

MINIMIZING TRACE ORGANIC EMISSIONS FROM COMBUSTION OF MUNICIPAL SOLID WASTE BY THE USE OF CARBON MONOXIDE MONITORS

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ABSTRACT

Emissions of trace toxic organic compounds such as polychlorinated dibenzo-*p*-dioxins (PCDD) and polychlorinated furans (PCDF) from combustion of municipal solid waste (MSW) in municipal waste combustors (MWC) have been found to vary from as low as 50 pg to over 10 mg per cubic meter. Laboratory tests and fundamental kinetic theory show that thermal destruction efficiency of organic compounds depends on temperature, time and oxygen concentration. Calculations of combustion of municipal refuse reveal the range of excess air and refuse moisture within which it is possible to maintain the temperatures needed to destroy organic compounds. Outside of this range, when either too much or too little excess oxygen is provided, a great increase in the products of incomplete combustion is noted, including not only difficult to measure trace organic compounds such as dioxins and furans, but also carbon monoxide (CO), which is readily measured in the parts per million range. Analysis of PCDD and PCDF data from various plants confirms that these emissions are related not only to furnace temperature, oxygen concentration, refuse moisture content, and air distribution, but also to the effectiveness of the combustion control system in maintaining oxygen levels within a narrow range. PCDD and PCDF emissions have been found to be at ac-

ceptable levels when CO emissions are maintained at less than 100 ppm. This finding indicates that continuous measuring of CO is useful for finding and maintaining optimum combustion conditions when burning municipal solid waste.

BACKGROUND

Analysis of emissions from the combustion of municipal solid waste (MSW) has revealed the presence of trace amounts of polychlorinated dibenzo-*p*-dioxins (PCDD) and dibenzofurans (PCDF). The risk to public health of these emissions from a number of apparently well-designed and operated refractory and water-wall refuse combustors has been estimated and found to be acceptable in reference to current guidelines [1]. The fact that some municipal waste combustors (MWC) have been found to emit much higher quantities of these highly toxic pollutants has created questions which are being addressed throughout the world. This has stimulated testing and analysis directed at finding out how to obtain and maintain acceptably low levels of these emissions, so that the performance of many existing plants can be improved, and that of future plants will be satisfactory. Archaic incinerators with no combustion and emission controls have been shut down in many countries.

In view of public statements that dioxin emissions are inevitable, and cannot be safely controlled by proper design and operation, it has become imperative that these doubts be addressed, and that satisfactory methods of assuring optimum waste combustion be found. Means for continuously supervising the performance of waste combustion systems must be developed and provided so that regulators and the general public can have confidence in thermal destruction technology.

Experience in other combustion systems has shown that carbon monoxide (CO) is a sensitive and useful indicator of completeness of combustion, and destruction of organic compounds in fuels and waste materials. This has led to the definition of (carbon) combustion efficiency in terms of the ratio of carbon dioxide (CO₂) to the sum of CO plus CO₂, and inclusion of this ratio in guidelines and regulations [2, 3].

If it can be shown that there is a suitable relationship between carbon combustion efficiency and the destruction of dioxins and furans so that CO can serve as an indicator of destruction of dioxins and other trace organic compounds, then CO measurements could be used not only to optimize combustion conditions but also to provide continuous supervision and monitoring of refuse combustion.

In view of the fact that this use of CO measurements has become widespread in fossil fuel combustion and in hazardous waste combustion, it is logical that this practice be extended to the combustion of municipal solid waste.

There have been many warnings from hazardous waste incinerator operators that the relationship between CO readings and the destruction and removal efficiency (DRE) of specific compounds is not so simple. In addition, a tendency is noted for CO readings to "spike" under momentary upsets, obviating the use of CO readings for alarm and shutdown purposes. Rather, it can be accepted as an indicator of good combustion. The desired range of CO readings will depend upon the system to which they are applied, and must be determined by parametric testing of the system [4]. In order to determine the utility of CO measurements in MSW combustion, actual operating data must be examined and analyzed.

Over the last few years more and more data has become available which makes it possible to relate combustion conditions to CO measurements concurrent with PCDD and PCDF emissions. When complete combustion data is also obtained, it becomes possible to perform valuable analyses, relating boiler output, oxygen concentrations and air and gas flow rates, as well as furnace temperatures (under deliberately or

even accidentally varied conditions) to emission data. This makes it possible to develop cause and effect relationships between the various parameters as well as insights into ways and means for improving and optimizing combustion conditions, as evidenced by reduced CO and organic emissions.

The purpose of this paper is to present data showing the relationships between combustion conditions, PCDD and PCDF emissions, and CO measurements.

CREATION AND DESTRUCTION OF DIOXINS AND FURANS

The chemical kinetics of combustion and compound destruction are well understood in theory and on a laboratory scale, as shown above. However, when considering the complex happenings during combustion even of fossil fuels, we recognize the even greater difficulty of understanding what happens when hydrocarbons are burned in the presence of chlorine, resulting in emissions of chlorinated dioxins and furans. While there is much speculation on these mechanisms, there is general agreement that when subjected to appropriate temperatures, oxygen concentrations and residence times these compounds can be formed at low temperatures, and destroyed at high temperatures to high destruction efficiencies [5].

Mass-Balances of PCDD and PCDF

Tests at Hamilton (SWARU) Ontario, under rather poor combustion conditions, showed that the weight of dioxins (PCDD) in the refuse supplied were about the same as the weight in the gases leaving the boiler [6]. However, the furans (PCDF) in the refuse were much lower than the PCDD and about double the dioxins at the exit, increasing by about twenty times. This indicates that formation takes place, somehow, during the process.

Tests at Prince Edward Island (PEI), Ontario, on a two-chamber starved-air refuse combustor, showed that the stack emissions of PCDD averaged about 20% of the PCDD in the refuse fed [7]. While PCDF were only found in two garbage samples, PCDF emissions were about 50% greater than PCDD emissions. PCDD and PCDF were measured in the gases entering the boiler, and found to be much lower than those in gases leaving the boiler. Their precursors, which were roughly fifty times greater in quantity, behaved differently: chlorobenzenes decreased and chlorophenols increased.

One explanation for these phenomena has been

offered by Vogg and Stieglitz, who investigated the thermal behavior of PCDD/PCDF on fly ash obtained from an ESP of a municipal incinerator [8]. They found that when treated in an oven, at 572°F (300°C) a ten-fold increase in PCDD occurred, that at 400°C it was reduced to one-quarter of the concentration of the untreated fly ash, at 932°F (500°C) to 1%, and to below the detection limit at 1100°F (600°C).

Whatever the theories of creation and destruction, what matters ultimately are the actual emissions from operating municipal waste combustors (MWC's), and the measures which are effective in reducing them to acceptable levels.

CONDITIONS REQUIRED FOR THE DESTRUCTION OF PCDD/PCDF

Laboratory data shows that purely thermal (non-flame) destruction of dioxins begins at temperatures of 1200°F (600°C) and higher, provided sufficient oxygen and retention time are available. These data are consistent with the fundamental principles of chemical kinetics [9].

Figure 1 shows that the thermal destruction curves for a number of typical chlorinated hydrocarbons. On semi-logarithmic coordinates these destruction curves follow a straight line. The lines for dibenzo-*p*-dioxins (PCDD), dibenzo-furans (PCDF) and biphenyls (PVC), are very similar. Decachlorobiphenyl and hexachlorobenzene requires much higher temperatures to achieve equal levels of destruction. It is worth noting that the difference in reaction temperature which is necessary to compensate for retention times of 0.5 and 4 sec is only about 20°C at 99.99% destruction efficiency. Of greater significance is the effect of oxygen concentration: while 1365°F (740°C) is sufficient to reach "four nines" in air (21% oxygen), about 1562°F (850°C) is indicated when the oxygen concentration is reduced to 2.5%. Under the conditions which take place in practical combustion systems, most of the oxygen is consumed, and while final oxygen concentration may average over 6% oxygen, there may be pockets which have lower levels, or indeed a lack of sufficient oxygen to permit complete combustion. Furthermore, we may not be satisfied with four nines. Extrapolation of the destruction curves beyond the data (generally limited to four nines) indicates that 1700°F (900°C) or more may achieve destruction to parts per million or greater, although at these low concentrations of the pollutants these extrapolations may not be valid.

