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# DATA ANALYSIS RESULTS FOR TESTING AT A TWO-STAGE MODULAR MSW INCINERATOR: OSWEGO COUNTY ERF, FULTON, NEW YORK

## VOLUME I

## DRAFT FINAL REPORT

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# ACKNOWLEDGEMENTS

This report was prepared by Radian Corporation. Radian authored Sections 1, 2, 3, 4, 5, 7, and 8. Major contributors were Ms. Katerine Wertz and Ms. Mary Bishop under the project direction of Mr. Winton Kelly. Dr. Al Paulson of Rensselaer Polytechnic Institute contributed the analysis of replication in Section 6.

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# SUMMARY

The New York State Department of Environmental Conservation (NYSDEC) and the New York State Energy Research and Development Authority (NYSERDA) are participating in a joint program that will provide the basis for:

- Determining the operating characteristics and general design features of municipal solid waste (MSW) incinerators which minimize the production of polychlorinated dibenzo-p-dioxins (CDD) and polychlorinated dibenzofurans (CDF), and
- Selecting air pollution control devices to meet air quality and emission requirements.

This report presents a statistical and engineering analysis of the results of an emission testing program at a starved air, two chamber, mass burn, refractory design incineration facility.

The objective of the program was to determine facility operating conditions consistent with efficient combustion and minimal emissions of CDD and CDF at a modular MSW incinerator. In this report, the abbreviations CDD and CDF are used to indicate the sum of mono through octa-chlorinated homologues of dibenzo-p-dioxins and dibenzofurans, respectively. The overall test program combined the efforts of: NYSERDA, NYSDEC, the New York State Department of Health (NYSDOH), Radian Corporation, and the host site--the Oswego County Energy Recovery Facility (ERF). Radian Corporation was under contract to NYSERDA to provide technical and sampling support.

The program was conducted on Unit #1 at the Oswego County Energy Recovery Facility located in Fulton, New York. The facility consists of four identical Consumat incinerators, each equipped with a waste heat boiler and an electrostatic precipitator (ESP) for particulate control. A schematic of the facility is shown in Figure S-1. Manual sampling was performed for CDD and CDF flue gas concentrations at three locations, the secondary chamber exit, ESP inlet and ESP outlet; HCl and particulate sampling was performed at the

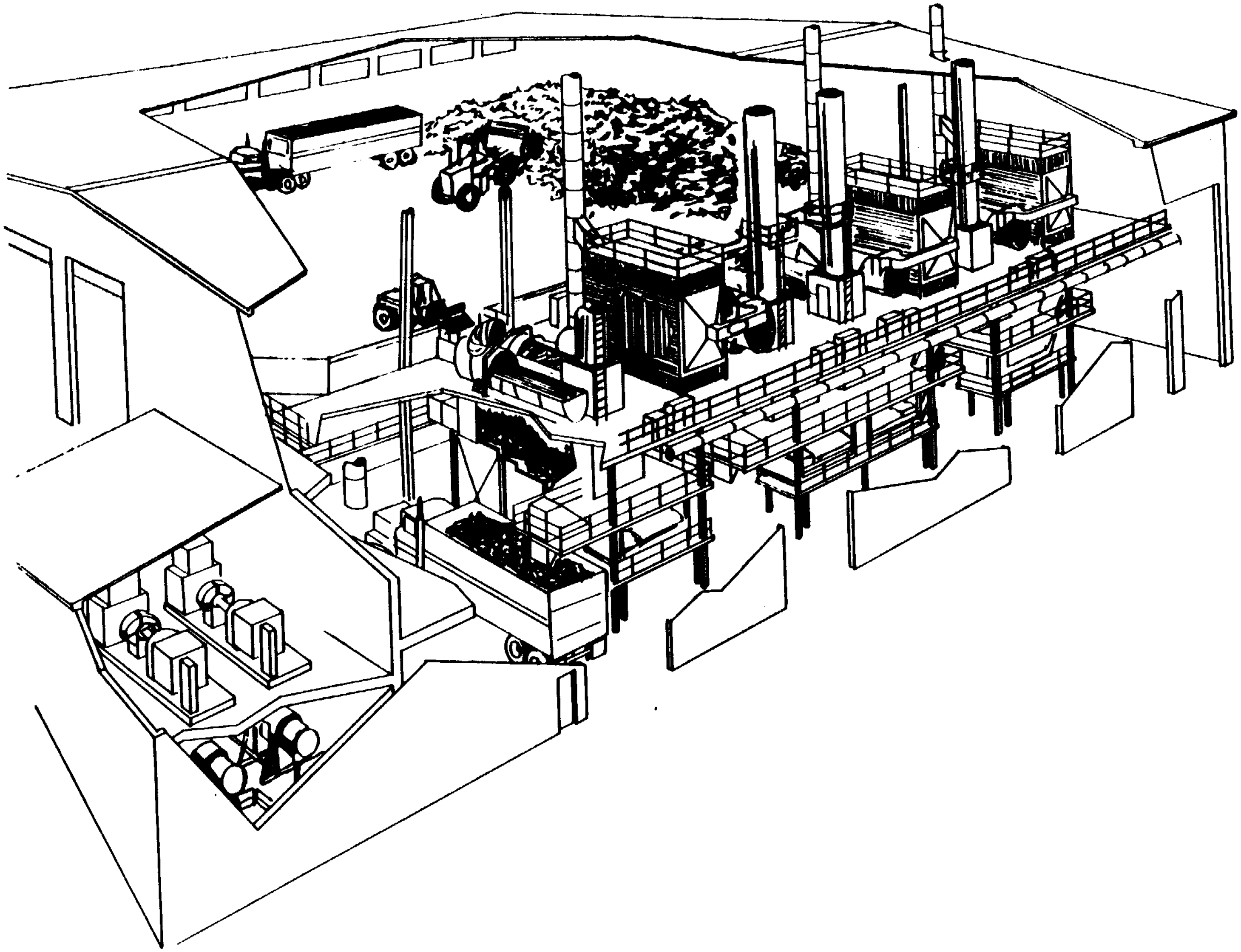

Figure S-1. Oswego County ERF Layout

ESP inlet and outlet. Plant operating data and combustion gas variables were monitored during the manual CDD and CDF test runs.

Specific objectives of this project were:

1. To determine the relationships over the range of operating conditions between combustion gas variables recorded by continuous emission monitors (CEMs), plant process variables, and emission levels of CDD and CDF;
2. To determine the potential for monitoring combustion gas variables as surrogate indicators in lieu of sampling for CDD and CDF; and
3. To determine the relationships between concentrations of other chlorinated compounds (potential precursors) to CDD and CDF formation and emissions of CDD and CDF collected at various operating conditions.

In an attempt to measure and observe the effects of operating conditions on combustion gas composition and CDD and CDF formation, twelve test runs were performed under four different operating conditions:

1. Start of campaign (immediately following a scheduled maintenance period, normal primary and secondary chamber operating temperatures);
2. End of campaign (just prior to a scheduled maintenance period, normal primary and secondary chamber operating temperatures);
3. Mid-range secondary chamber temperature (mid-campaign); and
4. Low secondary chamber temperature (mid-campaign).

Flue gas samples were collected simultaneously at the secondary chamber exit (hotzone), ESP inlet, and ESP outlet. Combustion gas variables were monitored at the secondary chamber exit and ESP outlet.

An overview of the sampling approach and data that were collected is shown in Table S-1. The start and end of campaign tests were selected to show the effects of fouling of heat recovery equipment, air distribution equipment, and ESP plates, as well as buildup of ash in the secondary chamber, on CDD and CDF emissions. In addition, these tests were selected to determine if time since maintenance affects combustion efficiency. The mid-range and low

### Table S-1.

### SAMPLING AND ANALYSIS SUMMARY

1. Number of Test Runs
   - Three runs each:
     - -- start of campaign (clean, after major maintenance shutdown)
     - -- low secondary chamber temperature (approximately mid-campaign)
     - -- mid-range secondary chamber temperature (approximately mid-campaign)
     - -- end of campaign (fouled, prior to major maintenance shutdown)

2. Flue Gas Sampling
   - MM5 sampling for CDD, CDF, precursors, and HCl
   - M5 sampling for total particulates (ESP inlet and outlet only)
   - Fixed gas analysis-integrated bag sampling (EPA Method 3) (secondary chamber exit only)
   - Volumetric gas flowrate and flue gas moisture (EPA Methods 2,4)
   - Continuous monitoring of flue gas moisture and temperature (secondary chamber exit only), $O_2$, $CO_2$, CO, $SO_2$, $NO_x$, and THC (secondary chamber exit only)

3. Ash/Refuse Sampling
   - Grab samples/composite of:
     - -- incinerator bottom ash
     - -- refuse feed

4. Process Data Collected
   - Temperature
     - -- primary chamber
     - -- secondary chamber
     - -- boiler inlet, outlet
   - Pressure
     - -- incinerator draft
     - -- boiler differential
     - -- primary combustion air
     - -- secondary combustion air
   - Ram cycles
     - -- transfer ram #1, #2
     - -- ash ram
     - -- feed loader ram
   - Incinerator charging indicators
     - -- load light
     - -- load normal
     - -- load heavy

5. Process Rate Estimates
   - Refuse feed rate
   - Bottom ash rate
   - ESP dust rate

secondary chamber temperature conditions were selected to see how varying the temperature would influence the composition of combustion gases and types and amounts of organic pollutants emitted. Sampling at the secondary chamber exit was performed by Radian Corporation, while sampling at the ESP inlet and outlet was performed by the NYSDEC. Manual CDD and CDF sampling was conducted according to the December 1984 draft procedure recommended by the Environmental Standards Workshop. Sample analysis was performed by the NYSDOH.

A number of graphical and statistical procedures were used to determine the relationships among three major groups of variables:

1. Plant operating conditions as represented by operating variables;
2. Combustion gas variables as measured by continuous emission monitors; and
3. CDD and CDF total and individual homologue concentrations measured at three sampling locations.

Statistical methods that were used in this analysis include: Pearson product-moment correlations, analysis of variance (ANOVA), cluster analysis, and time series analysis. These statistical methods were used in conjunction with visual inspections of graphical representations and engineering evaluation of the results. A significant component of the data analysis involved the interpretation of the statistically significant relationships from engineering and combustion chemistry points of view. All statistically significant relationships between variables were reviewed. The apparently casual relationships are not discussed in detail in the text but are included in Appendix C.

## FINDINGS RELEVANT TO SPECIFIC PROJECT OBJECTIVES

Objective 1: To determine the relationships over the range of operating conditions between combustion gas variables recorded by continuous emission monitors (CEMs), plant process variables, and emission levels of CDD and CDF.

Several statistically significant relationships were found between combustion gas variables, plant process variables, and CDD and CDF concentrations.

These relationships are discussed later in this summary and in Section 7 (the main body of this report).

Objective 2: To determine the potential for monitoring combustion gas variables as surrogate indicators in lieu of sampling for CDD and CDF.

The results show that for this facility, there is little potential for monitoring combustion gas variables as surrogate indicators of CDD and CDF emissions, in lieu of manual sampling for CDD and CDF. For example, even though there were several statistically significant relationships between CDD and CDF concentrations and CO concentrations, they were not strong enough or consistent enough to be used as surrogate indicators. In addition, the majority of CO correlations were with extreme value single value representations, which cannot be continuously monitored.

Objective 3: To determine the relationships between concentrations of other chlorinated compounds (potential precursors) to CDD and CDF formation and emissions of CDD and CDF collected at various operating conditions.

There were no significant relationships between total chlorobenzene, total chlorophenol, and total polyaromatic hydrocarbon (PAH) concentrations and total CDD and CDF concentrations.

## CDD and CDF Results

The CDD and CDF concentration and mass rate data measured during this study are presented in Table S-2. Normalized CDD and CDF concentrations to 7 percent $O_2$ are shown in Table S-3. The substituted 2,3,7,8-TCDD and -TCDF isomer concentrations are presented in Table S-4; these isomers are shown separately because they have been the subject of concern from a public health aspect.

As shown in Tables S-2 and S-3, there is a distinct sampling location effect. For all but one test run, CDD measured at the ESP inlet is greater than the amount measured at the secondary chamber exit; the same is true for the ESP outlet and inlet. This trend is not present for CDF concentrations. Excluding the low secondary chamber temperature test runs, CDF concentrations

## Table S-2.
## TOTAL CDD AND CDF CONCENTRATIONS AND MASS EMISSION RATES

| TEST CONDITION[a] | RUN NUMBER | SECONDARY CHAMBER EXIT | | | | ESP INLET | | | | ESP OUTLET | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | TOTAL CDD, ng/dscm | TOTAL CDD, ug/hr | TOTAL CDF, ng/dscm | TOTAL CDF, ug/hr | TOTAL CDD, ng/dscm | TOTAL CDD, ug/hr | TOTAL CDF, ng/dscm | TOTAL CDF, ug/hr | TOTAL CDD, ng/dscm | TOTAL CDD, ug/hr | TOTAL CDF, ng/dscm | TOTAL CDF, ug/hr |
| Start of Campaign, SCE = 1800 deg. F | 1 | 18.4 | 307.6 | 175.7 | 2937.4 | 31.1 | 516.8 | 83.6 | 1389.1 | 80.0 | 1508.7 | 129.7 | 2446.0 |
| | 2 | 2.9 | 50.3 | 545.5 | 9453.5 | 31.2 | 512.6 | 83.9 | 1378.4 | 70.5 | 1317.6 | 123.2 | 2302.5 |
| | 3 | 9.5 | 156.2 | 250.5 | 4119.9 | 16.8 | 272.6 | 47.4 | 769.1 | 72.4 | 1402.3 | 120.9 | 2341.7 |
| | AVG. | 10.3 | 171.4 | 323.9 | 5503.6 | 26.4 | 434.0 | 71.6 | 1178.9 | 74.3 | 1409.5 | 124.6 | 2363.4 |
| Mid-range Secondary Chamber Temperature, SCE = 1750 deg. F | 4 | 3.2 | 49.6 | 59.0 | 914.2 | 33.3 | 522.2 | 101.4 | 1590.2 | 72.6 | 1319.8 | 125.3 | 2277.9 |
| | 5 | 17.7 | 275.8 | 127.0 | 1978.7 | 28.0 | 432.0 | 86.4 | 1332.9 | 54.4 | 942.8 | 102.7 | 1779.8 |
| | 6 | 4.3 | 63.7 | 519.0 | 7689.2 | 20.8 | 315.6 | 83.8 | 1271.4 | 47.2 | 790.7 | 134.8 | 2258.2 |
| | AVG. | 8.4 | 129.7 | 235.0 | 3527.4 | 27.4 | 423.3 | 90.5 | 1398.2 | 58.1 | 1017.8 | 120.9 | 2105.3 |
| End of Campaign, SCE = 1800 deg. F | 7 | 54.7 | 803.9 | 400.5 | 5886.0 | 39.1 | 556.7 | 134.5 | 1915.0 | 80.8 | 1258.9 | 156.2 | 2433.6 |
| | 8 | 27.2 | 423.8 | 154.5 | 2407.1 | 58.9 | 926.7 | 241.2 | 3794.8 | 41.8[b] | 687.5[b] | 119.3[b] | 1962.1[b] |
| | 9 | 27.2 | 451.5 | 280.5 | 4656.1 | 42.2[b] | 666.1[b] | 140.1[b] | 2211.3[b] | 124.3 | 2101.3 | 259.3 | 4383.5 |
| | AVG. | 36.4 | 559.7 | 278.5 | 4316.4 | 46.7 | 716.5 | 171.9 | 2640.4 | 82.3 | 1349.2 | 178.3 | 2926.4 |
| Low Secondary Chamber Temperature, SCE = 1650 deg. F | 10 | 63.4 | 975.9 | 171.1 | 2633.8 | 173.6 | 2925.9 | 295.9 | 4987.2 | 218.9 | 3756.3 | 279.6 | 4798.0 |
| | 11 | 38.5 | 584.8 | 224.1 | 3403.9 | 121.1 | 1880.6 | 203.5 | 3160.2 | 170.6 | 2840.6 | 233.5 | 3887.9 |
| | 12 | 40.9 | 539.2 | 125.0 | 1648.0 | 125.7 | 1873.0 | 193.5 | 2883.2 | 147.6 | 2149.1 | 181.2 | 2638.4 |
| | AVG. | 47.6 | 700.0 | 173.4 | 2561.9 | 140.1 | 2226.5 | 231.0 | 3676.9 | 179.0 | 2915.3 | 231.4 | 3774.7 |
| 12 Run Average | | 25.7 | 390.2 | 252.7 | 3977.3 | 60.2 | 950.1 | 141.3 | 2223.6 | 98.4 | 1673.0 | 163.8 | 2792.5 |

[a] SCE = Secondary Chamber Exit; temperatures represent setpoints for condition indicated.

