4	100	4
-Mass Burn Rotary Waterwall	250	24	100	24
-Modular Starved Air	50	4	50	4
-Modular Excess Air	50	4	50	4
-RDF Stoker	200	24	150	24
-Bubbling Fluidized Bed	100	4	100	4
-Circulating Fluidized Bed	100	4	100	4
-Coal/RDF Co-Fired	150	4	150	4

Load^a

Not to exceed 110% of average load demonstrated during most recent CDD/CDF compliance tests (4-hour avg).

PM Control Device Inlet Temperature^a

Not to exceed 17°C (30°F) above average PM control device inlet operating temperature demonstrated during most recent CDD/CDF compliance test (4-hour avg).

^a Applies to all technologies.

1990 Clean Air Act Amendments [48]. A summary of the promulgated GCP requirements is presented in Table 1.

Important clarifications and changes between the proposed and promulgated GCP are:

CO Emissions

The proposed CO emission limits for both new and existing RDF spreader stokers were 150 ppm with a 4-hr averaging time. The promulgated CO standard for new units was 150 ppm on a 24-hr averaging time, and the promulgated guideline for existing units was 200 ppm on a 24-hr average [12]. The changes in the CO rules resulted from statistical evaluations of new long term data sets from RDF spreader stokers [46]. CO emissions from RDF spreader stokers are inherently more variable than from mass burn or modular combustors. Semi-suspension firing of a finer sized waste results in a greater dependency of short term CO emissions on variations in waste properties. The longer averaging time in the promulgated rules was to account for the inherently higher sensitivity of RDF combustors to feed conditions. The higher emission limit for existing units was due to the difficulty of controlling emissions

in some units. Most notably, some small RDF combustors have relatively small furnaces and only two RDF feeders. While these units have state-of-the art feeders, they are much more sensitive to variations in waste feed conditions than larger units with more feeders and greater furnace volumes.

The proposed CO emission limit for both new and existing rotary waterwall combustors was 150 ppm on a 4-hr average. The promulgated standard for new units was 100 ppm on a 24-hr average and the promulgated guideline for existing units was 250 ppm on a 24-hr average [12]. A statistical evaluation of new long term CO emission data sets for rotary waterwall combustors indicated that the most recently constructed units are capable of achieving a CO emission limit of 100 ppm (24-hr average) and that older units are capable of achieving a CO emission limit of only 250 ppm (24-hr average) [46].

Steam Load Requirements

The proposed rules would have precluded operation above 100% steam load on a 1-hr averaging time. The promulgated rules preclude operation above 110% of the maximum average load level (4-hr average), as dem-

onstrated during the most recent CDD/CDF compliance test [12]. The increase from 100% to 110% was to account for variations in steam load [49]. For example, a unit operating at an average steam load of 100% of maximum rated capacity (MRC) might typically operate at between 90% and 110% of MRC. The average maximum operating load is to be defined by the average load recorded during the most recent CDD/CDF compliance test and, since each CDD/CDF test takes about 4 hr, the load averaging time was changed to 4 hr for consistency.

Downstream Temperature

The proposed rules specified a maximum temperature of 230°C (450°F) at the PM control device inlet. The promulgated rules stated that the operation of each MWC is to be controlled so that the flue gas temperature at the primary PM control device inlet does not exceed 17°C (30°F) above the maximum temperature demonstrated on the most recent CDD/CDF compliance test [12]. This revision explicitly couples the permitted maximum PM control device operating temperature to conditions which are shown to avoid excess CDD/CDF emissions [50]. Existing MWCs which now operate their PM control devices above 230°C (450°F) and which can comply with CDD/CDF emission requirements would not be required to reduce downstream temperatures as an organic emission control measure. The revision also ensures that a facility does not operate at a low PM control device operating temperature such as 150°C during compliance tests and then operate at 230°C during other time periods.

Start-up and Shutdown

Several comments were made on the proposed rules regarding exemption of GCP requirements during periods of start-up, shutdown, and malfunction and the use of auxiliary fuels during these periods [47, 51]. The final rules provided a 3-hr exemption from the GCP requirements during start-up, shutdown, and malfunction. An evaluation of CO emissions from several facilities indicated that the CO emission requirement could be met if auxiliary fuel is used and a 3-hr exemption is allowed for each start-up and shutdown period [51]. The use of auxiliary fuels is not explicitly required since all units will have to use an auxiliary fuel to preheat the unit prior to start-up (the beginning of waste feed to the combustor) in order to comply with the CO emission limit in the first time period after the completion of start-up.

Certification

The proposed rules required certification of the chief facility operator and shift supervisors by ASME. The

final rules also allow certification by equivalent state-approved certification programs [12].

CONCLUSIONS

Organic compounds such as CDD/CDF may originate in the waste, but it is unlikely that they will pass through the incinerator or combustor undestroyed. They may also originate in the high temperature regions of the furnace from thermal decomposition products which are not completely oxidized due to insufficient combustion air, mixing, temperature, or residence time, or they may originate from reactions on the surface fly ash downstream of the combustion chamber.

Combustion control has traditionally been concerned with conditions in the high temperature regions of the furnace. The discovery of low temperature reactions on the surface of fly ash requires control of the time/temperature history of combustion products as they pass through the combustor and flue gas cleaning devices.

GCP can be used in MWCs to aid in continuous control of trace organic emissions. The principles of good combustion are embodied in seven GCP components. Four of the components deal with the furnace destruction of organics, two deal with low temperature formation of organics, and one deals with continuous monitoring and control of combustion parameters. The components of GCP must be met individually and collectively to ensure combustion control of organic emissions.

Maintaining combustion conditions to simultaneously satisfy all GCP components is a complex and difficult task, requiring substantial engineering design and operating expertise. Definition of the envelope of combustion operating parameters which lead to good combustion has to be experimentally determined for each type of combustor by the owners/operators of the facility.

Conditions which relate to the emission of trace organics can be monitored and controlled by the use of three parameters: the CO concentration of flue gases, steam load, and the temperature at the inlet to the primary PM control device. CO is a good indicator of the furnace destruction of organics. Steam load can be used to avoid operation at conditions which result in excessive PM carryover. Temperature at the inlet to the PM control device can be used to limit organic reaction rates on the surface of collected fly ash.

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