Since thermal destruction is clearly the result of a

combination of temperature, oxygen and time, it would seem that these conditions could be provided in combustion systems if the right amount of air is supplied at the right places to burn the fuel, with sufficient mixing of fuel and air. This may not be a problem with the liquids and gases tested in the laboratory, but it certainly must be more difficult to achieve these conditions when burning municipal solid waste.

The next question is, can municipal waste be burned in such a manner as to provide sufficient temperature, oxygen and time, first theoretically, and secondly, actually? The wide range of dioxin emissions from various plants indicates that achieving these ideal conditions is easier said than done.

Theoretical Temperature of Combustion Products

What temperatures are theoretically possible when burning MSW? The temperature to which the products of combustion can be raised depends on the heat released by the fuel, the amount of combustion air and the moisture content of the fuel. The temperatures resulting from combustion of combustible solids and volatile gases can be calculated by dividing the heat released by the quantity and specific heat of the gaseous products of combustion. Figure 2 shows calculated product temperatures determined by oxygen content of the product gases, excess of air supplied over that theoretically needed to complete combustion (stoichiometric air), and moisture content, for typical municipal refuse properties [3]. This temperature is approximately the temperature of the tip of the flame, hence is often called flame temperature. These temperatures can be increased by supplying preheated combustion air, typically by about 200°F.

The peak temperature occurs with no excess air or oxygen. In actual combustion some excess air is needed to make sure that enough air is available in all locations, and to accelerate combustion with excess oxygen. If less than stoichiometric air is supplied, the temperature will be less than the theoretical maximum, and some combustible gases will be produced. If more than theoretical air is used, the temperature will be less than the theoretical maximum due to cooling by dilution of the gases.

It is clear that the amount of excess air which can be permitted without falling below the required temperature depends on the moisture content, and vice versa. The combustion conditions which will assure destruction of dioxins are thus limited. The combustion control system must keep the combustion process within these constraints, as fuel feed rate and com-

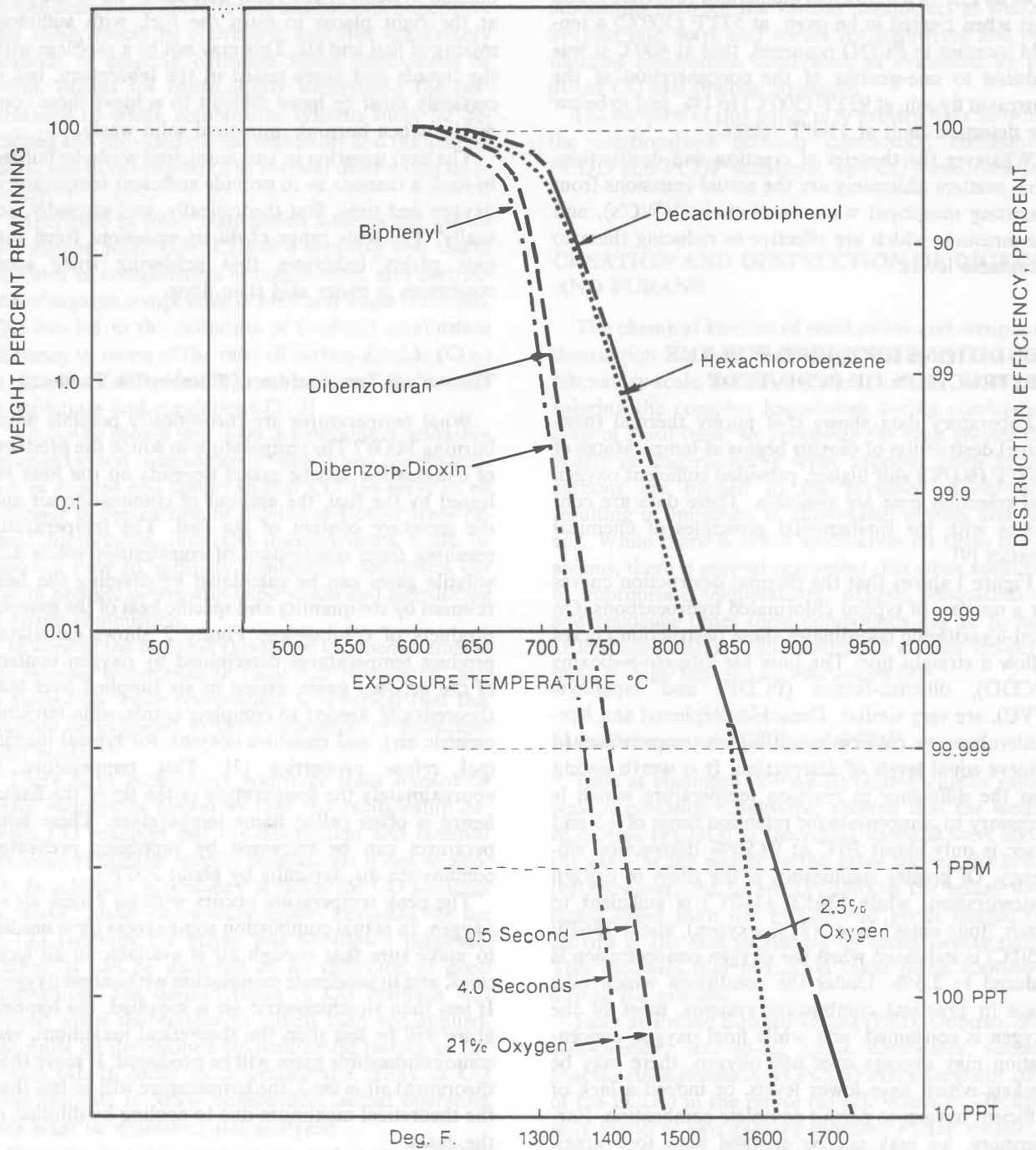


FIG. 1 DESTRUCTION EFFICIENCY OF CHLORINATED HYDROCARBONS VERSUS TEMPERATURE, TIME AND OXYGEN CONCENTRATION, BASED ON UNIVERSITY OF DAYTON LABORATORY DATA [10]