[b] Front half train results not reported; total train results assume no CDD or CDF detected in front half of sampling train.

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Table S-3.

TOTAL DIOXIN AND FURAN CONCENTRATIONS CORRECTED TO 7% OXYGEN

| | | SECONDARY CHAMBER EXIT | | ESP INLET | | ESP OUTLET | |
|---|---|---|---|---|---|---|---|
| TEST CONDITION[a] | RUN NUMBER | TOTAL CDD, ng/dscm @7% $O_2$ | TOTAL CDF, ng/dscm @7% $O_2$ | TOTAL CDD, ng/dscm @7% $O_2$ | TOTAL CDF, ng/dscm @7% $O_2$ | TOTAL CDD, ng/dscm @7% $O_2$ | TOTAL CDF, ng/dscm @7% $O_2$ |
| Start of Campaign, SCE = 1800 deg. F | 1 | 28.7 | 274.5 | 57.7 | 155.0 | 148.3 | 240.4 |
| | 2 | 4.7 | 881.6 | 62.8 | 169.0 | 142.1 | 248.2 |
| | 3 | 16.2 | 429.9 | 31.1 | 87.9 | 134.2 | 224.1 |
| | AVG. | 16.5 | 528.7 | 50.5 | 137.3 | 141.5 | 237.6 |
| Mid-range Secondary Chamber Temperature, SCE = 1750 deg. F | 4 | 5.3 | 98.7 | 66.1 | 201.4 | 144.1 | 248.8 |
| | 5 | 28.7 | 205.2 | 53.3 | 164.6 | 103.6 | 195.5 |
| | 6 | 6.9 | 838.8 | 40.7 | 164.0 | 92.3 | 263.9 |
| | AVG. | 13.6 | 380.9 | 53.4 | 176.7 | 113.3 | 236.1 |
| End of Campaign, SCE = 1800 deg. F | 7 | 78.3 | 574.0 | 68.8 | 236.7 | 142.1 | 274.8 |
| | 8 | 40.2 | 228.5 | 115.3 | 472.2 | 81.9[b] | 233.5[b] |
| | 9 | 40.6 | 419.3 | 73.3[b] | 243.4[b] | 216.0 | 450.6 |
| | AVG. | 53.0 | 407.3 | 85.8 | 317.4 | 146.7 | 319.6 |
| Low Secondary Chamber Temperature, SCE = 1650 deg. F | 10 | 110.1 | 297.2 | 349.8 | 596.2 | 441.1 | 563.3 |
| | 11 | 67.7 | 394.4 | 255.1 | 428.5 | 359.3 | 491.8 |
| | 12 | 75.8 | 231.6 | 264.8 | 407.6 | 310.9 | 381.7 |
| | AVG. | 84.5 | 307.7 | 289.9 | 477.4 | 370.4 | 478.9 |
| 12 Run Average | | 41.9 | 406.1 | 119.9 | 277.2 | 193.0 | 318.1 |

[a] SCE = Secondary Chamber Exit; temperatures represent setpoints for condition indicated.

[b] Front half train results not reported; total train results assume no CDD or CDF detected in front half of sampling train.

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## Table S-4.

## 2,3,7,8-TCDD AND 2,3,7,8-TCDF CONCENTRATIONS UNADJUSTED AND ADJUSTED TO 7% OXYGEN

| TEST CONDITION[a] | RUN NUMBER | SECONDARY CHAMBER EXIT |  |  |  | ESP INLET |  |  |  | ESP OUTLET |  |  |  |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
|  |  | 2,3,7,8-TCDD, ng/dscm | 2,3,7,8-TCDD, ng/dscm @7% $O_2$ | 2,3,7,8-TCDF, ng/dscm | 2,3,7,8-TCDF, ng/dscm @7% $O_2$ | 2,3,7,8-TCDD, ng/dscm | 2,3,7,8-TCDD, ng/dscm @7% $O_2$ | 2,3,7,8-TCDF, ng/dscm | 2,3,7,8-TCDF, ng/dscm @7% $O_2$ | 2,3,7,8-TCDD, ng/dscm | 2,3,7,8-TCDD, ng/dscm @7% $O_2$ | 2,3,7,8-TCDF, ng/dscm | 2,3,7,8-TCDF, ng/dscm @7% $O_2$ |
| Start of Campaign, SCE = 1800 deg. F | 1 | ND | ND | 4.2 | 6.5 | ND | ND | 3.6 | 6.6 | ND | ND | 5.5 | 10.2 |
|  | 2 | ND | ND | 9.3 | 15.0 | ND | ND | 3.6 | 7.2 | 0.1 | 0.3 | 4.9 | 9.9 |
|  | 3 | ND | ND | 5.7 | 9.7 | ND | ND | 2.6 | 4.8 | ND | ND | 4.9 | 9.1 |
|  | AVG. | ND | ND | 6.4 | 10.4 | ND | ND | 3.3 | 6.2 | 0.1 | 0.3 | 5.1 | 9.7 |
| Mid-range Secondary Chamber Temperature, SCE = 1750 deg. F | 4 | ND | ND | 2.6 | 4.4 | 0.3 | 0.5 | 3.4 | 6.7 | 0.2 | 0.4 | 4.2 | 8.3 |
|  | 5 | 0.3 | 0.5 | 5.7 | 9.1 | ND | ND | 3.5 | 6.6 | 0.1 | 0.3 | 4.0 | 7.7 |
|  | 6 | ND | ND | ND | ND | ND | ND | 3.9 | 7.6 | 0.2 | 0.5 | 4.7 | 9.1 |
|  | AVG. | 0.3 | 0.5 | 4.2 | 6.8 | 0.3 | 0.5 | 3.6 | 7.0 | 0.2 | 0.4 | 4.3 | 8.4 |
| End of Campaign, SCE = 1800 deg. F | 7 | 0.7 | 0.9 | 7.5 | 10.8 | ND | ND | 7.2 | 12.8 | 0.3 | 0.5 | 6.6 | 11.6 |
|  | 8 | ND | ND | 6.8 | 10.0 | 0.9 | 1.7 | 11.7 | 22.8 | 0.3 | 0.6 | 5.2 | 10.2 |
|  | 9 | 0.5 | 0.7 | 6.9 | 10.3 | 0.4 | 0.7 | 6.0 | 10.4 | 4.6 | 8.0 | 10.6 | 18.4 |
|  | AVG. | 0.6 | 0.8 | 7.1 | 10.4 | 0.7 | 1.2 | 8.3 | 15.3 | 1.7 | 3.0 | 7.5 | 13.4 |
| Low Secondary Chamber Temperature, SCE = 1650 deg. F | 10 | 1.3 | 2.2 | 9.3 | 16.2 | 1.3 | 2.6 | 7.1 | 14.3 | 1.0 | 2.1 | 11.9 | 23.9 |
|  | 11 | 0.6 | 1.1 | 11.4 | 20.1 | 0.4 | 0.9 | 5.9 | 12.4 | 0.4 | 0.8 | 9.7 | 20.5 |
|  | 12 | 0.5 | 0.9 | 5.3 | 9.9 | ND | ND | 8.2 | 17.2 | 0.4 | 0.7 | 7.4 | 15.6 |
|  | AVG. | 0.8 | 1.4 | 8.7 | 15.4 | 0.9 | 1.8 | 7.1 | 14.6 | 0.6 | 1.2 | 9.7 | 20.0 |
| 12 Run Average |  | 0.6 | 0.9 | 6.6 | 10.7 | 0.6 | 1.2 | 5.6 | 10.8 | 0.7 | 1.2 | 6.6 | 12.9 |

[a] SCE = Secondary Chamber Exit; temperatures represent setpoints for condition indicated.

are not linearly correlated (r=-0.260), while CDD and CDF concentrations are highly correlated at the ESP inlet (r=0.894) and outlet (r=0.930).

CDD and CDF homologue distribution graphs are presented in Figures S-2 through S-7. The figures show chlorination from the lower molecular weight homologues to the higher molecular weight homologues for both CDD and CDF between the secondary chamber exit and ESP inlet. The CDD and CDF homologue distribution is similar for the ESP inlet and outlet locations. However, the chlorination is more marked for CDF.

## CDD and CDF Formation

Several mechanisms have been hypothesized by researchers to account for the presence of CDD and CDF downstream of the combustion zone in municipal waste combustors. The hypotheses include: a) the presence of CDD and CDF in the refuse which are not destroyed in the combustion process; b) reaction of products of incomplete combustion in the gas phase or on flyash; c) de novo synthesis of CDD and CDF on flyash involving metal chloride catalysis; and d) de novo synthesis from particulate carbon.

At Oswego, the CDD level in the refuse ranged from 0.2 to 0.8 ng/g; the CDF level detected in the one refuse sample was 0.08 ng/g. The limited amount of refuse data available from the Prince Edward Island (PEI) and Pittsfield studies show CDD levels of 3 to 5 ng/g (1), with low or nondetectable levels of CDF. Using 12-run averages of the estimated refuse feed rates and the CDD and CDF concentrations given in Section 4, it is estimated that about 0.18 ng CDD/g refuse and 1.77 ng CDF/g refuse would be emitted in the flue gas, as measured at the secondary chamber exit. Comparing these values to the levels of CDD and CDF contained in the refuse would indicate that between 10 and 80 percent of the CDD contained in the refuse is destroyed in the combustion zone, while CDF forms in the combustion zone.

Figures S-8 and S-9 present estimates of the amount of CDD and CDF, respectively, emitted from the secondary chamber per g of refuse burned by run number. As shown in the figures, there is more CDD emitted at the low secondary chamber temperature and end of campaign test conditions. This may