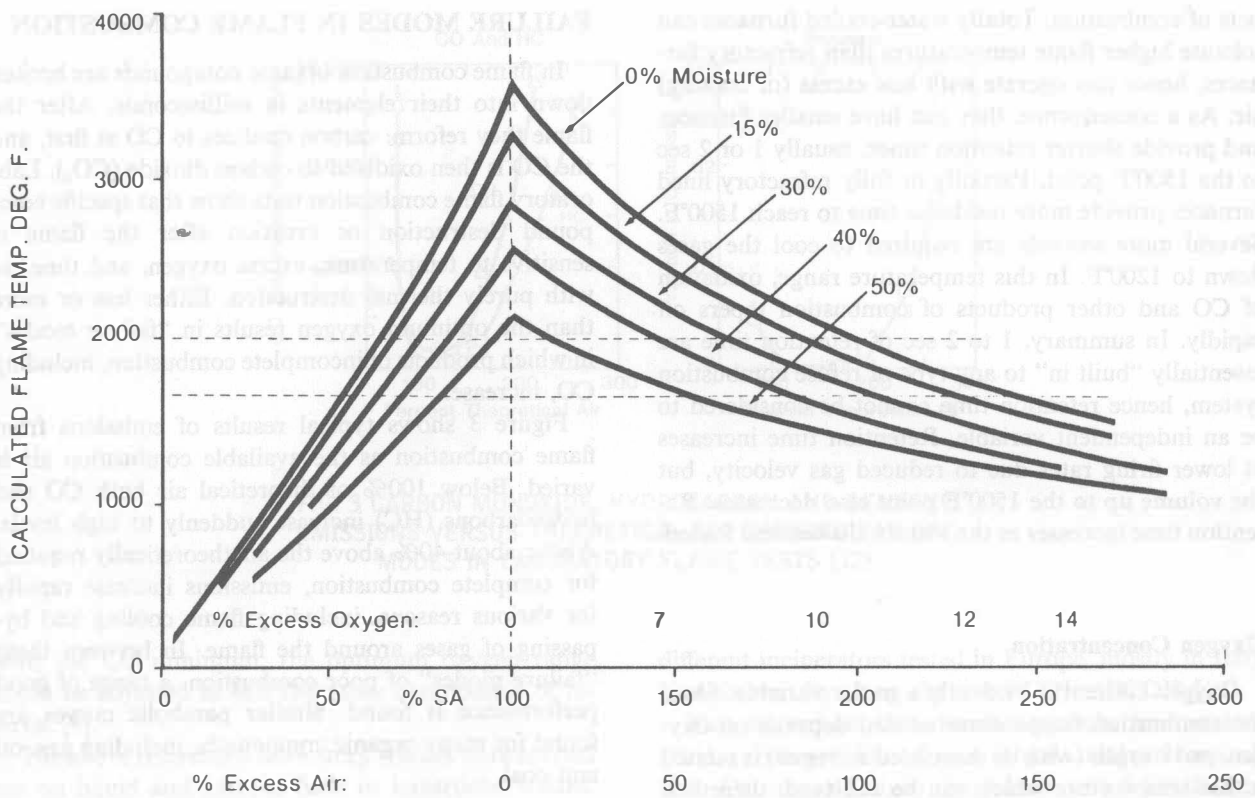


FIG. 2 THEORETICAL TEMPERATURE OF THE PRODUCTS OF COMBUSTION, CALCULATED FROM TYPICAL MSW PROPERTIES, AS A FUNCTION OF REFUSE MOISTURE AND EXCESS AIR OR OXYGEN [3]

position (especially moisture) and combustion air vary with time.

After calculating the temperature and volume of the gaseous products, it is possible to calculate the velocities of the gases as they pass through the furnace volumes. Knowing the furnace cross-section to flow, the time it takes for the gases to pass through the furnace can be calculated. The temperatures along the gas flow path, assuming plug flow and uniform gas and temperature distributions, can be determined by calculating the heat losses from the gases to the furnace walls and boiler surface. Actual conditions deviate substantially from these idealized assumptions, as a result of nonuniform supply of air and fuel, and less than perfect mixing of the reactants. Field testing [7] and modeling [11] can be used to evaluate the degree of departure from idealized calculated values.

Residence Time in Furnaces

The time which the combustion gases take to pass through the furnace volume is variously called the

residence, retention and detention time. It depends on the furnace dimensions, gas flow and temperature. Practical furnaces are designed to provide sufficient volume to permit the completion of flame combustion, followed by additional volume for mixing with secondary air, completion of carbon monoxide and hydrocarbon combustion, and reduction of the gas temperatures to a level which will not cause undue fouling of convection surfaces or superheater damage. This temperature may be between 1200 and 1500°F (650–815°C) when burning municipal refuse. The cooling may be done by water-cooled furnace walls, air injection, or both. Refractory furnaces may require air injection whereas water-cooled furnaces achieve cooling with considerably less excess air [3].

The furnace volume and retention time depend on the amount of excess air applied up to the flame zone (hence the flame temperature), the amount of additional air supplied after the flame zone, and the rate at which heat is removed from the gases by the furnace walls. Retention time in a furnace is therefore the consequence of the means of cooling the gaseous prod-

ucts of combustion. Totally water-cooled furnaces can tolerate higher flame temperatures than refractory furnaces, hence can operate with less excess (or cooling) air. As a consequence, they can have smaller furnaces and provide shorter retention times, usually 1 or 2 sec to the 1500°F point. Partially or fully refractory lined furnaces provide more residence time to reach 1500°F. Several more seconds are required to cool the gases down to 1200°F. In this temperature range, oxidation of CO and other products of combustion tapers off rapidly. In summary, 1 to 2 sec of retention time are essentially "built in" to any type of refuse combustion system, hence retention time cannot be considered to be an independent variable. Retention time increases at lower firing rates due to reduced gas velocity, but the volume up to the 1500°F point also decreases. Retention time increases as the waterwalls become fouled.

Oxygen Concentration

Oxygen content is evidently a major variable. Since the combustion temperature needed depends on oxygen, and oxygen (with its associated nitrogen) is related to the temperature which can be achieved, there is a somewhat limited range within which optimum conditions can be achieved. As the combustion process takes place, the oxygen in the combustion air is used up, reducing the excess oxygen available to continue the reactions. Too much combustion air provides ample oxygen but reduces the resulting temperature, and can also quench the reaction. Reducing combustion air increases tendencies to form pockets which are lacking in sufficient oxygen to complete the reactions. For these reasons, it is of utmost importance that combustion air be distributed very carefully in order to maintain optimum conditions throughout the furnace. Proper introduction of overfire air, and shaping of the combustion chamber are necessary to assure sufficient mixing to make up for less than perfect distribution of air and fuel on the fuel bed [11].

The amount of excess oxygen available in a combustion chamber when it is maintained at a given furnace temperature is affected by the refuse moisture content. Fuel moisture substantially affects the flame temperature by reducing the actual heat released by the refuse and by adding water vapor to the gas volume. As refuse moisture increases, less excess air is required to achieve the controlled furnace temperature. The reduced oxygen available increases the temperature required for compound destruction. High refuse moisture can be compensated to a certain extent by providing preheated combustion air.

FAILURE MODES IN FLAME COMBUSTION

In flame combustion organic compounds are broken down into their elements in milliseconds. After the flame they reform: carbon oxidizes to CO at first, and the CO is then oxidized to carbon dioxide (CO₂). Laboratory flame combustion tests show that specific compound destruction or creation after the flame is sensitive to temperature, excess oxygen, and time, as with purely thermal destruction. Either less or more than the optimum oxygen results in "failure modes" in which products of incomplete combustion, including CO, increase.

Figure 3 shows typical results of emissions from flame combustion as the available combustion air is varied. Below 100% of theoretical air both CO and hydrocarbons (HC) increase suddenly to high levels. Above about 40% above the air theoretically required for complete combustion, emissions increase rapidly for various reasons, including flame cooling and bypassing of gases around the flame. In between these "failure modes" of poor combustion, a range of good performance is found. Similar parabolic curves are found for many organic compounds, including gas, oil and coal.

Carbon Monoxide: An Indicator of Poor Combustion

For a given excess of combustion air, CO emissions are higher than those of HC and most organic compounds, indicating that CO is more difficult to destroy under the same conditions than most other organic compounds. It is generally found that under combustion conditions which destroy CO to low levels, other organic compounds are even more completely destroyed. Indeed, when CO levels represent 99.99% destruction of the carbon in the fuel, other compounds are often found to be destroyed to 99.99 to 99.999% [13].

Due to the parabolic relationship between excess oxygen and the CO emissions, there are points of equal CO on both sides of the parabola, at different oxygen concentrations. The same is true for other products of incomplete combustion (PIC's), although the minima may not be at the same oxygen concentration. It is necessary to know both the oxygen level and the CO level to determine where on this curve the point of operation lies. As a corollary, it would appear that by operating the combustion process under oxygen control, it could be held within the range of optimum operation, that is, minimum CO [4]. In case the minimum emissions of other compounds did not coincide

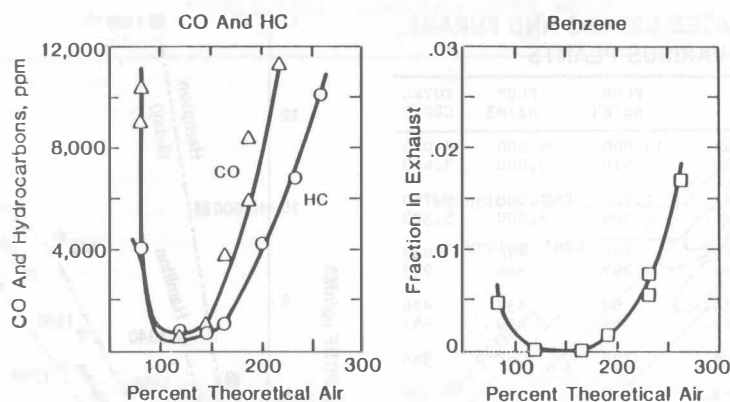


FIG. 3 CARBON MONOXIDE, HYDROCARBON AND BENZENE EMISSIONS VERSUS THEORETICAL AIR SHOWING FAILURE MODES IN LABORATORY FLAME TESTS [12]

with the CO minimum, the optimum oxygen range could be adjusted to suit the other compounds of interest [4].

The above referenced laboratory studies were carried out on liquid and gaseous fuels or hazardous wastes. The question is, do these principles apply to municipal solid waste? The answer must come from examination of test data from actual waste combustion systems.

Range of PCDD and PCDF Emissions from Various Plants

The total polychlorinated dibenzo-*p*-dioxins (PCDD) and polychlorinated dibenzo furans (PCDF) measured in stack gases of a number of municipal waste combustors are listed in Table 1. The PCDD data ranges from 19 pg to 13 μ g or over 600,000:1.

Additional data points are plotted in Fig. 4 the data from Hamilton, Ontario refuse-derived fuel (RDF) plant (SWARU) plots along with data from the 1983 tests of the Hampton, VA mass-burning plant [14]. The 1982 and 1984 data from Hampton roughly coincide, following a different ratio between PCDD and PCDF [15, 16]. Furnace temperatures at many of the data points show the reduction in dioxins and furans as temperatures increase. Emissions from Chicago Northwest [17], Zurich (Switzerland) and Stapelfeld (Hamburg, Germany) [11], are close to the zero axes of these linear scales. To display a wide range of data, a logarithmic scale, such as used in Fig. 5, is useful.

Most of the PCDD/PCDF data lies within a pair of lines ranging from $PCDF=PCDD$ to $PCDF=10\times PCDD$. Points representing tests of ten

different incinerators tested in Europe, mostly in Italy (not shown) lie along the line $PCDF=PCDD$ [18].

Two starved-air, two chamber modular incinerators (Prince Edward Island and Royal Jubilee Hospital, both Consumat designs) have been tested for dioxins and have similar performance envelopes; the PEI emissions coincides with the Zurich data, as can be seen in Table 2 [17, 19].

Figure 5 includes data on 12 tests of the Des Carriers incinerator in Montreal [20]. The data obtained in November falls on a distinctly different trend line from those from March, probably due to the seasonal difference in moisture content. For some reason the PCDF/PCDD ratio is much higher when refuse is dry.

DIAGNOSTIC TESTS OF PCDD AND PCDF EMISSIONS

While we can use theoretical principles in an attempt to predict what happens in combustion, it is only test data obtained from refuse combustion in full-scale systems which gives us indications of what actually happens, and especially what happens when various parameters are changed.

Early reports of dioxin and furan emission data revealed a wide variation between plants, and generally a much narrower variation within data from each specific plant. Obviously some plants held the variation within a tighter band, and some plants exhibited much lower emission levels than others. This was true of dioxin data obtained from fly ash analysis as well as analyses of stack emissions [21].

TABLE 1 POLYCHLORINATED DIOXINS AND FURANS EMITTED BY VARIOUS PLANTS

Plant Location	Type Fuel		PCDD ng/m ³	PCDF ng/m ³	TOTAL CDD'S
Hampton, VA	MSW	Max.	13,000	24,000	37,000
		Min.	670	3,000	3,670
Hamilton, ONT	RDF	Max.	1,700	7,000	8,700
		Min.	1,300	4,000	5,300
Victoria, BC	MSW	Min.	185	418	603
		Max.	297	666	963
Chicago, IL*	MSW	Min.	53	433	486
		Max.	61	490	451
Albany, NY*	RDF	Avg.	300	88	388
Zurich, SW	MSW	Avg.	113	89	202
PEI, ONT	MSW	Min.	62	95	157
		Max.	123	156	279
Stapeltefeld (Hamburg)	MSW	Max.	40	120	160
		Min.	20	90	110
WPA&B	dRDF	Max.	60	180	240
		Min.	6	26	32
Montreal, Q	MSW	March	0.745	0.542	1.2
		Nov.	0.013	0.019	0.03

*Corrected for unreported congeners by interpolation.

Fly Ash Parametric Testing

In a highly significant test of a waterwall incinerator in France, samples of collected fly ash (from the outlet hopper of the precipitator) were collected during periods of time while operating conditions were maintained as constant as possible at a number of operating conditions [22]. At firing rates ranging from minimum to maximum the overfire air was adjusted to maintain several different oxygen concentrations, as measured in the boiler outlet. Fly ash samples were taken from the precipitator hopper during each run and analyses for PCDD/PCDF. The dioxin concentrations of fly ash collected were determined for each operating condition.

Figure 6 shows the total PCDD concentration in the fly ash samples, plotted as a three-dimensional sheet, revealing the somewhat complex relationship between fly ash PCDD, boiler output and oxygen measured at the boiler outlet. It is clear that reducing the oxygen from 14% to 12% resulted in a dramatic drop in dioxin levels. Also, increasing boiler load reduced dioxins.

Of particular interest are the parabolic-shaped valley which progresses with reduced oxygen and increased steam output; the central peak; and, to the right, a continuous reduction to low levels of PCDD. This performance characteristic may be the result of maintaining a constant air supply to the grate, which is not an unusual operating practice. The optimum con-

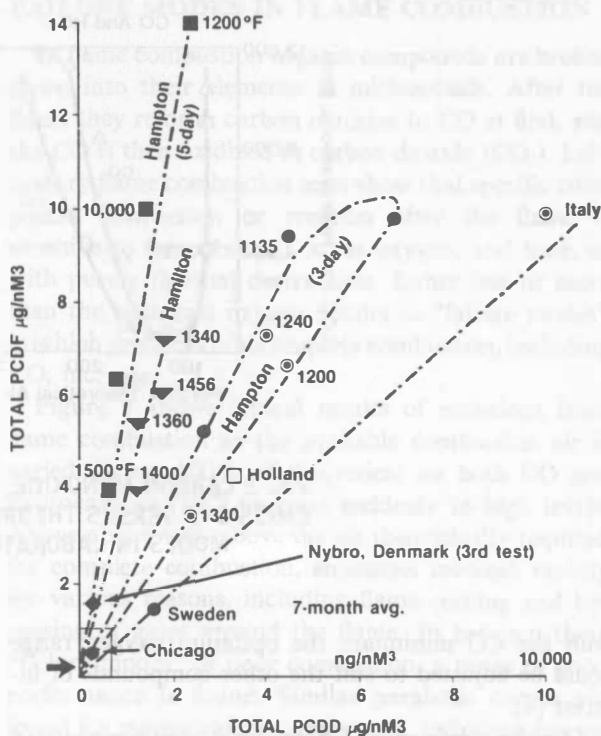


FIG. 4 STACK EMISSIONS OF PCDD PLOTTED VERSUS PCDF FOR VARIOUS PLANTS, AND OPERATING CONDITIONS AND FURNACE TEMPERATURES: LINEAR PLOT

ditions appear to be at loads far above those considered to be normal operation.

Multivariate tests such as these make it possible to diagnose the operation of the plant, to find cause and effect relationships which can be used to improve operation. The question which must be asked here is, how could the operators, or the control system of this plant know how to adjust the controls so that PCDD emissions would be kept at a minimum, staying away from trouble areas? Oxygen alone would not have been sufficient. For each load there might be a different control setting.