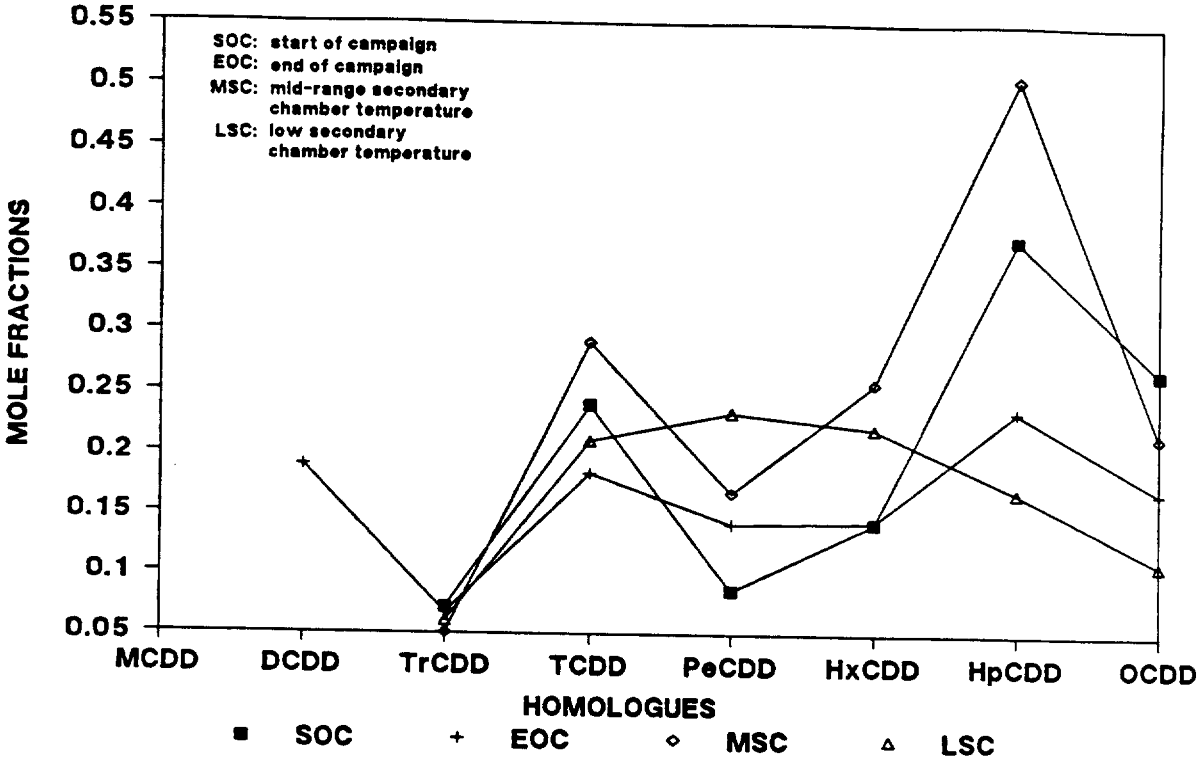

Figure S-2. CDD Mole Fractions at the Secondary Chamber Exit by Test Condition

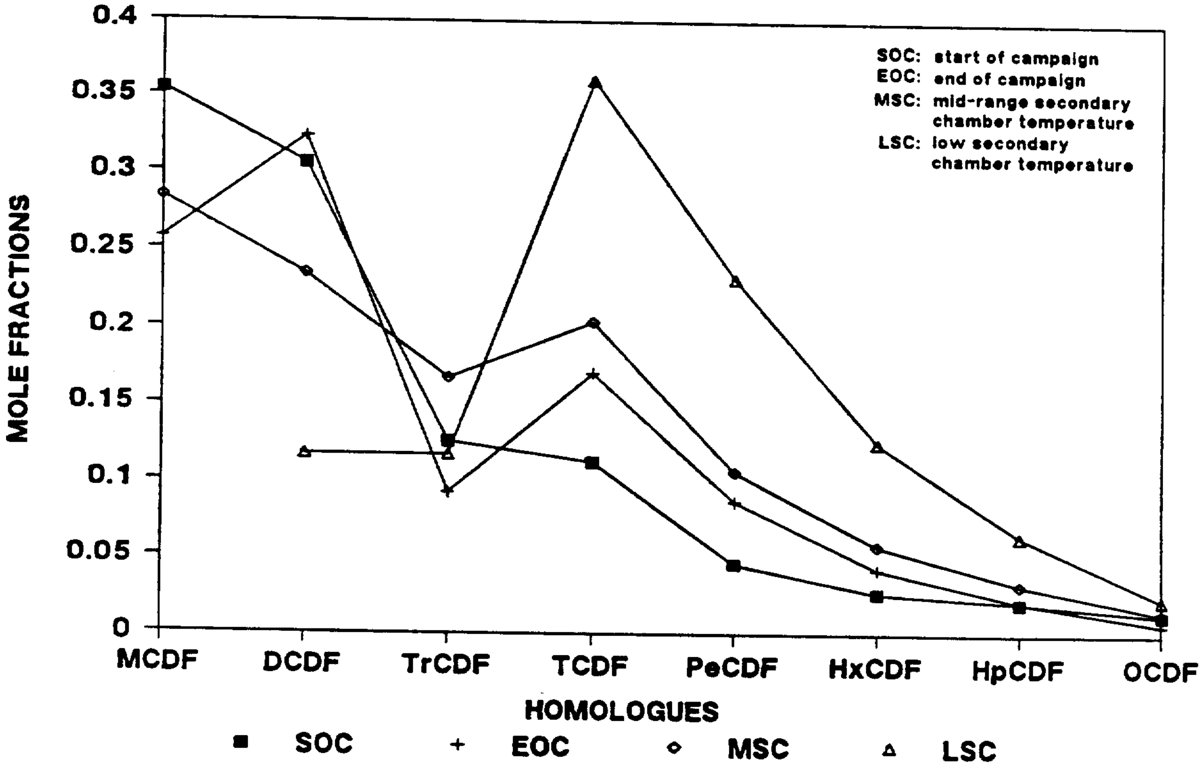

Figure S-3. CDF Mole Fractions at the Secondary Chamber Exit by Test Condition

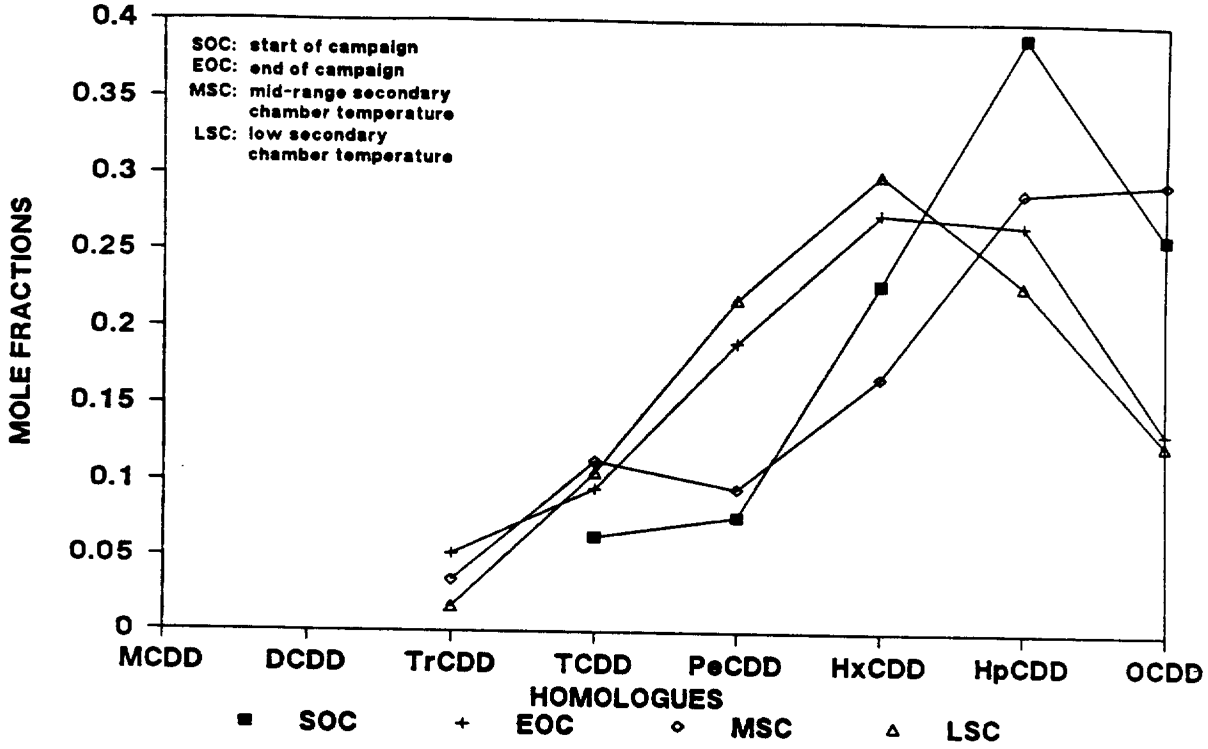

Figure S-4. CDD Mole Fractions at the ESP Inlet by Test Condition

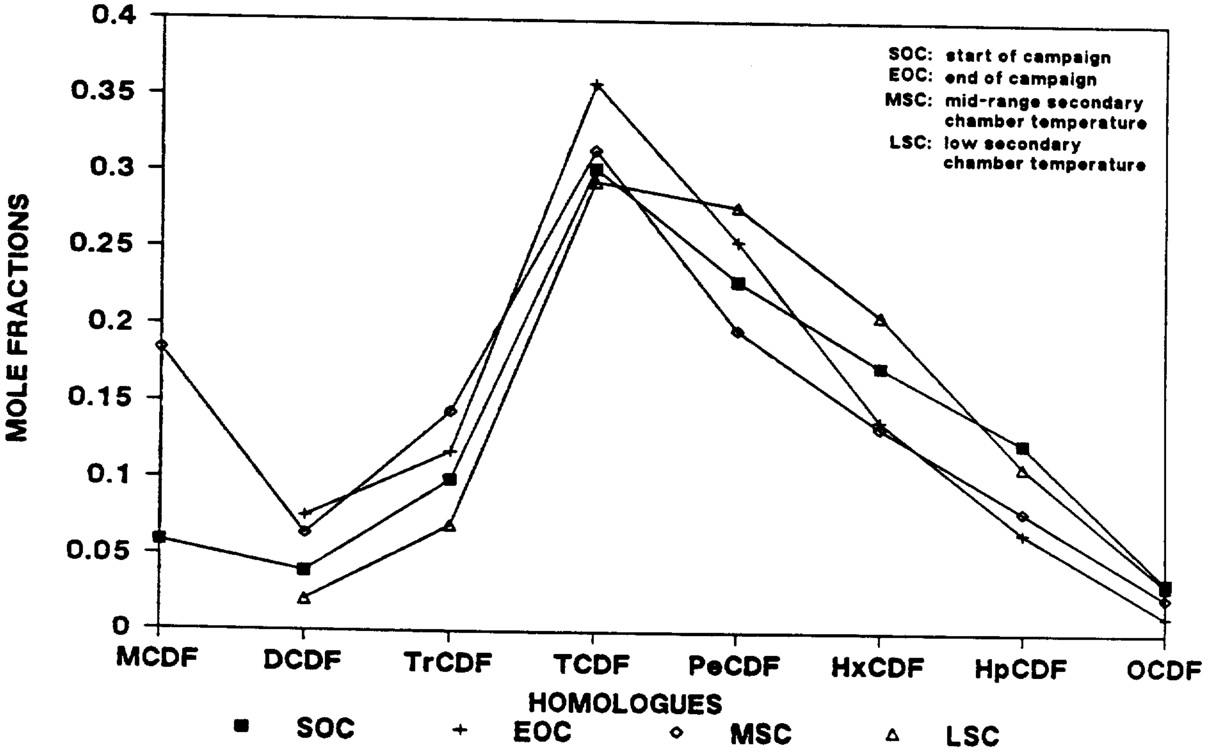

Figure S-5. CDF Mole Fractions at the ESP Inlet by Test Condition

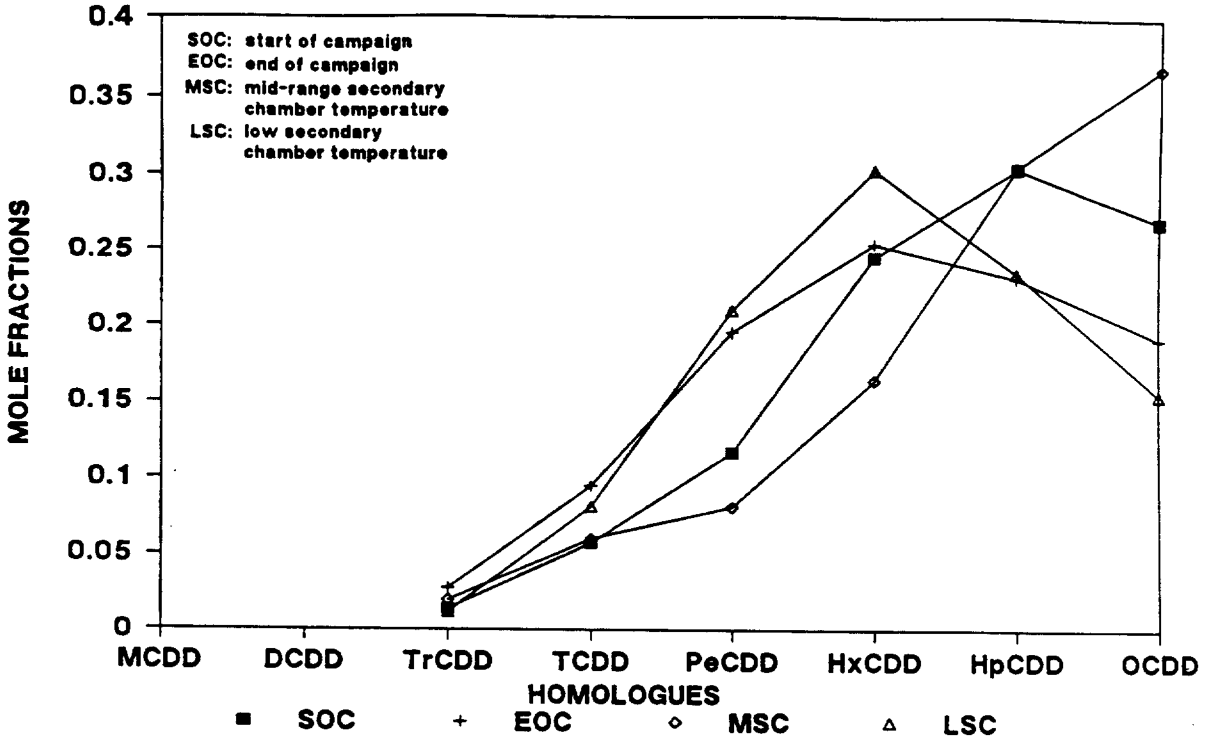

Figure S-6. CDD Mole Fractions at the ESP Outlet by Test Condition

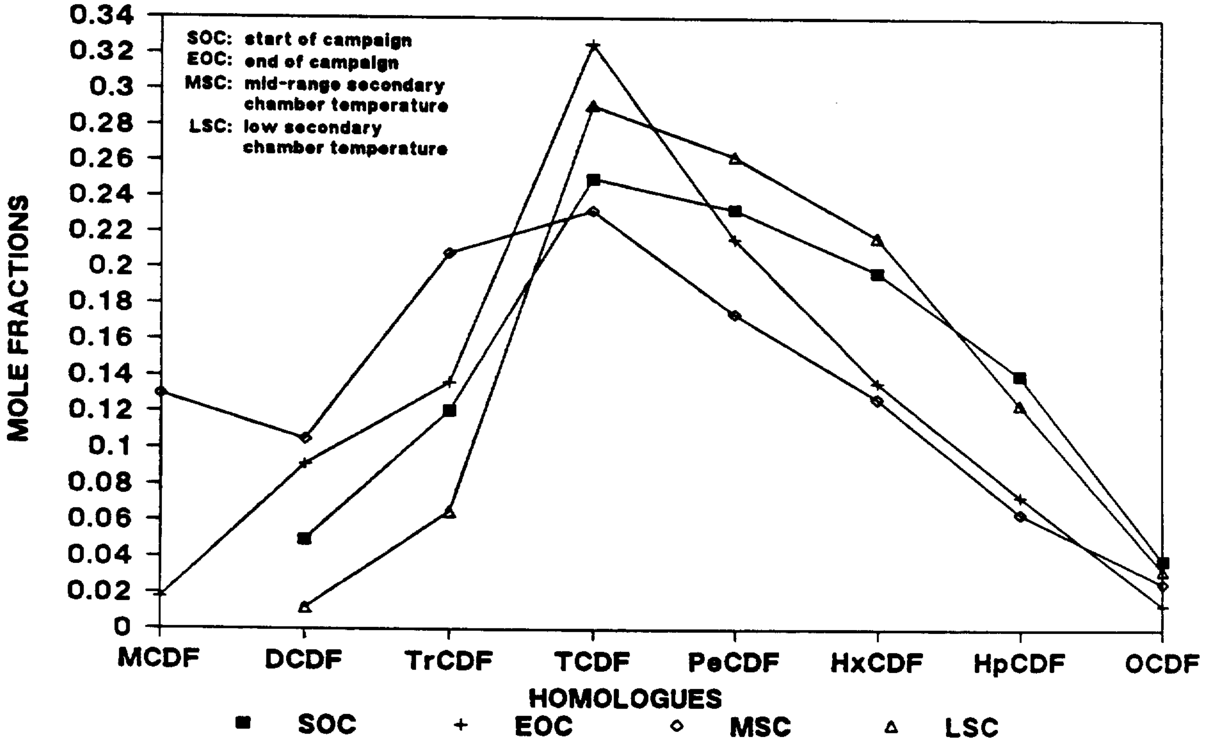

Figure S-7. CDF Mole Fractions at the ESP Outlet by Test Condition

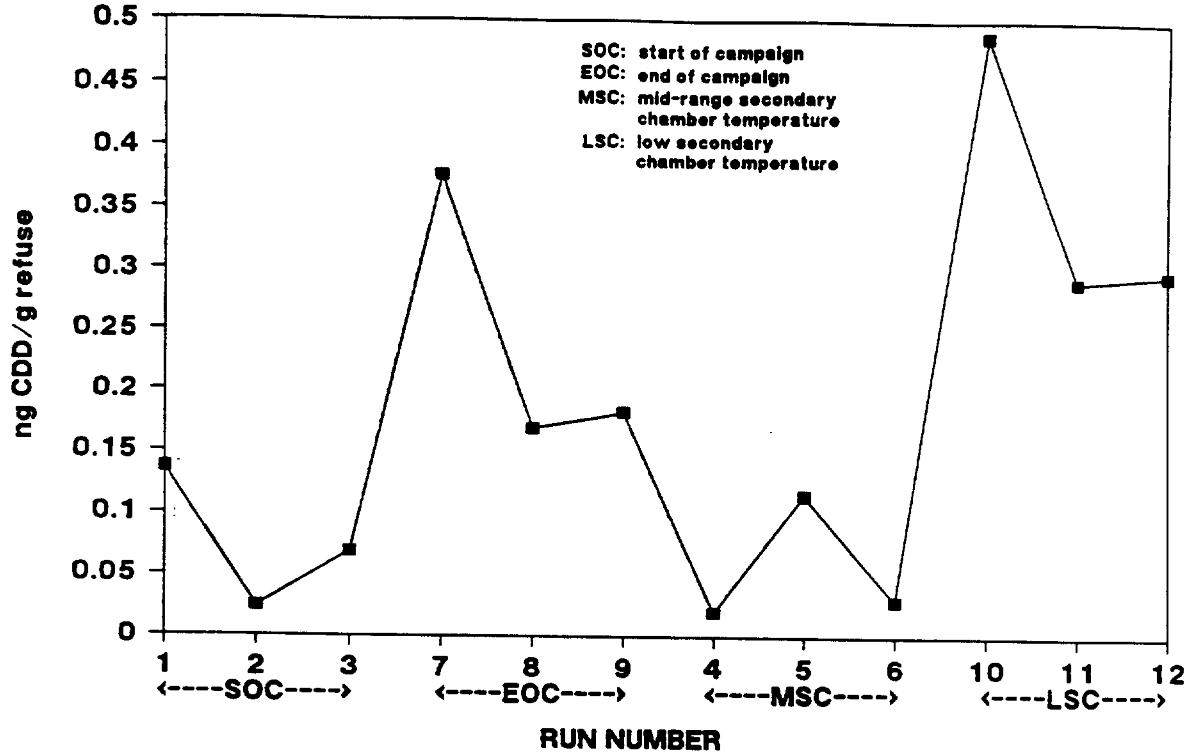

Figure S-8. ng CDD Measured at the Secondary Chamber Exit per g Refuse by Run Number