Comprehensive Diagnostic Test of Combustion Parameters

The first set of comprehensive refuse combustion data, including detailed gas flow analysis, temperature profiles, and stack gas composition data, as well as refuse analysis and analysis of fly ash and stack gas, was obtained at the SWARU plant in Hamilton, Ontario [6]. This plant burns coarse-shredded, magneti-

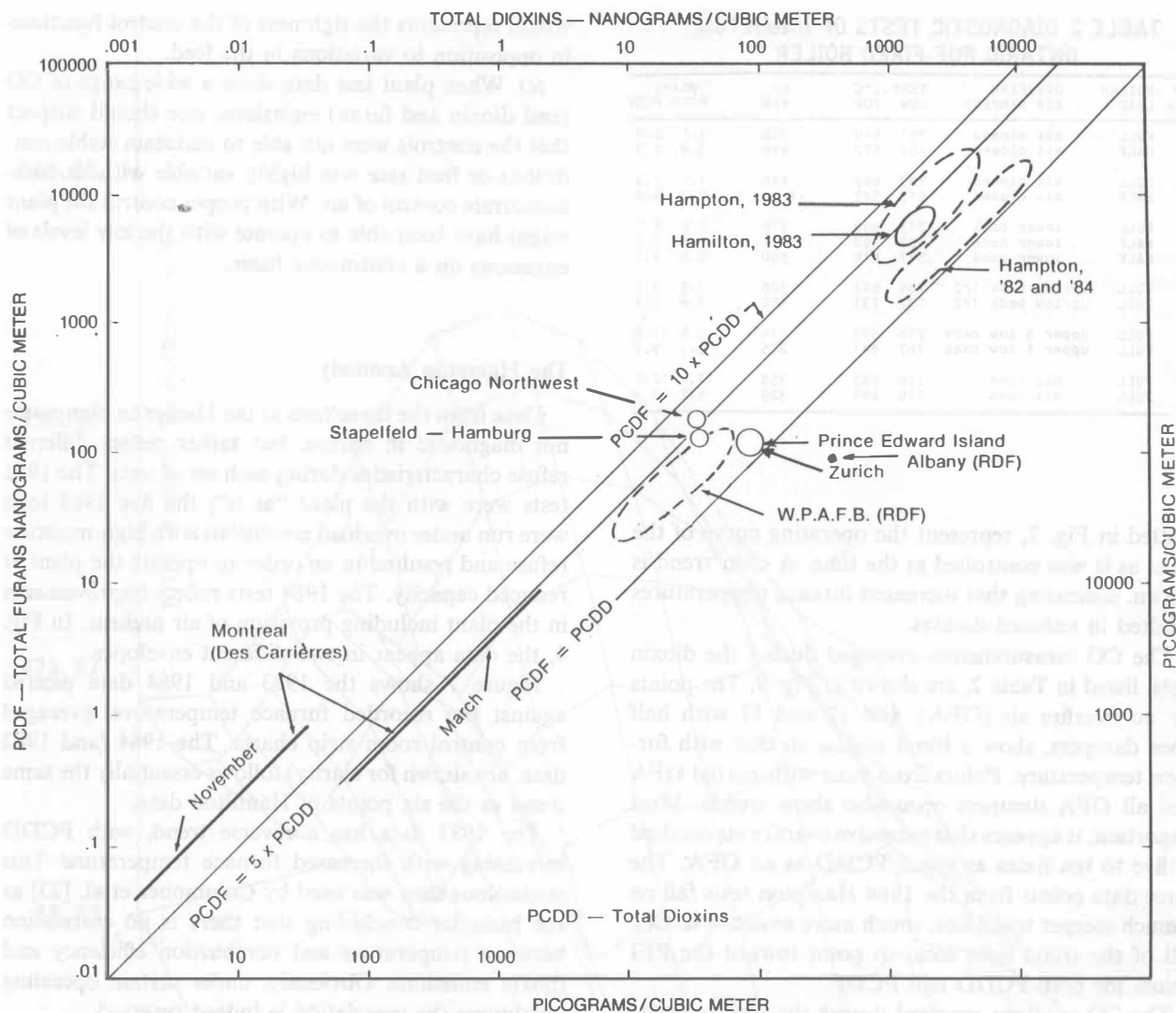


FIG. 5 LOGARITHMIC PLOT OF STACK EMISSION OF PCDD VERSUS PCDF FOR VARIOUS PLANTS AND OPERATING CONDITIONS

cally separated refuse-derived fuel (RDF). These tests were performed in a matrix, including four runs under "normal" operating conditions (as practiced prior to the testing program) and other runs wherein overfire air conditions were deliberately set to conditions far outside of normal operation. The data from the PCDD/PCDF diagnostic tests is shown in Table 2.

The four runs performed under what were considered to be normal conditions (no overfire air), represent two replicate tests, each consisting of a run at the minimum practical load [19, 13] and at normal load [12, 24]. These test conditions represent the full range of practical operation of the plant, and provide an

approximate definition of the 'operating curve' of this plant, hence are highly significant. The other twelve runs, all but one at full load, show performance resulting from opening various sets of overfire air dampers. Runs 11 and 17, with the upper and lower back dampers half open, had the lowest CO and PCDD and PCDF emissions at full load.

Furnace Temperature Versus Dioxin and CO Emissions

The lower furnace temperatures and corresponding PCDD emissions of tests 19 and 13, and 12 and 24,

TABLE 2 DIAGNOSTIC TESTS OF HAMILTON, ONTARIO RDF-FIRED BOILER

RUN Date	BOILER LOAD	OVERFIRE AIR DAMPERS	TEMP., °C		CO PPM	UG/M3	
			LOW	TOP		PCDD	PCDF
12	FULL	all closed	791	649	378	1.7	6.0
13	HALF	all closed	659	572	846	3.8	7.3
24	FULL	all closed	723	669	495	1.7	7.3
19	HALF	all closed	613	587	1017	5.0	9.4
21	FULL	lower back	713	650	518	2.2	7.7
4	HALF	lower back	597	508	992	2.6	3.7
26	HALF	lower back	547	618	500	5.8	8.9
11	FULL	up/low back 1/2	764	642	308	1.3	3.9
17	FULL	up/low back 1/2	737	731	450	1.4	5.4
5	FULL	upper & low back	718	599	414	3.5	11.0
10	FULL	upper & low back	767	641	275	3.1	9.2
25	FULL	all open	766	663	358	11.1	12.5
6	FULL	all open	779	664	329	4.7	10.3

plotted in Fig. 7, represent the operating curve of the plant as it was controlled at the time. A clear trend is shown, indicating that increased furnace temperatures resulted in reduced dioxins.

The CO measurements averaged during the dioxin tests, listed in Table 2, are shown in Fig. 9. The points for no overfire air (OFA), and 11 and 17 with half open dampers, show a trend similar to that with furnace temperature. Points from runs with partial OFA and all OFA dampers open also show trends. Most important, it appears that excessive overfire air resulted in five to ten times as much PCDD as no OFA. The three data points from the 1984 Hampton tests fall on a much steeper trend line, much more sensitive to CO. All of the trend lines seem to point toward the PEI points for both PCDD and PCDF.

The CO readings reported during the Chicago tests were in the 170 to 50 ppm range. Tests at Stapelfeld and other modern plants with computer control are reported to have CO readings in the 30 to 60 ppm range.

At this point it is worth noting that:

(a) In order to obtain strong evidence of the influence of multiparameter variations, it is necessary to plan tests which will spread the points, and which are run with only one parameter (hopefully) changed at a time. A strong trend can be seen in points 12, 24, 13 and 19, representing performance at the same air settings and the range from half to full firing rate. If only high fire had been tested (points 11, 12, 17, 21 and 24), only weak trends and no significant correlation would have been found.

(b) Trends and correlations can not be discerned when the plant is operated with essentially random variations of parameters. Such tests produce data which is bound into a circle or oval, the spread of

which represents the tightness of the control functions in opposition to variations in the feed.

(c) When plant test data show a wide range of CO (and dioxin and furan) emissions, one should suspect that the controls were not able to maintain stable conditions or feed rate was highly variable without commensurate control of air. With proper control the plant might have been able to operate with the low levels of emissions on a continuous basis.

The Hampton Anomaly

Data from the three tests at the Hampton plant were not diagnostic in nature, but rather reflect different refuse characteristics during each set of tests. The 1982 tests were with the plant "as is"; the five 1983 tests were run under overload conditions with high-moisture refuse and resulted in an order to operate the plant at reduced capacity. The 1984 tests reflect improvements in the plant including provision of air preheat. In Fig. 4, the data appear in two different envelopes.