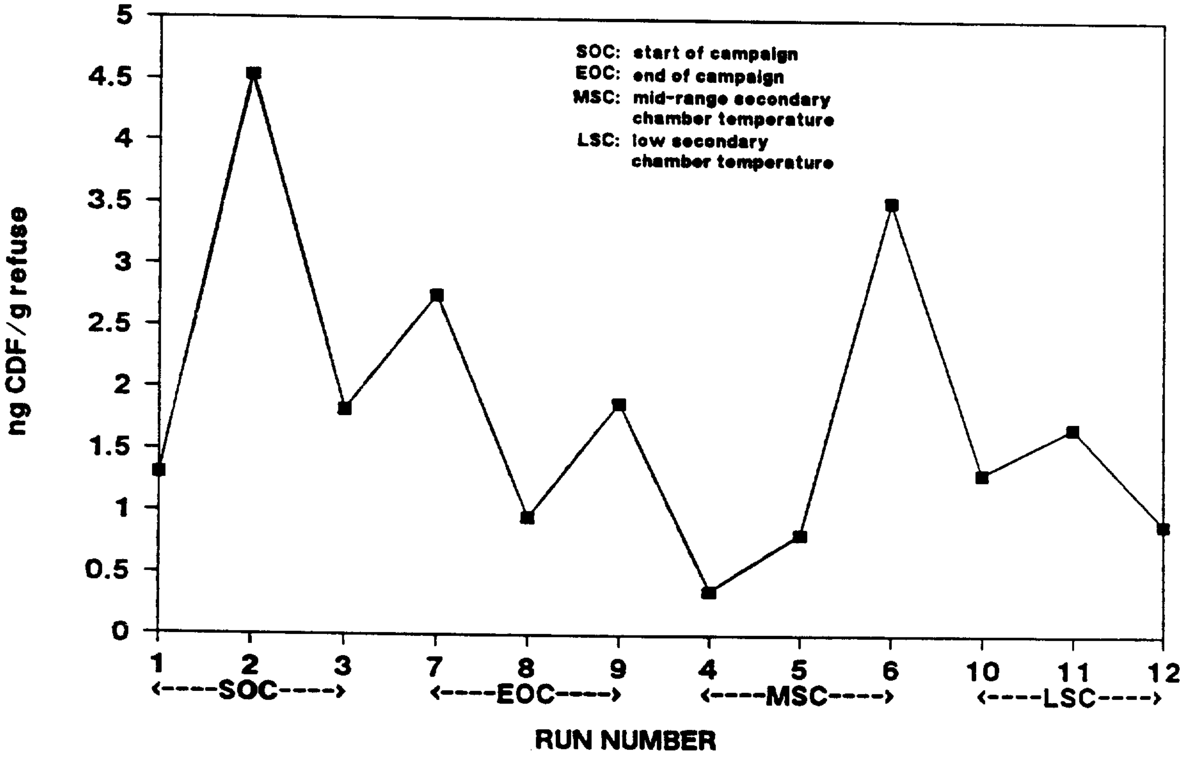

Figure S-9. ng CDF Measured at the Secondary Chamber Exit per g Refuse by Run Number be due to the low secondary chamber temperature allowing formation of CDD in the combustion zone, and excess ash buildup/fouled heat transfer surfaces (end of campaign test runs) possibly allowing the formation of CDD via metal catalysis from particulate carbon.

Experimental studies suggest that temperatures of 930 to 1440°F promote CDD formation, while temperatures >1440°F destroy CDD.(2,3,4) Bussa _et al_. show that PCB pyrolysis at 1020 to 1200°F forms CDF.(5) However, pyrolysis at temperatures greater than 1290°F causes 99 percent destruction of PCBs and no CDF formation. No bed temperatures are available at Oswego; however, flue gas temperatures measured in the primary and secondary chambers show that gases in the combustion zone reached or exceeded the 1200 to 1440°F needed to destroy CDD and CDF.

Total CDD and CDF concentrations were compared to the target precursor concentrations to determine if there were any relationships in the data; however, scatter plots of the data showed no discernible trends. It is important to note that, in the case of CDD, these precursors would be expected to first form predioxins before forming the CDD molecule. In addition, even if the predioxins form, this formation would not ensure CDD formation, as several known precursors reach an equilibrium with the predioxin.

Recent studies of CDD formation and destruction by Vogg and Steiglitz indicate that formation of CDD on flyash can occur at temperatures between approximately 430°F and 750°F (220°C and 400°C), peaking at 570°F (300°C)(6). In these studies, the flyash was heated for two hours without a change in CDD and CDF concentrations when the temperature was below 390°F (200°C), a 10-fold increase at 570°F (300°C) and complete destruction at 1110°F (600°C)(7,8).

Figures S-10 and S-11 present temperature profile plots for the Oswego facility. As shown in Figure S-10, formation of CDD and CDF on flyash between the combustion zone and the secondary chamber exit is unlikely to be occurring at this facility due to the high flue gas temperatures (1650°F to 1800°F) in

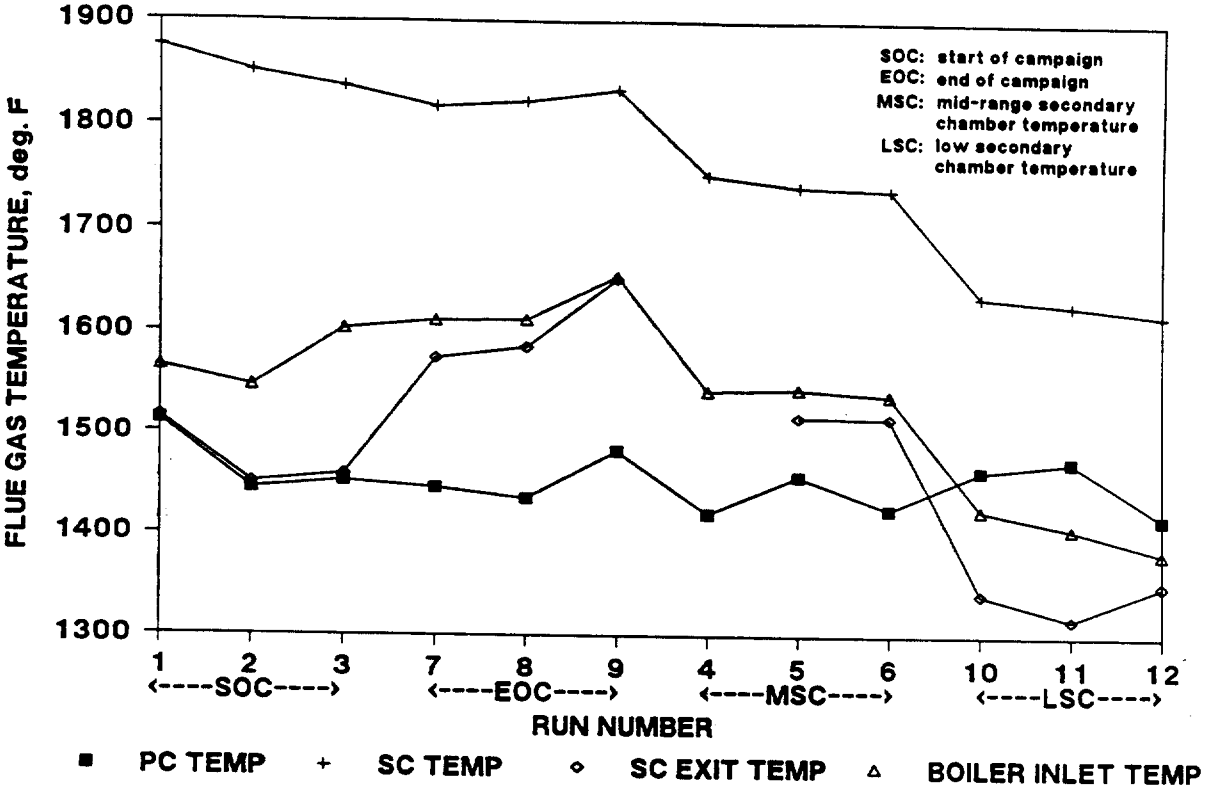

Figure S-10. Continuously Monitored Flue Gas Temperature by Run Number

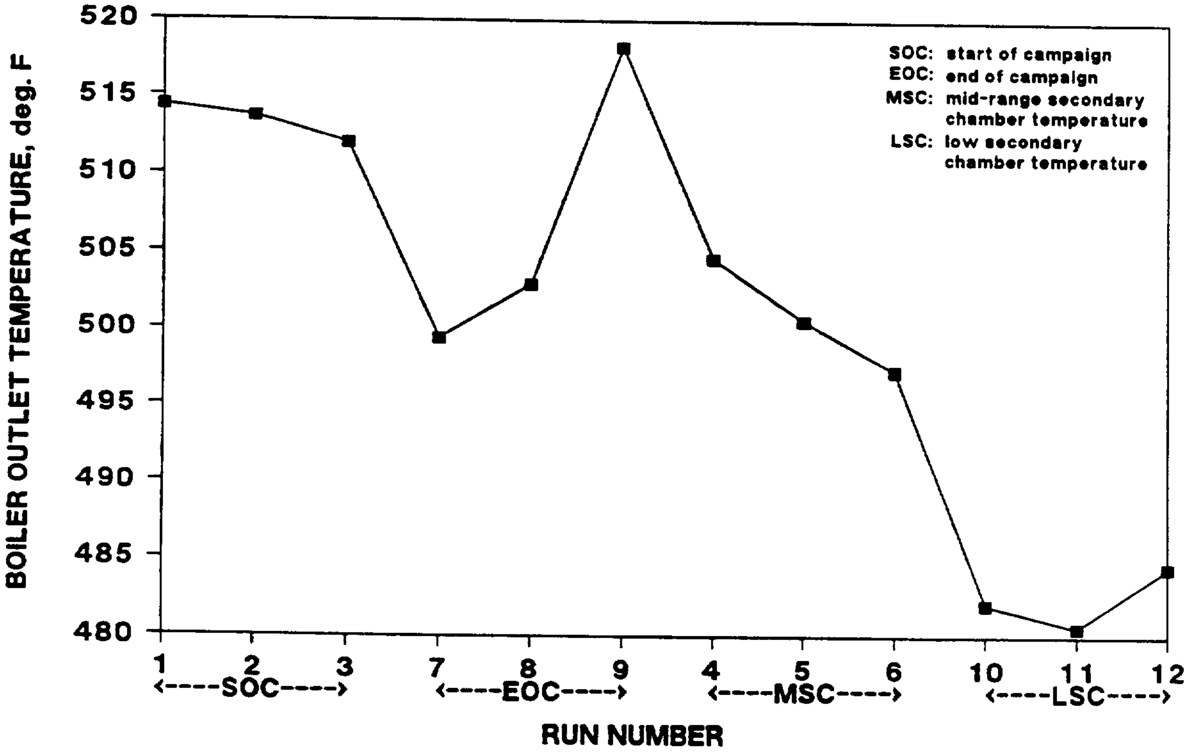

Figure S-11. Continuously Monitored Boiler Outlet Temperature by Run Number the secondary chamber. These temperatures are above the temperatures suggested by Vogg and Steiglitz as optimum for such formation. However, as shown in the figures, the flue gases pass through the suggested optimal temperature window at some point between the secondary chamber exit and the ESP inlet (boiler outlet). In addition, the ESP operating temperature for this program was between 428°F and 500°F, indicating CDD and CDF could potentially form via catalytic interaction with the flyash between these locations.

Other researchers have proposed that CDD and CDF can be formed at temperatures of about 570°F (300°C) from particulate carbon entrained in MWC flue gases(9). As stated above, the flue gas would reach this temperature at some point between the secondary chamber exit and ESP inlet, as heat is removed from the boiler train, and CDD and CDF could possibly form from particulate carbon.

A control strategy designed to minimize the CDD and CDF emissions at this facility must, therefore: 1) maximize destruction of CDD, CDF, and precursors in the combustion zone, 2) minimize formation of CDD and CDF in the waste heat recovery equipment, and 3) lower the ESP operating temperature. The formation of CDD and CDF in the boiler train could possibly be minimized by cooling the flue gas to below 570°F (300°C) as quickly as possible.

### Secondary Chamber Temperature Effects

The Oswego CDD and CDF data were compared to the results from a test program conducted at PEI since this program included tests at both high and low secondary chamber temperature test conditions. The three 33 ton-per-day two-stage Consumat incinerators at PEI are similar to those at Oswego. The primary and secondary chamber temperature setpoints as well as the CDD and CDF boiler inlet (or secondary chamber exit) and stack (or ESP inlet) concentrations are shown in Table S-5.

Table S-5.

OSWEGO AND PEI DATA

|  | PEI |  | OSWEGO |  |
|---|---|---|---|---|
|  | Primary Chamber Setpoint, °F | Secondary Chamber Setpoint, °F | Primary Chamber Setpoint, °F | Secondary Chamber Setpoint, °F |
| Normal Operation | 1290 | 1830 | 1450 | 1850 |
| Low Secondary Chamber Temperature | 1290 | 1650 | 1450 | 1650 |
| Mid-range Secondary Chamber Temperature | - | - | 1450 | 1750 |
| High Secondary Chamber Temperature | 1290 | 2075 | - | - |

|  | CDD, ng/NM$^3$ @ 7% $O_2$ |  | CDF, ng/NM$^3$ @ 7% $O_2$ |  | CDD, ng/dscm @ 7% $O_2$ |  |  | CDF, ng/dscm @ 7% $O_2$ |  |  |
|---|---|---|---|---|---|---|---|---|---|---|
|  | Boiler Inlet | Stack | Boiler Inlet | Stack | SCE | ESP Inlet | Stack | SCE | ESP Inlet | Stack |
| Low Secondary Chamber Temperature | 25 | 126 | 18 | 101 | 85 | 290 | 370 | 308 | 477 | 479 |
| Mid-range Secondary Chamber Temperature | - | - | - | - | 14 | 53 | 113 | 381 | 177 | 236 |
| High Secondary Chamber Temperature | 1.2 | 66 | 0 | 101 | - | - | - | - | - | - |

As shown in the table, CDD and CDF concentrations are generally higher for the mid-range secondary chamber temperature condition at Oswego than for the high secondary chamber temperature test condition at PEI. This may be due to the higher temperatures in the secondary chamber at PEI causing partial destruction of CDD and CDF. The CDD and CDF concentrations measured at both facilities were highest for the low secondary chamber temperature test condition; the secondary chamber temperature setpoint was the same for the two facilities. The primary chamber temperature setpoints were different for the two facilities; it is not known what effect this may have had on the CDD and CDF concentrations measured.