Figure 7 shows the 1983 and 1984 data plotted against the recorded furnace temperature, averaged from control room strip charts. The 1984 (and 1982 data, not shown for clarity) follows essentially the same trend as the six points of Hamilton data.

The 1983 data has a reverse trend, with PCDD increasing with increased furnace temperature! This anomalous data was used by Commoner et al. [23] as the basis for concluding that there is no correlation between temperature and combustion efficiency and dioxin emissions. Obviously, under certain operating conditions the correlation is indeed reversed.

The explanation for this anomaly is simple: this test was run on the "other side" of the failure mode parabola, where excess air is reduced, resulting in higher temperatures, but with reduced oxygen, or poor mixing, CO and PCDD increase.

The charts included in the 1983 report show that temperature, oxygen and carbon monoxide readings were fluctuating through a wide range during the test periods. Figure 8 shows a series of dots representing simultaneous high and low peak readings of CO and oxygen. Note that oxygen ranged from 2.4% to 10% during Day 2. At times the operating conditions were good, with CO below 300 parts per million (ppm). Unfortunately, the average for the day was closer to 1400 ppm, probably contributing to the high dioxin levels. The 1982 tests showed oxygen ranging from 16% down to 5%, representing mostly the excess air side of the parabola. The very low and very high oxygen levels apparently both account for high dioxin levels.

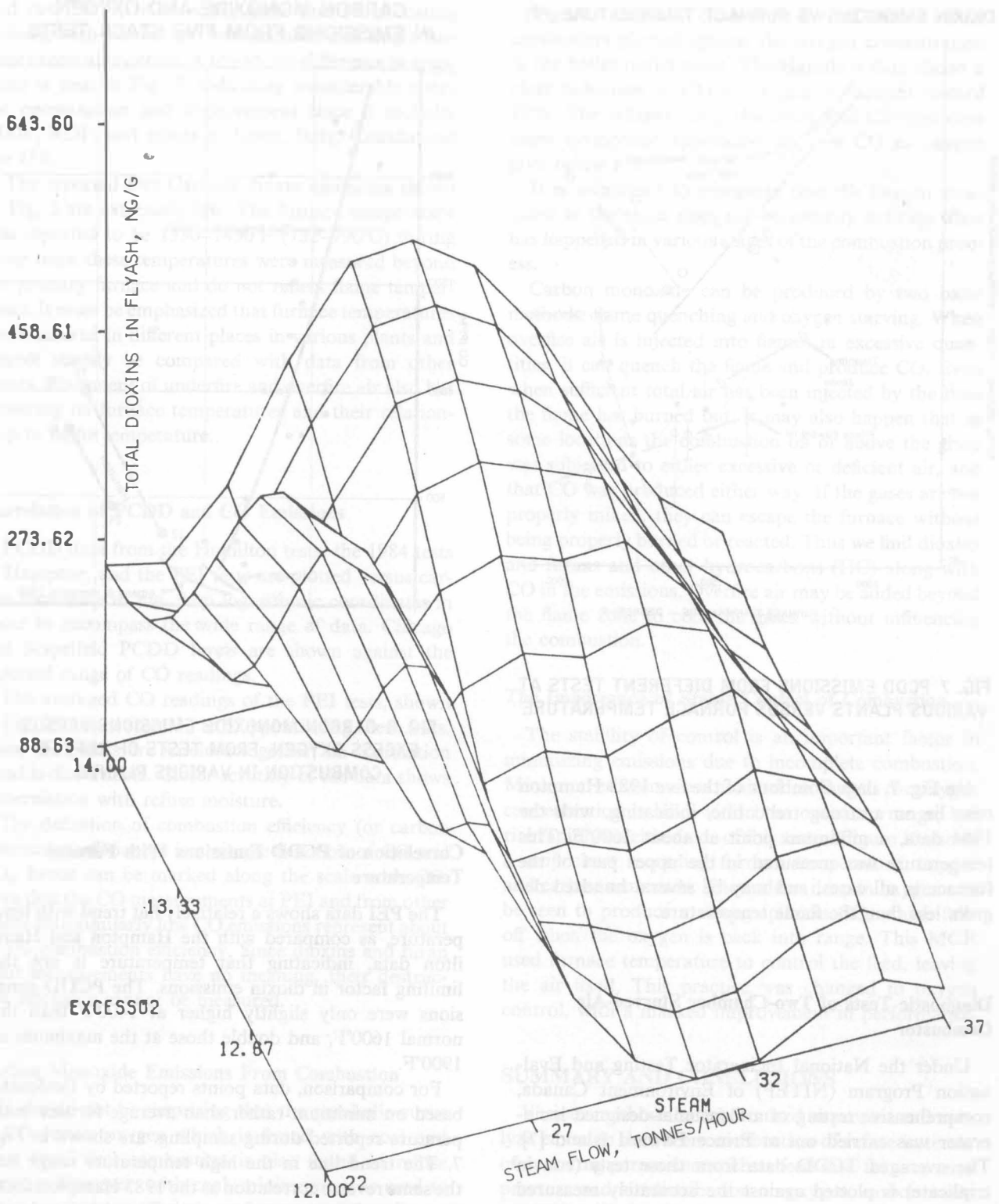


FIG. 6 THREE-DIMENSIONAL GRAPH OF BOILER LOAD, OXYGEN AND DIOXINS IN FLY ASH FROM PARIS INCINERATOR [22]

DIOXIN EMISSIONS VS FURNACE TEMPERATURE (°F)

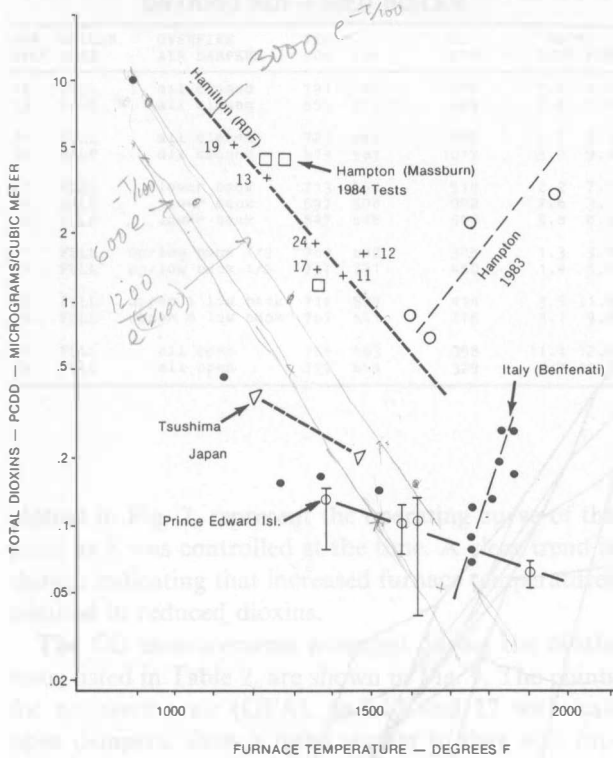


FIG. 7 PCDD EMISSIONS FROM DIFFERENT TESTS AT VARIOUS PLANTS VERSUS FURNACE TEMPERATURE

On Fig. 7, data from four of the five 1983 Hampton runs lie on a strong trend line, indicating, with the 1984 data, a minimum point at about 1600°F. This temperature was measured in the upper part of the furnace in all cases, and may be several hundred degrees less than the flame temperature.

Diagnostic Tests of Two-Chamber Starved-Air Combustor

Under the National Incinerator Testing and Evaluation Program (NITEP) of Environment Canada, comprehensive testing of a Consumat-designed incinerator was carried out at Prince Edward Island [7]. The averaged TCDD data from these tests (run in triplicate) is plotted against the accurately measured secondary chamber temperature in Fig. 7. The TCDF data (not shown for clarity) shows the same trend. The four tests were run in triplicate at the lowest and highest practical temperatures and two normal temperature runs with different loading time cycles.