Figures S-12 and S-13 show CDD and CDF concentrations for both facilities by secondary chamber temperature setpoint. As shown in the figures, CDD concentrations generally decrease with increasing secondary chamber temperature. CDF concentrations do not show this pattern but are relatively constant with respect to secondary chamber temperature.

### Heat Transfer Surface Area Effects

As part of the Oswego test program, an attempt was made to determine the effect of incinerator maintenance on CDD and CDF formation. The start of campaign test runs (Runs 1-3) were designed to evaluate operation of the boiler with clean heat transfer surfaces and clean air distribution equipment. These test runs would be expected to have lower CDD and CDF levels than the end of campaign test runs (Runs 7-9), since the air distribution system would be operating as designed, and combustion should be more uniform. The end of campaign test runs were performed when the furnace was near the end of the normal cycle between shutdowns for inspection and cleaning and maintenance. Testing at this condition demonstrates operation with ash buildup in the secondary chamber as well as dirty heat transfer surfaces and ESP plates. This would tend to cause higher temperatures and lower retention times in the incinerator and boiler. The primary and secondary chamber temperature setpoints chosen for these sets of tests were 1450°F and 1800°F, respectively.

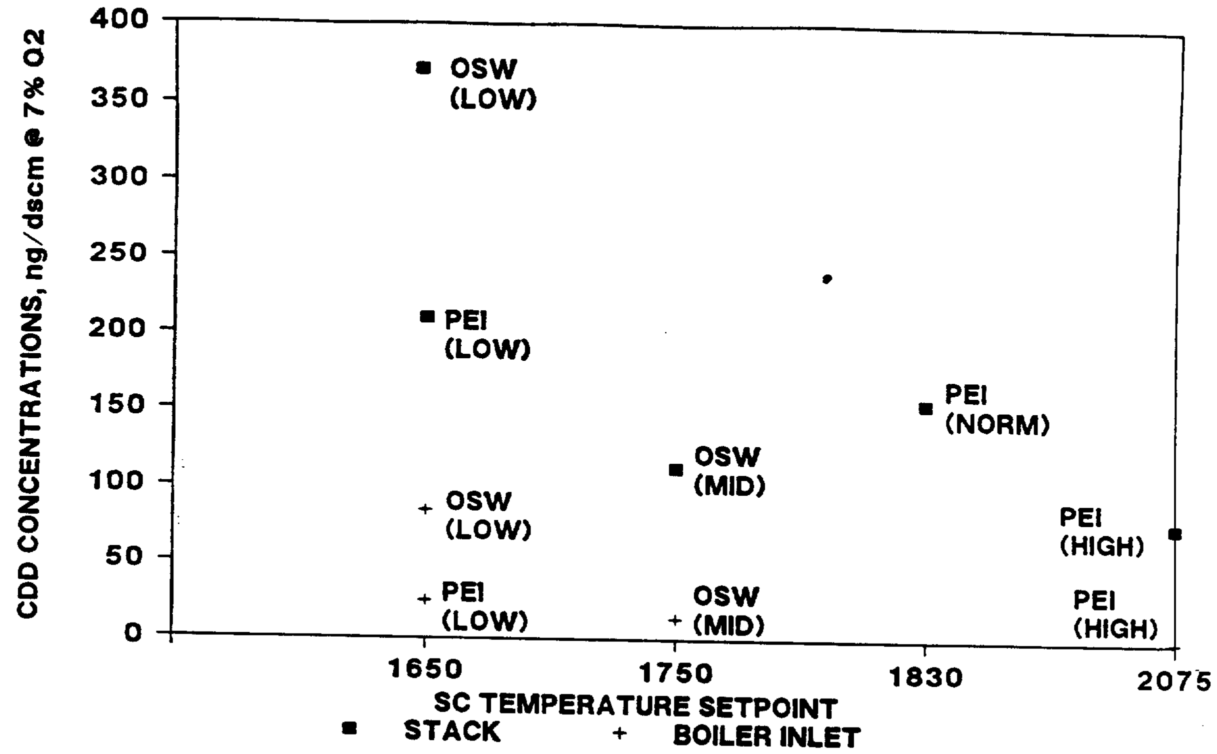

Figure S-12. CDD Concentrations at the Boiler Inlet and Stack vs. Secondary Chamber Temperature

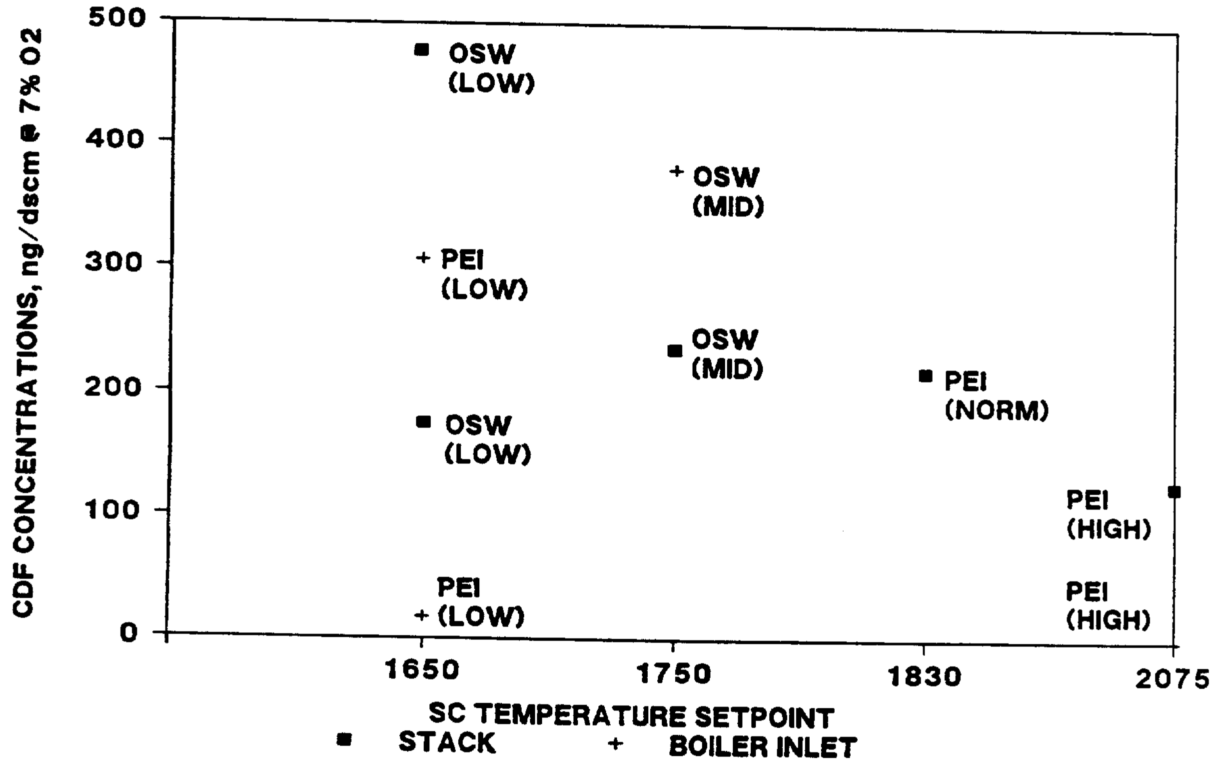

Figure S-13. CDF Concentrations at the Boiler Inlet and Stack vs. Secondary Chamber Temperature

The data in Table S-3 show that, as expected, the average CDD and CDF concentrations at each sampling location are generally lower for the start of campaign runs than for the end of campaign runs. However, the differences seen are not large, in some instances less than 10 percent.

## STATISTICAL ANALYSIS

ANOVA models were used to test for statistical differences between average CDD and CDF concentrations measured over the three locations by operating condition and over operating condition by location. Duncan's multiple range tests were used to determine which CDD and CDF average concentrations were different.

The first set of ANOVA models was performed to determine if the main effects of location and operating condition or the interaction of the two caused significant differences in CDD and CDF concentrations. Main effects and interaction effects were found to be significant for CDD concentrations but not for CDF concentrations.

Thus, mean CDD concentrations were significantly different between locations and between operating conditions. There also existed an interaction effect between location and operating condition for CDD concentrations. The significant interaction effect, however, did not diminish the main effects of location and operating condition. This was tested by considering the interaction effect as an error term and then testing whether or not both the main effects were still significant.

Since the main effects of location and operating condition and the interaction of the two were not significant for the CDF model, another set of ANOVA models was constructed to explore the main effects separately. Again, the main effects were not significant. That is to say, there was no difference between locations or between operating conditions for CDF concentrations.

The second set of ANOVA models was run to investigate trends within each location and operating condition separately. Since the main effects of location and operating condition were significant for CDD concentrations, significant trends existed between operating conditions within each location and between locations within each operating condition. For CDF concentrations, a significant difference between operating conditions was found only at the ESP inlet and outlet. For the start of campaign and low secondary chamber temperature operating conditions, there were marginally significant differences between locations.

## CDD and CDF Relationships with Operating Variables and CEM Data

Pearson product-moment correlations were performed to determine if any linear relationships existed between CDD and CDF concentrations measured at the secondary chamber exit, ESP inlet and ESP outlet and single value representations (SVRs) of combustion gas variables (CEM) and process variables. The combustion gas variables, except $O_2$, were normalized to 7 percent $O_2$; the process variables were not adjusted. The CDD and CDF data were normalized to 7 percent $O_2$ when comparisons were made with the combustion gas variables (except $O_2$); the data were not adjusted for the remaining correlations. The combustion gas and process variables were measured continuously at 10- to 20-second intervals during the approximately 3- to 4-hour CDD and CDF test runs. To compare or correlate the CDD and CDF concentrations to the combustion gas and process variables, the multiple readings had to be summarized into a single value that captures as much information as possible. The statistical summaries of the data are termed single value representations (SVRs). The most significant correlations are shown in Table S-6. As shown in the table, CO concentrations correlated the most frequently with CDD and CDF concentrations. In most instances, it was extreme values of CO (e.g., P90, P95, etc.) that correlated with the CDD and CDF concentrations.

## Front and Back Half CDD and CDF Sampling Train Distribution

Figures S-14 through S-17 present CDD and CDF front and back half train distributions by test run. As shown in the figures, there is a definite shift in CDD and CDF fractions from the front half of the sampling train at the ESP

## Table S-6.

## PEARSON CORRELATION MATRIX FOR CDD AND CDF WITH COMBUSTION GAS VARIABLES AND PROCESS DATA ($|r| \geq 0.8$)[a,b]

| Parameter/loc. | Dioxin or Furan/loc. | SVR | Pearson Corr. Coeff. (r) |
|---|---|---|---|
| CO/ESP outlet | 2378-TCDF/ESP outlet | P90 | 0.835 |
| CO/ESP outlet | 2378-TCDF/ESP inlet | P99 | 0.845 |
| $CO_2$/ESP outlet | 2378-TCDF/ESP inlet | P75 | 0.814 |
| $CO_2$/ESP outlet | 2378-TCDF/ESP inlet | P90 | 0.845 |
| $CO_2$/ESP outlet | 2378-TCDF/ESP inlet | P95 | 0.863 |
| CO/ESP outlet | TOTAL CDF/ESP inlet | AMEAN | 0.835 |
| CO/ESP outlet | TOTAL CDD/ESP inlet | LMEAN | 0.805 |
| CO/ESP outlet | TOTAL CDD/ESP outlet | P75 | 0.811 |
| CO/ESP outlet | TOTAL CDD/ESP inlet | P90 | 0.904 |
| CO/ESP outlet | TOTAL CDD/ESP outlet | P90 | 0.898 |
| CO/ESP outlet | TOTAL CDF/ESP outlet | P90 | 0.834 |
| CO/ESP outlet | TOTAL CDD/ESP inlet | P95 | 0.897 |
| CO/ESP outlet | TOTAL CDF/ESP inlet | P95 | 0.876 |
| CO/ESP outlet | TOTAL CDD/ESP outlet | P95 | 0.805 |
| CO/ESP outlet | 2378-Sub. CDF/ESP inlet | AMEAN | 0.845 |
| CO/ESP outlet | 2378-Sub. CDD/ESP inlet | LMEAN | 0.803 |
| CO/ESP outlet | 2378-Sub. CDF/ESP inlet | LMEAN | 0.802 |
| CO/ESP outlet | 2378-Sub. CDF/ESP outlet | LMEAN | 0.834 |
| CO/ESP outlet | 2378-Sub. CDF/ESP outlet | P75 | 0.897 |
| CO/ESP outlet | 2378-Sub. CDD/ESP inlet | P90 | 0.886 |
| CO/ESP outlet | 2378-Sub. CDF/ESP inlet | P90 | 0.845 |
| CO/ESP outlet | 2378-Sub. CDD/ESP outlet | P90 | 0.860 |
| CO/ESP outlet | 2378-Sub. CDF/ESP outlet | P90 | 0.905 |
| CO/ESP outlet | 2378-Sub. CDD/ESP inlet | P95 | 0.854 |

## Table S-6.

## PEARSON CORRELATION MATRIX FOR CDD AND CDF WITH COMBUSTION GAS VARIABLES AND PROCESS DATA ($|r| \geq 0.8$)[a,b]

(continued)

| Parameter/loc. | Dioxin or Furan/loc. | SVR | Pearson Corr. Coeff. (r) |
|---|---|---|---|
| CO/ESP outlet | 2378-Sub. CDF/ESP inlet | P95 | 0.883 |
| $O_2$/ESP outlet | Total CDD/ESP inlet | SS | 0.802 |
| SCE temp. | Boiler inlet temp. | -- | 0.856 |
| CO/SCE | Total CDD/SCE | AMEAN | 0.891 |
| CO/SCE | Total CDD/SCE | P75 | 0.852 |
| CO/SCE | Total CDD/SCE | P90 | 0.921 |
| CO/SCE | Total CDD/SCE | MAX | 0.801 |
| $CO_2$/SCE | Total CDD/SCE | SS | 0.806 |
| THC/SCE | Total CDD/SCE | P1 | -0.858 |
| THC/SCE | Total CDD/SCE | P5 | -0.870 |
| THC/SCE | Total CDD/SCE | P10 | -0.875 |
| THC/SCE | Total CDD/SCE | P25 | -0.883 |
| THC/SCE | Total CDD/SCE | MEDIAN | -0.892 |
| THC/SCE | Total CDD/SCE | P75 | -0.894 |
| THC/SCE | Total CDD/SCE | P90 | -0.864 |
| Boiler draft | 2378-Sub. CDD/SCE | CV | 0.819 |
| CO/SCE | 2378-Sub. CDD/SCE | AMEAN | 0.800 |
| CO/SCE | 2378-Sub. CDF/SCE | P10 | 0.807 |
| CO/SCE | 2378-Sub. CDF/SCE | P25 | 0.827 |
| CO/SCE | 2378-Sub. CDF/SCE | MEDIAN | 0.851 |
| CO/SCE | 2378-Sub. CDD/SCE | P75 | 0.838 |
| CO/SCE | 2378-Sub. CDF/SCE | P75 | 0.896 |
| CO/SCE | 2378-Sub. CDD/SCE | P90 | 0.930 |
| CO/SCE | 2378-Sub. CDF/SCE | P90 | 0.917 |
| CO/SCE | 2378-Sub. CDD/SCE | MAX | 0.801 |

## Table S-6.

## PEARSON CORRELATION MATRIX FOR CDD AND CDF WITH COMBUSTION GAS VARIABLES AND PROCESS DATA ($|r| \geq 0.8$)[a,b]

(continued)

| Parameter/loc. | Dioxin or Furan/loc. | SVR | Pearson Corr. Coeff. (r) |
|---|---|---|---|
| $SO_2$/SCE | 2378-Sub. CDD/SCE | MAX | 0.847 |
| $SO_2$/SCE | 2378-Sub. CDF/SCE | MAX | 0.854 |
| THC/SCE | 2378-Sub. CDD/SCE | AMEAN | -0.877 |
| THC/SCE | 2378-Sub. CDD/SCE | P1 | -0.903 |
| THC/SCE | 2378-Sub. CDD/SCE | P5 | -0.908 |
| THC/SCE | 2378-Sub. CDD/SCE | P10 | -0.911 |
| THC/SCE | 2378-Sub. CDD/SCE | P25 | -0.915 |
| THC/SCE | 2378-Sub. CDD/SCE | MEDIAN | -0.925 |
| THC/SCE | 2378-Sub. CDD/SCE | P75 | -0.929 |
| THC/SCE | 2378-Sub. CDD/SCE | P90 | -0.885 |
| THC/SCE | 2378-Sub. CDD/SCE | P95 | -0.803 |
| $O_2$/SCE | $CO_2$/SCE | -- | -0.942 |

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[a] Correlations of CEMs (except $O_2$) with CDD or CDF, data corrected to 7 percent $O_2$. Correlations of process data with CDD or CDF, data not corrected to 7 percent $O_2$. Correlations of $O_2$ with CDD or CDF, data not corrected to 7 percent $O_2$.

[b] N = number of points, N ≥10; all correlations are statistically significant at the 95 percent level.

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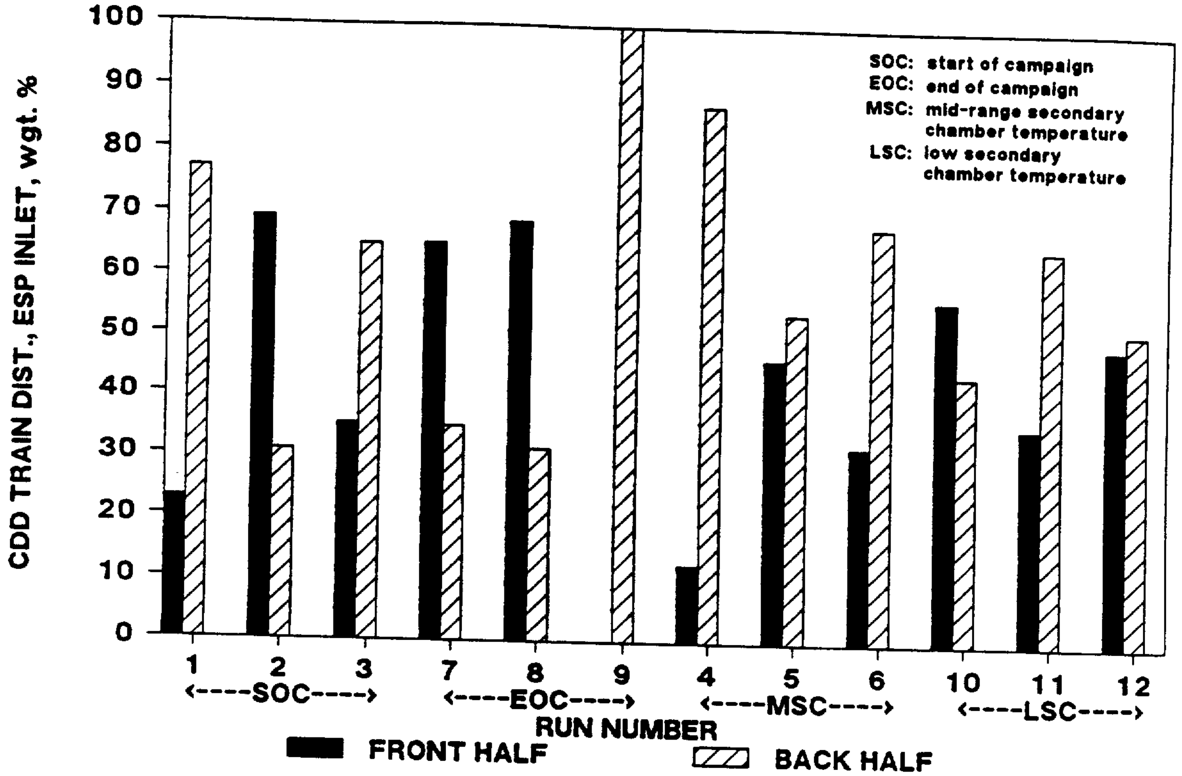

Figure S-14. Front and Back Half CDD Distribution at the ESP Inlet by Run Number

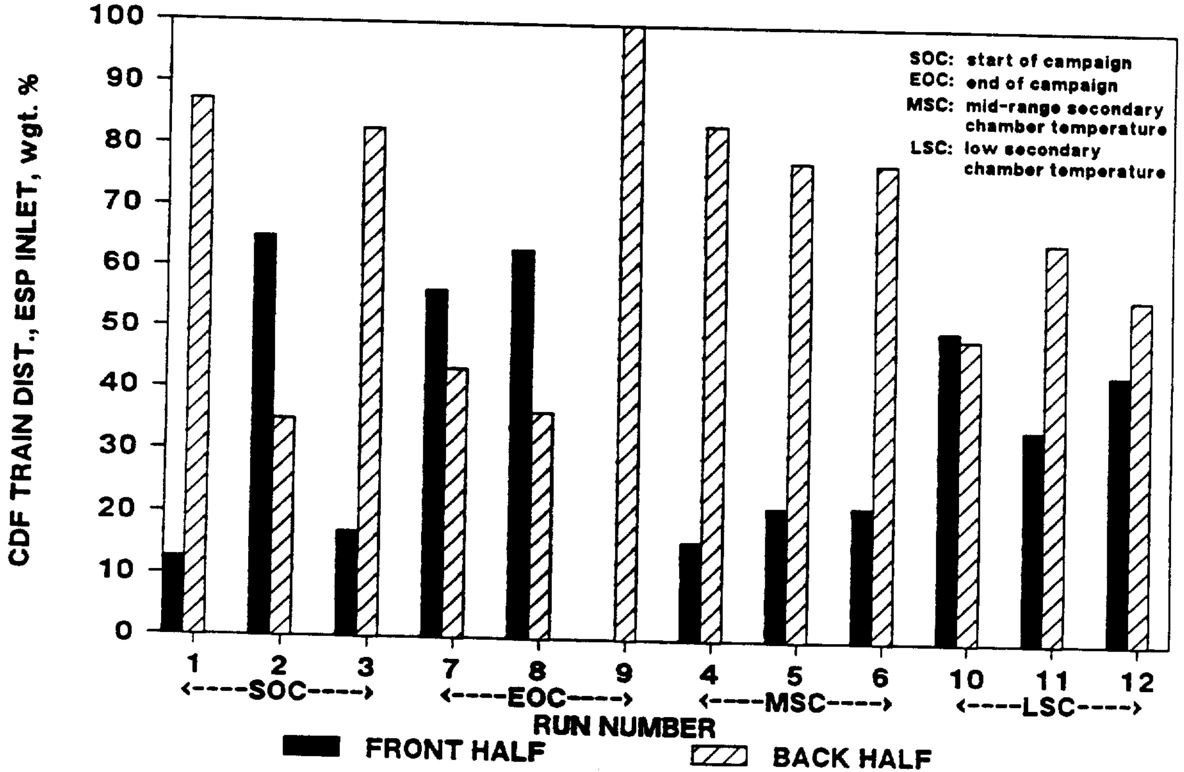

Figure S-15. Front and Back Half CDF Distribution at the ESP Inlet by Run Number

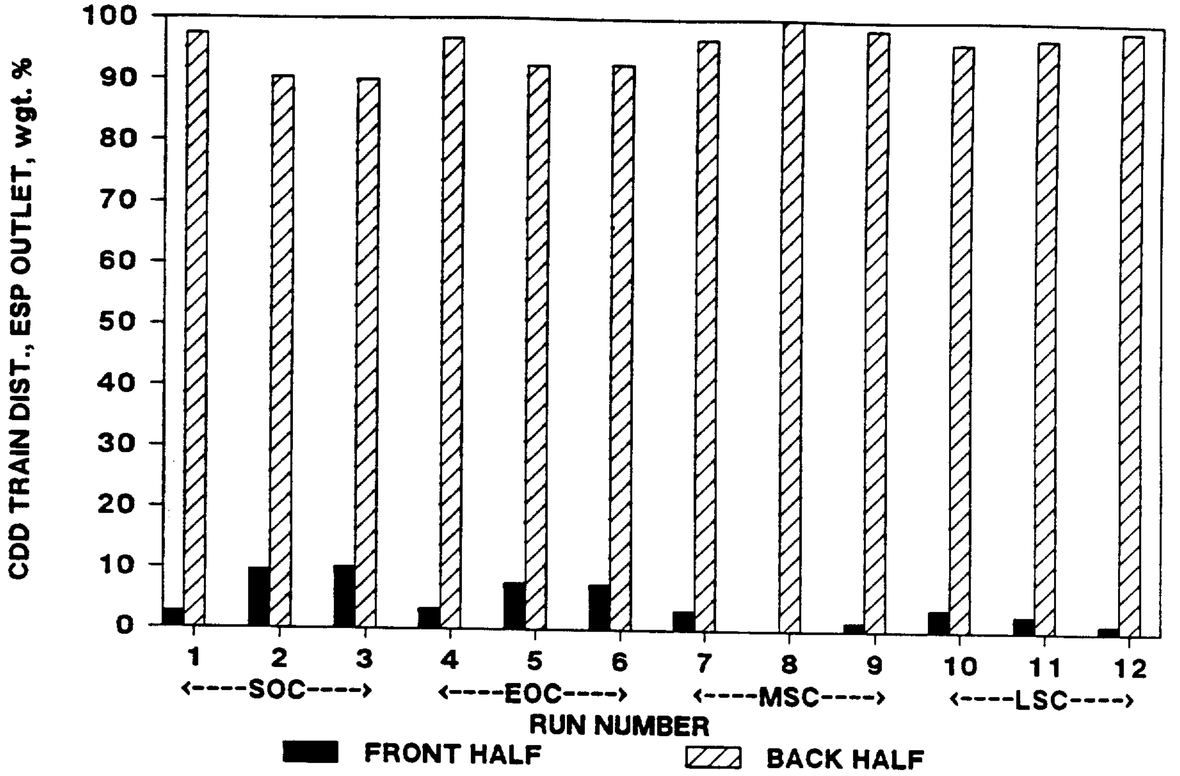

Figure S-16. Front and Back Half CDD Distribution at the ESP Outlet by Run Number

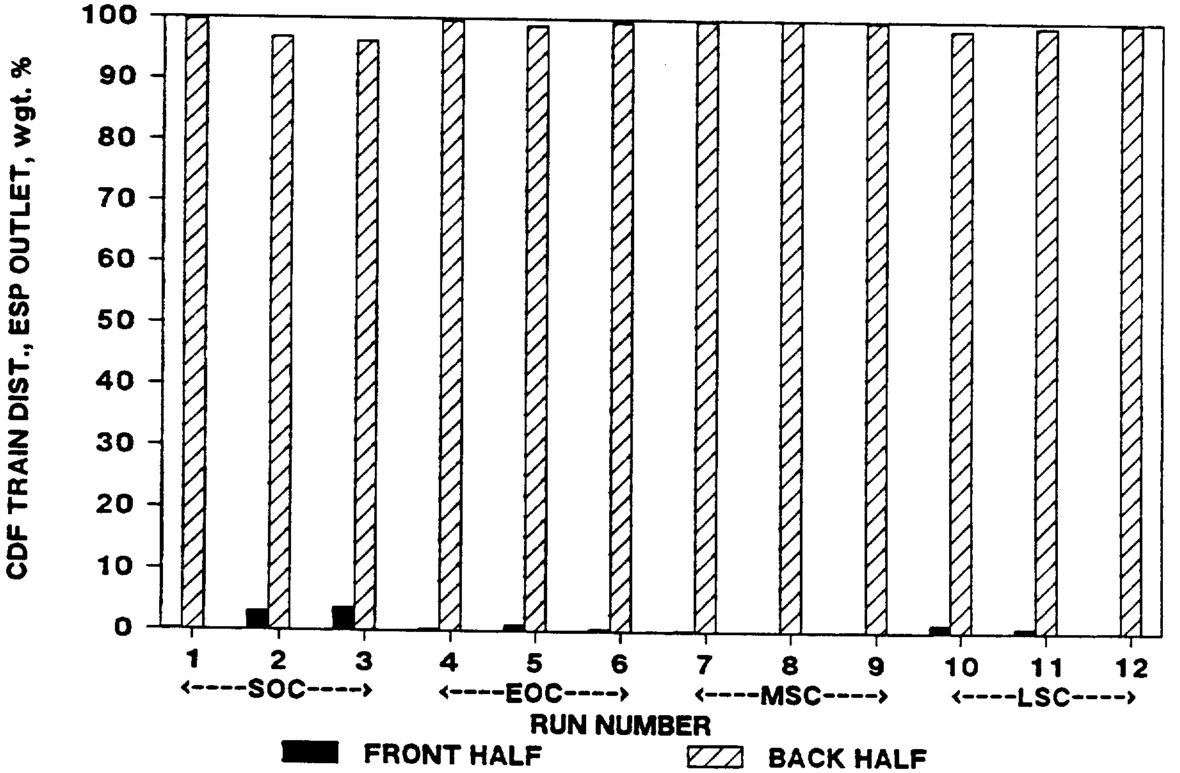

Figure S-17. Front and Back Half CDF Distribution at the ESP Outlet by Run Number inlet to the back half of the train at the ESP outlet. The front half of the sampling train includes the particulate filter, while the back half includes the XAD trap which is designed to capture organic constituents in the flue gas. The shift from the front to the back half of the train as the flue gas passes through the ESP, a particulate control device, implies that the particulate CDD and CDF (front half) is being removed by the ESP, while the gaseous CDD and CDF (back half) is caught in the train at the ESP outlet. However, there are uncertainties in the phase separation effectiveness of the sampling train. Because of the semivolatile characteristics of CDD and CDF congeners, it is possible that the filterable (front half) measurements do not represent particulate phase alone, and the back half (non-filterable) measurements do not represent only gas phase CDD and CDF.

ANOVA models were used to test whether location had an effect on the CDD and CDF fractions at the ESP inlet and outlet. The results show that location does have a statistically significant effect on the train fractions where CDD and CDF are collected.

### ESP Control Efficiency

The CDD and CDF ESP removal efficiencies were negative for all test runs because CDD and CDF concentrations increased across the ESP. The particulate removal efficiencies ranged from 84 to 95 percent. Based on ANOVA models, operating condition was not shown to affect CDD or CDF removal efficiency.

## REFERENCES

1. Visalli, J.R. "A Comparison of Dioxin, Furan and Combustion Gas Data from Test Programs at Three MSW Incinerators." Hazardous Waste Management. December 1987.

2. Ahling, B. and A. Lindskog. Emission of Chlorinated Organic Substances from Combustion. In: Pergamon Series on Environmental Science, Volume 5, 1982. pp. 215-225.

3. Buser, H. R. and C. Rappe. Formation of Polychlorinated Dibenzofurans (PCDFs) from the Pyrolysis of Individual PCB Isomers. Chemosphere, 8(3):157-174, 1979.