CARBON MONOXIDE AND OXYGEN IN EMISSIONS FROM FIVE STACK TESTS

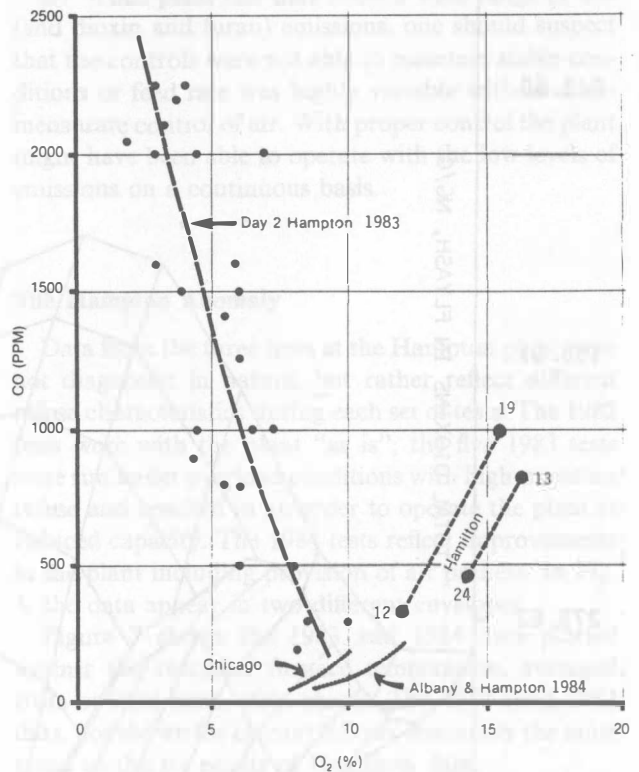


FIG. 8 CARBON MONOXIDE EMISSIONS VERSUS EXCESS OXYGEN, FROM TESTS OF REFUSE COMBUSTION IN VARIOUS PLANTS

Correlation of PCDD Emissions With Furnace Temperature

The PEI data shows a relatively flat trend with temperature, as compared with the Hampton and Hamilton data, indicating that temperature is not the limiting factor in dioxin emissions. The PCDD emissions were only slightly higher at 1400°F than the normal 1600°F, and double those at the maximum of 1900°F.

For comparison, data points reported by Benfenati, based on minimum rather than average furnace temperature reported during sampling, are shown in Fig. 7. The trend line in the high temperature range has the same reverse correlation as the 1983 Hampton data. The other Benfenati points show a parabolic shape, somewhat in agreement with two points from tests of the Tsushima, Japan plant. [24, 25]

It is remarkable to note the degree of agreement between sets of data from different plants burning RDF

and raw MSW, in traveling grate and reciprocating stokers, with starved-air two-chamber and single furnace excess air systems. A ten-to-one difference in emissions is seen in Fig. 7, indicating considerable room for optimization and improvement since it includes MSW, RDF, and plants in Japan, Italy, Canada and the U.S.

The reported Des Carriere dioxin emissions shown in Fig. 5 are extremely low. The furnace temperature was reported to be 1350–1450°F (732–790°C) during those tests: these temperatures were measured beyond the primary furnace and do not reflect flame temperature. It must be emphasized that furnace temperatures are measured in different places in various plants and cannot readily be compared with data from other plants. Placement of underfire and overfire air also has a bearing on furnace temperatures and their relationship to flame temperature.

Correlation of PCDD and CO Emissions

PCDD data from the Hamilton tests, the 1984 tests at Hampton, and the PEI tests are plotted versus carbon monoxide in Fig. 9 on logarithmic coordinates in order to encompass the wide range of data. Chicago and Stapelfeld PCDD levels are shown against the reported range of CO readings.

The averaged CO readings of the PEI tests, shown in Fig. 9, ranged from 33 to 67 ppm during these tests. Since the points are so close together, no correlation trend is discernable. Closer scrutiny of the data shows a correlation with refuse moisture.

The definition of combustion efficiency (or carbon destruction efficiency) is a simple function of CO and CO₂, hence can be marked along the scale with CO. Note that the CO measurements at PEI and from other plants with similarly low CO emissions represent about 99.5% combustion efficiency. Since dioxins and furan input measurements have no meaning, their destruction efficiency cannot be measured.

Carbon Monoxide Emissions From Combustion

It should not be surprising that the parabolic curve of CO versus oxygen which is found with coal and other fossil fuel combustion is also found in refuse burning. However, with coal, minimum air is used to achieve maximum efficiency, whereas traditionally refuse was burned with excessive air in order to protect refractory from slagging conditions. Today the trend in refuse burning is toward minimum air since this increases plant efficiency and power production.

Figure 8 shows CO data from several tests of refuse combustors plotted against the oxygen concentration in the boiler outlet gases. The Hamilton data shows a clear reduction in CO as oxygen is reduced toward 10%. The Albany [26], Hampton and Chicago data show asymptotic approaches to zero CO as oxygen goes below 8%.

It is important to recognize that the oxygen measured in the stack does not necessarily indicate what has happened in various stages of the combustion process.

Carbon monoxide can be produced by two basic methods: flame quenching and oxygen starving. When overfire air is injected into flames in excessive quantities, it can quench the flame and produce CO. Even when sufficient total air has been injected by the time the flame has burned out, it may also happen that in some locations the combustion on or above the grate was subjected to either excessive or deficient air, and that CO was produced either way. If the gases are not properly mixed, they can escape the furnace without being properly burned or reacted. Thus we find dioxins and furans and other hydrocarbons (HC) along with CO in the emissions. Overfire air may be added beyond the flame zone to cool the gases without influencing the combustion.

The Importance of Stable Control of Combustion

The stability of control is an important factor in minimizing emissions due to incomplete combustion. Minimum emissions are achieved as long as the oxygen concentration is held within the optimum range, but rise rapidly on either side of this range. Figure 10 shows a strip chart recording furnace temperature, oxygen and carbon monoxide. The sudden drop in oxygen can be seen to produce a strong spike in CO, which falls off when the oxygen is back into range. This MCR used furnace temperature to control the feed, leaving the air fixed. This practice was changed to oxygen control, with a marked improvement in performance.

SUMMARY AND CONCLUSIONS

Various methods have been used to present and analyze emission data from combustion of refuse in terms of operating parameters such as feed rate, furnace temperature and air distribution on oxygen, carbon monoxide and trace toxic compounds such as dioxins and furans measured in the gaseous combustion products.

The wide range of emissions of dioxins and furans reported for various types of refuse combustion systems can be partially explained by the furnace temperatures,