4. Dow Chemical. The Trace Chemistries of Fire - A Source of and Routes for the Entry of Chlorinated Dioxins into the Environment. Dow Chemical U.S.A, 1978. 46 pp.

5. Rappe, C., S. Marklund, P.A. Bergquist and M. Hansson. Polychlorinated Dioxins (PCDDs) Dibenzofurans (PCDFs) and Other Polynuclear Aromatics (DCPNAs) Formed During PCB Fires. Chemica Scripta, 20:56-61, 1982.

6. Stieglitz, L. and H. Vogg. "New Aspects of PCDD/PCDF Formation in Incineration Processes." Preliminary Proceedings, Municipal Waste Incineration, October 1-2, 1987, Montreal, Quebec.

7. Clark, M. "Air Pollution Control Status Report." Waste Age. November 1987. p.102-117.

8. Hagenmaier, H., M. Kraft, H. Brunner, and R. Haag. "Catalytic Effects of Flyash from Waste Incineration Facilities on the Formation and Decomposition of Polychlorinated Dibenzo-p-dioxins and Polychlorinated Dibenzofurans." Environmental Science and Technology, November 1987, Vol. 21, No. 11, p.1080-1084.

9. Vogg, H. and L. Stieglitz. Chemosphere. 1986. Vol. 15, p.1373.

# Section 1

# INTRODUCTION

The New York State Department of Environmental Conservation (NYSDEC) and the New York State Energy Research and Development Authority (NYSERDA) are participating in a joint program that will provide the basis for:

- Determining the operating characteristics and general design features of municipal solid waste (MSW) incinerators which minimize the production of polychlorinated dibenzo-p-dioxins (CDD) and polychlorinated dibenzofurans (CDF), and
- Selecting air pollution control devices to meet air quality and emission requirements.

This report presents a statistical and engineering analysis of the results of an emission testing program at a starved air, two chamber, mass burn, refractory design incineration facility.

The objective of the program was to determine facility operating conditions consistent with efficient combustion and minimal emissions of CDD and CDF at a modular MSW incinerator. The overall test program combined the efforts of: NYSERDA, NYSDEC, the New York State Department of Health (NYSDOH), Radian Corporation, and the host site--the Oswego County Energy Recovery Facility (ERF). Radian Corporation was under contract to NYSERDA to provide technical and sampling support.

The test program was conducted in Fulton, New York on Unit #1 at the Oswego County ERF, which is owned and operated by the County of Oswego. Twelve test runs were performed during August and September 1986. Triplicate test runs were conducted for each of four incinerator operating conditions.

Flue gas samples were collected simultaneously at the secondary chamber exit (i.e., hot zone), electrostatic precipitator (ESP) inlet, and final exhaust stack (ESP outlet) to measure CDD, CDF, precursors, and HCl. Combustion gases ($CO$, $CO_2$, $O_2$, $SO_2$, $NO_x$, and THC (secondary chamber exit only)) were monitored at the secondary chamber exit and ESP outlet. Particulate tests were performed at the ESP inlet and outlet. Process data were measured continuously during the CDD and CDF sampling periods.

In addition to the flue gas measurements, refuse samples were collected to determine if CDD, CDF, or potential precursors were present in the fuel. Incinerator bottom ash samples were collected for loss-on-ignition analysis (moisture and volatile/nonvolatile residues) to monitor the relative ash burnout at the four different operating conditions. Table 1-1 lists the sampling dates and times for each test run at each sampling location.

Secondary chamber exit flue gas sampling, refuse sampling, bottom ash sampling, and bottom ash loss-on-ignition analyses were performed by Radian personnel. Flue gas sampling at the ESP inlet and the exhaust stack was conducted by NYSDEC personnel. The remaining analyses (CDD, CDF, precursors, HCl and particulate) were performed by the NYSDOH Laboratory of Organic Analytical Chemistry operating as Health Research Incorporated (HRI).

This report presents the statistical and engineering analysis results of these test data. The remainder of the report is organized as follows. Section 2 presents a detailed description of the facility tested. Section 3 contains a description of the test and sampling locations. Section 4 provides a summary of the test data. Section 5 presents a discussion of the relationships between and among process variables and combustion gas variables. Section 6 discusses the variability between test runs, test conditions, and sampling locations. Section 7, the main focus of the report, contains the analyses of the CDD and CDF test results and their relationships to combustion gases and process conditions. The sampling and analytical methods used in this test program are described in Section 8. Complete results, example calculations, field data, laboratory reports and various other supporting data are included as appendices to this report.

Table 1-1

OSWEGO RUNTTIME SUMMARY

| Run Number | Run Date | Secondary Chamber Exit | | ESP Inlet[a] | | ESP Outlet[a] | | |
|---|---|---|---|---|---|---|---|---|
| | | MM5 | CEMs | M5 | MM5 | M5 | MM5 | CEMs |
| 1 | 8/26/86 | 1519-1727<br>1850-2015 | 1603-1731<br>1850-1902 | 1045-1156 | 1505-1823 | 1045-1150 | 1505-1820 | 1040-1115<br>1124-1156<br>1455-1640<br>1655-1825 |
| 2 | 8/27/86 | 1247-1423<br>1547-1721 | 1235-1719 | 0935-1040 | 1250-1718 | 0935-1040 | 1247-1715 | 1245-1420<br>1423-1520<br>1522-1644<br>1700-1720 |
| 3 | 8/28/86 | 1352-1528<br>1625-1801 | 1351-1804 | 0935-1103 | 1351-1755 | 0935-1057 | 1351-1755 | 0925-1008<br>1010-1111<br>1345-1531<br>1533-1744 |
| 4 | 9/03/86 | 1409-1519<br>1530-1543<br>1700-1803<br>1823-1844<br>1907-1914 | -- | 0900-1005 | 1414-1930 | 0900-1005 | 1400-1924 | 1315-1406<br>1429-1528<br>1603-1616<br>1704-1927 |
| 5 | 9/04/86 | 1137-1303<br>1415-1427<br>1442-1458<br>1520-1610 | 1128-1306<br>1418-1428<br>1441-1500<br>1519-1632 | 0858-1003 | 1130-1650 | 0858-1001 | 1130-1650 | 0900-0930<br>0932-1010<br>1122-1308<br>1413-1519<br>1545-1630 |
| 6 | 9/05/86 | 1230-1354<br>1502-1626 | 1230-1411<br>1501-1639 | 0900-1006 | 1230-1634 | 0900-1004 | 1230-1635 | 0940-1013<br>1108-1403<br>1407-1638 |
| 7 | 9/16/86 | 1256-1420<br>1525-1546<br>1607-1710 | 1256-1356<br>1402-1419<br>1525-1625 | 0940-1047 | 1250-1715 | 0940-1045 | 1255-1715 | 1042-1113<br>1118-1431<br>1434-1730 |
| 8 | 9/17/86 | 1148-1312<br>1430-1513<br>1525-1606 | 1147-1247<br>1256-1321<br>1429-1505<br>1509-1513<br>1525-1551 | 0850-0955 | 1153-1612 | 0850-0955 | 1153-1612 | 0835-0924<br>0928-1034<br>1039-1041<br>1133-1319<br>1324-1623 |

[a] Times are from NYSDEC field data sheets.

OSWEGO RUN TIME SUMMARY (Continued)

| Run Number | Run Date | Secondary Chamber Exit |  | ESP Inlet[a] |  | ESP Outlet[a] |  |  |
|---|---|---|---|---|---|---|---|---|
|  |  | MM5 | CEMs | M5 | MM5 | M5 | MM5 | CEMs |
| 9 | 9/18/86 | 1124-1205<br>1240-1322<br>1428-1449<br>1511-1612 | 1115-1206<br>1241-1319<br>1428-1450<br>1508-1546 | 0855-0959 | 1125-1620 | 0855-0959 | 1125-1620 | 1110-1326<br>1331-1621 |
| 10 | 9/24/86 | 1500-1535<br>1647-1738<br>1847-1936<br>1946-2021 | 1500-1516<br>1525-1529<br>1638-1717<br>1743-1753<br>1838-1923<br>1928-1932<br>1943-2031 | 1005-1110 | 1500-2031 | 1005-1110 | 1500-2030 | 1002-1015<br>1020-1039<br>1042-1135<br>1500-1517<br>1521-1752<br>1757-2051 |
| 11 | 9/25/86 | 1200-1324<br>1440-1604 | 1200-1254<br>1258-1303<br>1440-1532<br>1535-1613 | 0835-0943 | 1125-1615 | 0835-0937 | 1125-1615 | 0902-0904<br>0907-0950<br>1135-1333<br>1337-1615 |
| 12 | 9/26/86 | 1000-1124<br>1235-1359 | 0959-1053<br>1056-1102<br>1234-1331<br>1334-1407 | 1712-1830[b] | 1000-1408 | 1712-1830[b] | 1000-1408 | 0950-1131<br>1135-1414<br>1620-1743<br>1746-1835 |

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[a] Times are from NYSDEC field data sheets.

[b] Run was performed September 25, 1986.

This information is organized as follows:

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|---|---|
| Appendix A | Summary of Statistical Procedures |
| Appendix B | Analysis of Variance Results |
| Appendix C | Pearson Product-Moment Correlation Matrices |
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| Appendix H | Bottom Ash Loss-on-Ignition Data |
| Appendix I | MM5 Sample Calculations and Flow Data |
| Appendix J | Oswego County Test Logs |
| Appendix K | Scatter Plots |
| Appendix L | Time Series Plots |
| Appendix M | Interlaboratory Report |
| Appendix N | Inorganic Laboratory Report |
| Appendix O | QA/QC Report |

# Section 2

## PROCESS DESCRIPTION

The Oswego County Energy Recovery Facility (ERF) and the incinerator that was tested are described in this section. Design information was obtained from on-site observations, site drawings, and information supplied by the facility.

### OSWEGO COUNTY ENERGY RECOVERY FACILITY

The Oswego County ERF is a mass-burning incineration plant with heat recovery. Most of the produced steam is sold to Armstrong World Industries which is located adjacent to the facility in Fulton, New York. Any excess steam is used to generate electricity in turbine generators which is sold to a utility grid. The facility is designed to produce a total of 56,000 lb/hr of steam or 3700 kilowatts of electricity. The facility began commercial operation in 1985.

The facility layout is shown in Figure 2-1. The facility is designed to burn 200 tons per day (TPD) of municipal refuse in four identical incinerators, each rated at 50 TPD. This design refuse feed rate is a nominal value quoted by the vendor. The actual incinerator operating rate is approximately 55 to 58 TPD of refuse per incinerator. Oswego County generally achieves good burnout at this higher feed rate due to refuse quality and operating controls. The average plant daily throughput for this testing program, based on refuse delivery data for the weeks of August 25, September 1, September 15, and September 22, 1986, was about 250 TPD. Assuming each incinerator burns a similar quantity of refuse, each incinerator burned about 62.5 TPD during this test program. This is approximately 20 percent above design. Each incinerator is equipped with a separate waste heat boiler (marine firetube) and an ESP for particulate emissions control. A separate stack serves each of the four units. The incinerators operate 24 hours per day, 7 days per week except for scheduled cleaning and maintenance shutdowns.

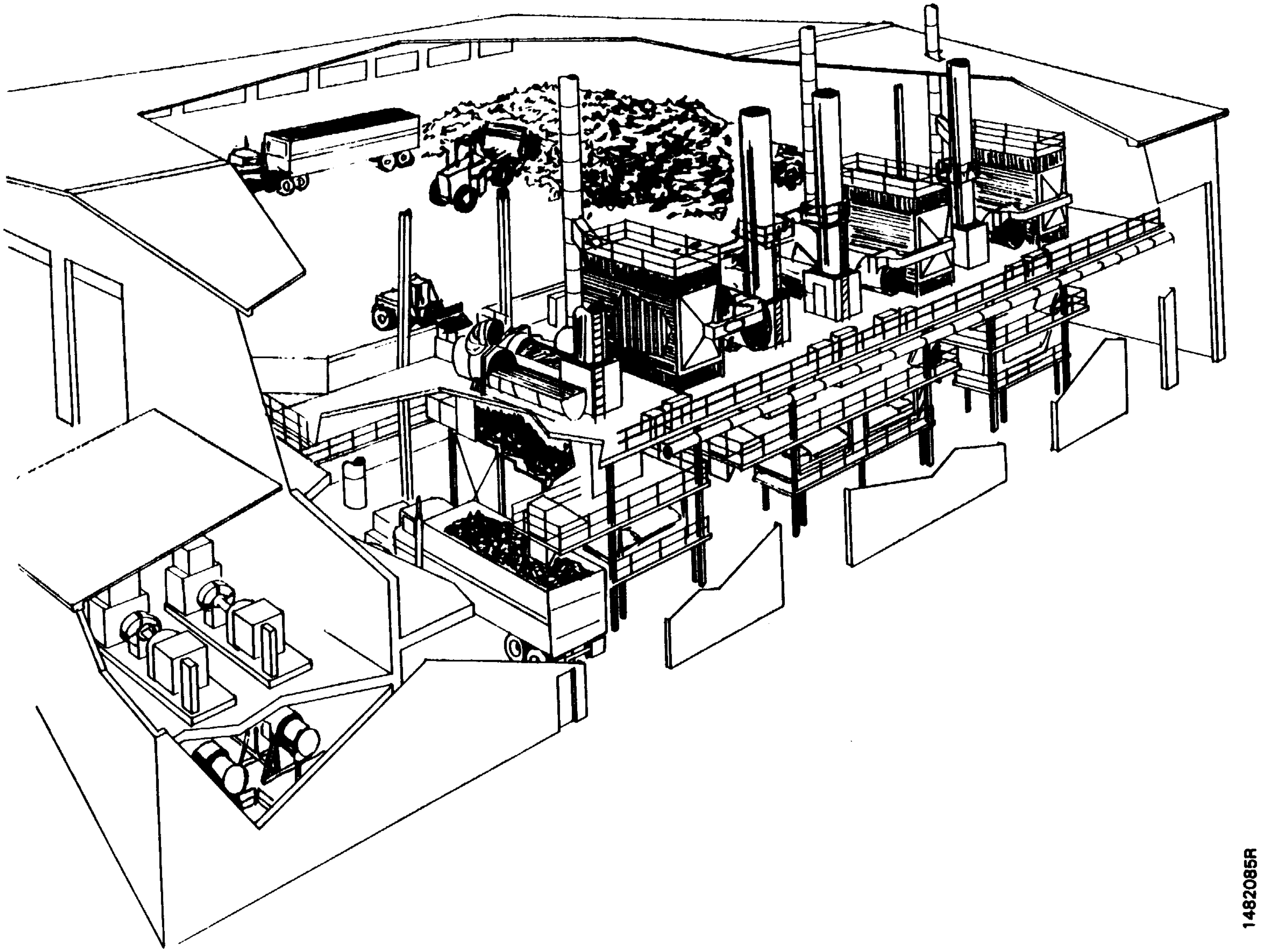


Figure 2-1. Oswego County ERF Layout

The Oswego County Department of Solid Waste operates an integrated refuse collection and disposal system. Residential and commercial refuse is collected in County-owned trucks and accumulated into semi-trailers at County-owned transfer stations for transport to the County landfill or the incineration facility. Wastes from private haulers are also accepted at the transfer stations and at the incineration facility. Solid wastes from industrial sources are usually transported directly to the incinerator if they are suitable for burning.

A limited amount of refuse sorting is performed at the transfer stations. Noncombustibles (e.g., large metal items, rocks, demolition wastes, etc.) and combustibles that are not suitable for charging to the incinerators (e.g., tree stumps, bed mattresses, etc.) are sorted at the transfer stations and sent directly to the landfill.