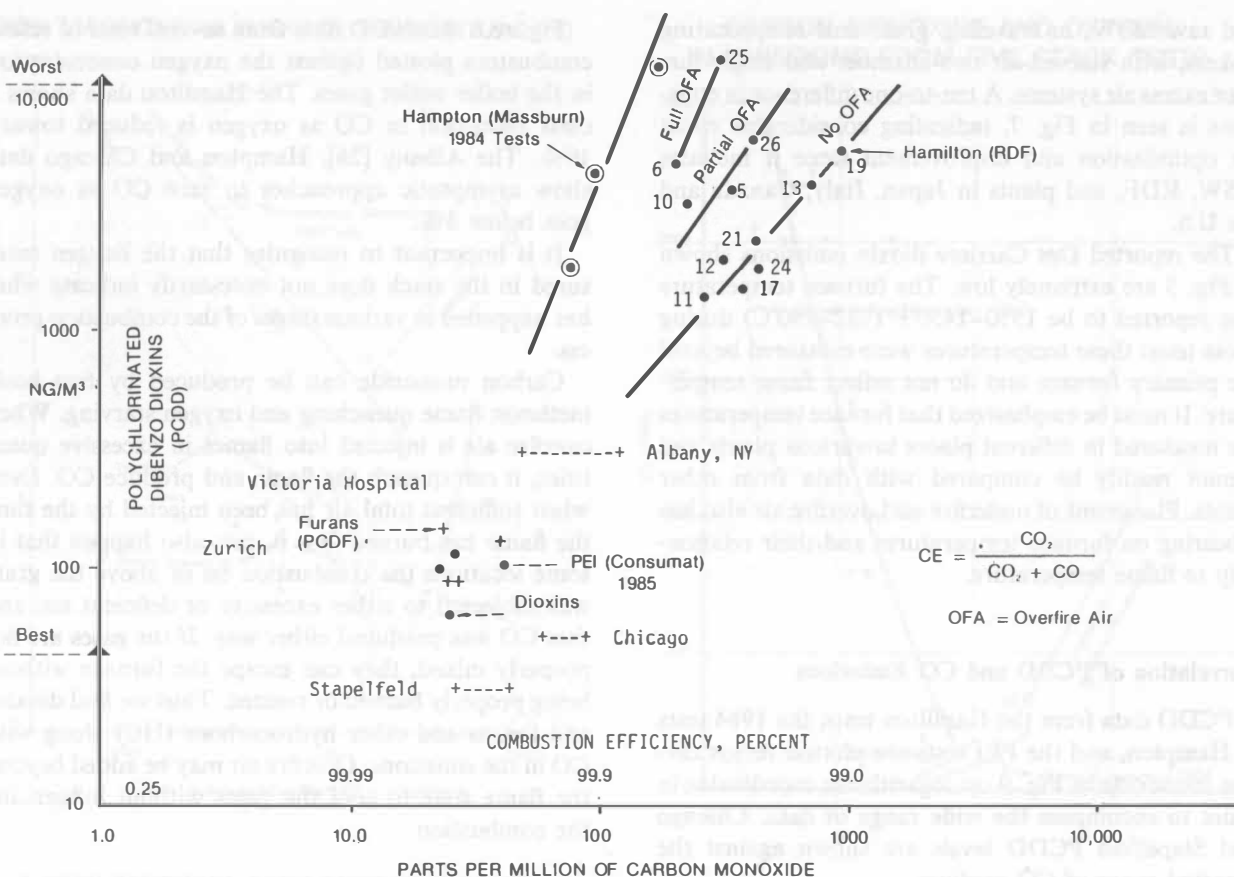


FIG. 9 LOGARITHMIC PLOT OF PCDD VERSUS CARBON MONOXIDE DE AND COMBUSTION EFFICIENCY FROM VARIOUS TESTS

but air distribution and other factors are also important. Furnace temperatures can be calculated from a knowledge of refuse composition, especially moisture, and excess air [3, 28].

There appears to be a consistent relationship between carbon monoxide and dioxin emissions. Some test data shows that air distribution and moisture can change this relationship.

Excess oxygen is related to emissions of CO: either too little or too much combustion air causes an increase in CO; there is a limited range of oxygen at which minimum CO is achieved.

The CO emissions from refuse combustion have a parabolic relationship with excess oxygen due to failure modes of too little, too much or misplaced combustion air, similar to those observed in flame combustion of liquid and gaseous hydrocarbons and coals.

Tests of MWC's during which parameters are deliberately maintained and systematically varied reveal the relationships between temperature, excess oxygen

and moisture on emissions of CO and trace organics such as dioxins and furans.

Increasing furnace temperatures beyond a certain point has not been found to reduce dioxin emissions. At some point oxygen concentration and other factors appear to become more important.

Air supplied to adjust furnace temperature should not be applied in such a way that it can quench the flame or otherwise arrest the completion of combustion.

Changes in refuse moisture content tend to shift the optimum excess oxygen concentration. CO readings may be useful as an indicator of the need for this shift.

Similarities are noted between refuse combustors of different types in different countries, yet major differences in emissions are also apparent, indicating differences in the effectiveness of air distribution, furnace shape, and combustion controls. There is evidently considerable room for improvement and optimization of these factors.

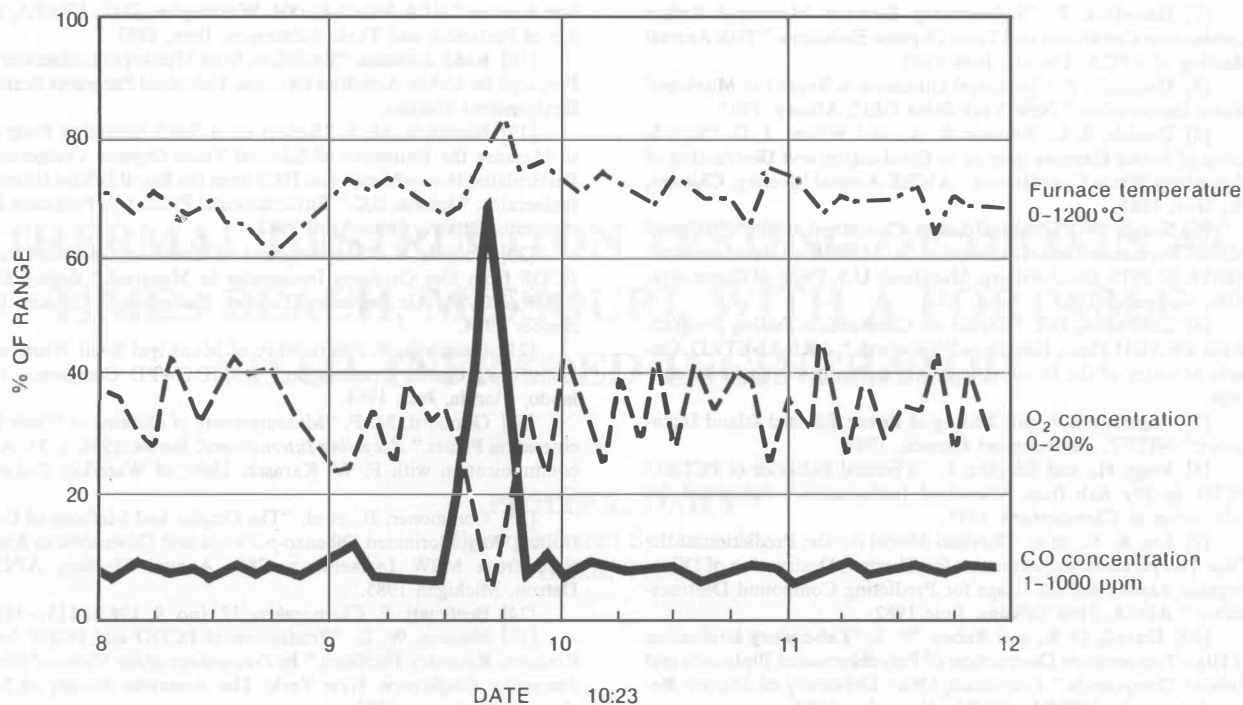


FIG. 10 STRIP CHART RECORDING OF FURNACE TEMPERATURE, OXYGEN CONCENTRATION AND CARBON MONOXIDE CONCENTRATIONS WITH FURNACE TEMPERATURE CONTROLLING (SYSVA, MALMO) [27]

The level of dioxin and furan emissions from a large group of municipal waste combustors has been evaluated for health risk and found to be at or below thresholds of concern.

Improving municipal waste combustor design, operation and control can make it possible to obtain and maintain optimum combustion conditions and minimize emissions of trace toxic organic compounds such as dioxins and furans.

Limited test data indicates that, for a given combustion system configuration and operating mode, a direct relationship exists between CO and PCDD and PCDF emissions. If this relationship can be demonstrated, CO measurements can be used as indicators of optimum combustion efficiency and minimum dioxin emissions.

Charts produced by continuous monitoring of furnace temperature, excess oxygen and CO show that CO is a sensitive indicator of upset conditions, and that there is a range of excess oxygen within which minimum CO can be achieved and maintained.

Carbon monoxide measurements appear to be useful as an indicator of the conditions which produce dioxins. By using CO monitors for optimization of design and operation, as well as for continuous monitoring of

refuse combustion systems, it should be possible to assure government agencies and the general public that consistent and high combustion efficiency and minimum emissions of trace toxic compounds for being achieved.

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Key Words: Carbon Monoxide; Combustion; Dioxins; Emissions; Furans; Incinerators; Moisture; Municipal Solid Waste (MSW); Municipal Waste Combustors (MWC); Oxygen; PCDD; PCDF; Trace Organics