Some refuse is delivered directly to the incinerator facility from collection routes that are nearer to the incinerator than a transfer station. Similar refuse sorting is performed to remove items not suitable for combustion.

In addition to the sorting at the transfer stations, an additional sorting step is usually performed daily during the third shift at the facility. The refuse pile is spread on the receiving floor and additional unsuitable items are hand-picked from the refuse.

The refuse pile on the receiving floor is worked with a large front-end loader to mix the individual truck loads. The loader spreads out obviously wet and difficult to burn refuse so that there is a more homogeneous feed. Smaller front-end loaders transfer the refuse to the feed hoppers of the four incinerators.

Industrial wastes are also received at the facility. There are a number of product packaging and container production plants in Oswego County. These plants produce a large quantity of paper and plastic wastes from the printing and cutting of containers. No sludges or hazardous wastes are accepted at the facility. Refuse trucks are weighed entering and leaving the facility to determine the amount of refuse received per day.

This high heat value industrial refuse, and the mixing and sorting that is performed on the residential and commercial wastes, produces a mixed solid waste that is generally more uniform in moisture content, density, and heat content than unsorted, stratified refuse receipts. This should provide for a steadier and more controllable operation of the incinerators.

Refuse is received six days per week during daylight hours, except for holidays. Before holidays, a larger quantity of refuse is stored at the facility to ensure that a sufficient quantity of refuse has accumulated to allow continuous operation during the period when no refuse is received. Incoming trucks dump the refuse into a receiving area which is enclosed except for four large doors.

## OVERALL SYSTEM DESCRIPTION

Each incinerator system consists of a Consumat incinerator rated at 50 TPD, a waste heat recovery boiler, an ESP, an exhaust fan, and an exhaust stack.

Batch loads of refuse are fed to the primary chamber and moved through the chamber along the stepped bottom by air-cooled transfer rams. At the far end of the primary chamber, an ash ram discharges the incinerator bottom ash into a quench tank approximately once every 40 to 50 minutes, under normal operating conditions.

Combustible gases and any entrained particulate matter leave the primary chamber through a short, circular, refractory-lined vertical interconnection at the front end of the secondary chamber. In the secondary chamber, the flue gas is mixed with preheated secondary air to complete the combustion of the unburned gas and particulate matter. The hot flue gas is then drawn through a single-pass firetube waste heat recovery boiler.

The cooled flue gas is then sent to an ESP for particulate control. The cleaned flue gas then exits out a 135-foot exhaust stack. The subsystems of the facility are discussed in more detail below.

## Feed System Description

Each feed system is operated from a fixed interval timer. The timer is set to initiate a feed cycle at a specified time after the previous cycle has completed (approximately seven to eight minutes under normal operating conditions). The frequency of the feed cycle (i.e., refuse feed rate) is dependent upon the primary chamber temperature. The feed cycle consists of the following steps:

- The fire door opens and the loader ram pushes the batch refuse load into the primary chamber from the feed chamber, and then retracts.
- The fire door closes and the feed chamber door opens to receive another batch refuse load from the load hopper.
- The hopper then opens to receive another load of refuse.

The transfer rams (#1 and #2) push the refuse through the primary chamber. Transfer ram #1 operates each cycle (about seven or eight minutes) just before a new batch of feed is delivered to the hopper. Under normal operating conditions, transfer ram #2 operates every other feed cycle (approximately every 14 or 15 minutes), just before the #1 transfer ram operates; every sixth feed cycle (about 50 minutes), the ash ram clears the incinerator bottom ash from the primary chamber and the sequence progresses up the unit to the loading ram (i.e., the #2 and #1 transfer rams operate). These cycle times and count sequences are usually constant, but would be adjusted if a change in refuse quality required longer or shorter residence times in the burning zone (i.e., the primary chamber). For the low secondary chamber temperature operating condition, the feed cycle frequency was decreased to once every nine minutes. Due to the smaller amount of ash generated, the ash ram frequency was decreased to approximately once every 70 minutes. In addition, the sequence of transfer ram operation was changed; the #2 transfer ram operated every third feed cycle (approximately 24 or 25 minutes.)

As stated previously, the refuse loading rate is dependent on the temperature in the primary chamber. The typical setpoint is 1450$^{o}$F; this setpoint was maintained during all test runs. The total combustion air rate is held constant; therefore, the refuse quantity in the furnace is used to maintain the desired primary chamber temperature. The target operating temperature is set on a process controller which activates a required load size signal for the operator to follow. Any excursions in the primary chamber temperature usually result from the variability of the refuse composition. There are three load size signals:

- Load light. The load light signal is sent by the controller if the temperature in the primary chamber falls below 1400°F. A smaller charge increases the air-to-fuel ratio which causes the refuse to burn faster and thus raises the temperature in the primary chamber.
- Load normal. The load normal signal indicates that the temperature in the primary chamber is between 1400 and 1500°F.
- Load heavy. The load heavy signal is illuminated when the temperature is greater than 1500°F in the primary chamber. This indicates that a large charge is necessary to slow or quench the combustion rate of the material already present in the primary chamber.

The effect of changing the load size is not observed immediately upon charging because the batch refuse load must go through two feed cycles before it actually begins to burn. In the first cycle, (transfer ram #1) the feed transfer ram pushes the refuse into the first section of the incinerator where it is dried and ignited. The next feed cycle (transfer ram #1) pushes the dried refuse into the middle section of the furnace where the refuse is burned.

### Combustion Air Distribution

Each incinerator is equipped with a forced draft fan that provides both primary and secondary combustion air. Combustion air is circulated around the primary chamber in a shroud where it is preheated and then split into primary and secondary air. The air split is controlled by a motor-operated damper at the forced draft fan outlet and varies based on the secondary chamber temperature. (If the damper is completely open, combustion air to the primary chamber is decreased.) The normal setpoint is 1750°F. Secondary air passes through the control damper and is circulated around the secondary chamber in a shroud before it passes through distribution holes located at four points in the secondary chamber.

Primary air enters through the bottom of the primary chamber and is introduced through the transfer rams (four pipes in each ram face) to keep them cool and to provide an even distribution of the primary combustion air. Since the forced draft fan operates at a constant speed, the primary chamber combustion air rate is dependent upon the secondary chamber temperature.

### Waste Heat Boilers

Flue gas exiting the incinerator passes through a waste heat boiler manufactured by ABCO Incorporated. The steam produced by the four waste heat boilers is combined and a large portion is piped to a neighboring plant. The remainder is directed to turbine generators; the electricity produced supplies the plant and a utility grid.

### Flue Gas Emission Control System

Flue gas exiting the waste heat boiler is treated in a one-field ESP manufactured by PPC Incorporated. Each incinerator system is equipped with a dedicated ESP. The design particulate removal efficiency is 80 percent. The total plate area is 4,486 $ft^2$ and the design specific collection area (SCA) is 294 $ft^2$/1000 acfm for each ESP. Actual SCA, based on flue gas flowrates measured at the ESP inlet, ranged from 219 $ft^2$/1000 acfm to 252 $ft^2$/1000 acfm during this test program. Actual SCA was lowest for the start of campaign test series. The cleaned flue gas then exits through an induced draft fan and is exhausted to the atmosphere.

### Ash Handling System

Incinerator bottom ash is discharged to a quench tank where it is removed by a plate/chain conveyor, at an incline of about $45^0$, and is deposited into a truck for disposal in a landfill. The flyash that is removed from the flue gas by the ESP is collected in a hopper. The ash is then transported by a screw conveyor, deposited into the quench tank, and discharged with the bottom ash.

### Process Operation Control System

Each incinerator system is equipped with automatic process controllers. The primary operating variables are the primary and secondary chamber temperatures.

The facility continuously monitors the primary and secondary chamber temperatures, boiler inlet temperature, and steam production rate and pressure. The facility also monitors $O_2$, CO, and opacity.

The secondary chamber temperature is automatically modulated by the combustion air split. The primary chamber temperature is controlled by the loader operators based on signals generated by the control system. The feed cycle, transfer ram, and ash ram time intervals are manually adjusted to achieve the desired chamber temperatures and acceptable refuse volume reduction (burnout). The facility is designed to reduce the refuse volume by 90 percent; no estimates of actual volume reduction achieved were made during this program.

## Section 3

## TEST AND SAMPLING LOCATIONS DESCRIPTION

The testing program at the Oswego County facility was designed to allow a comprehensive evaluation of CDD and CDF emissions over a range of process operating conditions, and to aid in the selection of air pollution control devices required to meet air quality and emission limit requirements. Flue gas sampling was performed at three locations to determine the relationship(s) between CDD, CDF, precursors, combustion gas variables, and plant operating conditions. In addition, total particulates and HCl were measured at the ESP inlet and outlet. However, these tests were not performed concurrently with the CDD and CDF emission tests.

Process data were collected continuously during each CDD and CDF test to document the incinerator operating conditions. Refuse samples were collected to determine whether detectable levels of CDD, CDF or potential precursors were present in the refuse feed. Incinerator bottom ash was sampled to monitor the relative ash burnout between test conditions. An overview of the sampling and data collection is presented in Table 3-1. The process streams that were sampled in this study are shown in Figure 3-1.

At the ESP inlet and outlet (exhaust stack), the NYSDEC collected samples to measure the CDD, CDF, precursor, particulate and HCl concentrations in the flue gas. The flue gas flowrate, temperature, and moisture content were also determined at these locations. Continuous emission monitors (CEMs) were operated at the ESP outlet to measure $O_2$, CO, $CO_2$, $SO_2$ and $NO_x$.

Radian performed similar tests at the furnace flue gas hotzone (secondary chamber exit). Samples were collected to measure CDD, CDF, precursor and HCl concentrations, as well as flue gas temperature, moisture content and

## Table 3-1

## SAMPLING AND ANALYSIS SUMMARY

1. Number of Test Runs
   - Three runs each:
     - start of campaign (clean, after major maintenance shutdown; normal primary and secondary chamber temperatures)
     - low secondary chamber temperature (approximately mid-campaign)
     - mid-range secondary chamber temperature (approximately mid-campaign)
     - end of campaign (fouled, prior to major maintenance shutdown; normal primary and secondary chamber temperatures)

2. Flue Gas Sampling
   - MM5 sampling for CDD, CDF, precursors, and HCl
   - M5 sampling for total particulates (ESP inlet and outlet only)
   - Fixed gas analysis-integrated bag sampling (EPA Method 3) (secondary chamber exit only)
   - Volumetric gas flowrate and flue gas moisture (EPA Methods 2,4)
   - Continuous monitoring of flue gas moisture and temperature (secondary chamber exit only), $O_2$, $CO_2$, CO, $SO_2$, $NO_x$, and THC (secondary chamber exit only)

3. Ash/Refuse Sampling
   - Grab samples/composite of:
     - incinerator bottom ash
     - refuse feed

4. Process Data Collected
   - Temperature
     - primary chamber
     - secondary chamber
     - boiler inlet, outlet
   - Pressure
     - incinerator draft
     - boiler differential
     - primary combustion air
     - secondary combustion air
   - Ram cycles
     - transfer ram #1, #2
     - ash ram
     - feed loader ram
   - Incinerator Charging Indicators
     - load light
     - load normal
     - load heavy

## Table 3-1

## SAMPLING AND ANALYSIS SUMMARY (Continued)

5. Process Rate Estimates
    - Refuse feed rate
    - Bottom ash rate
    - ESP dust rate

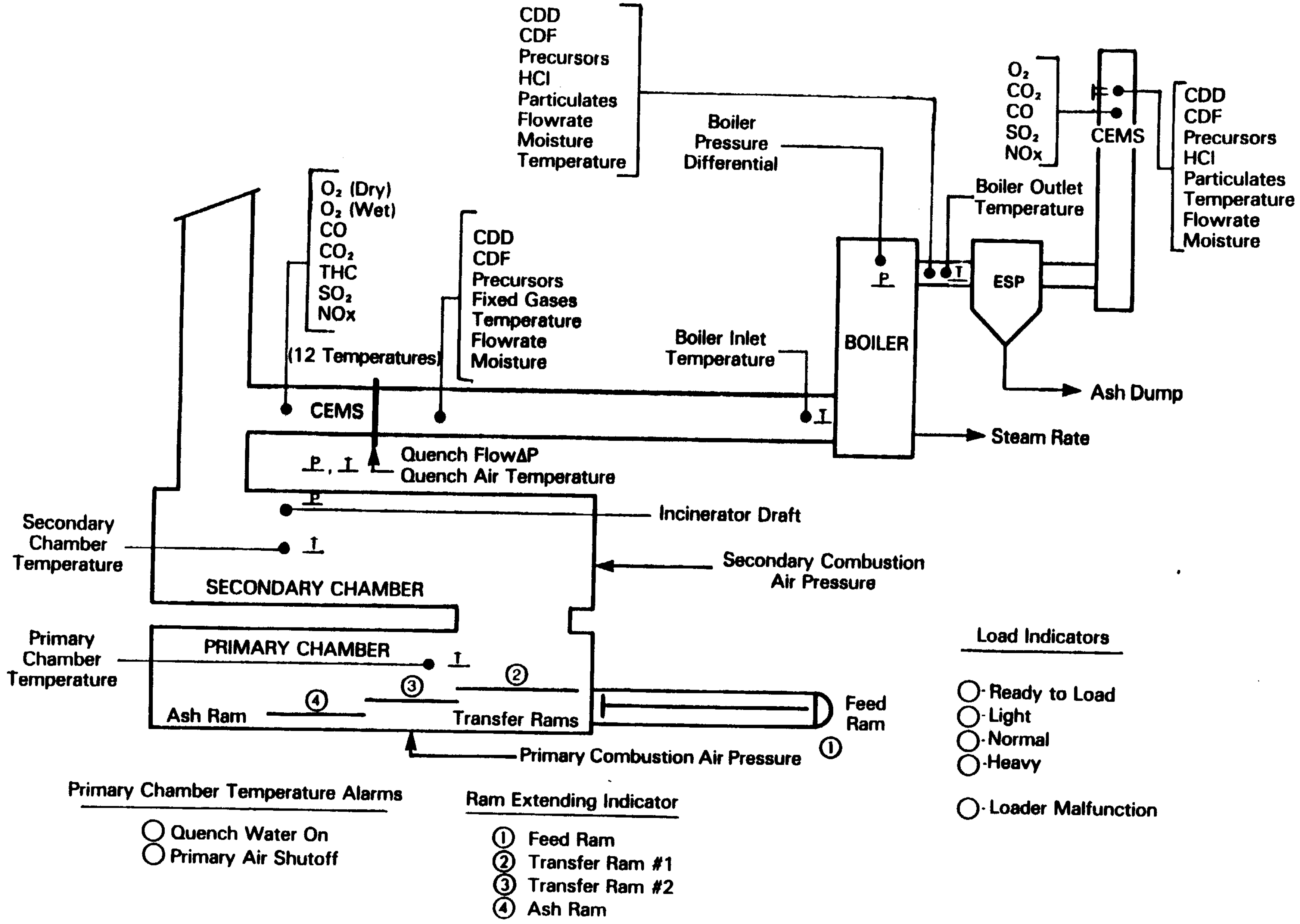


Figure 3-1. Oswego County Process Schematic

flowrate. Continuous analyzers were operated to measure $O_2$, CO, $CO_2$, $SO_2$, $NO_x$, THC and moisture. A probe containing 12 thermocouples was used to continuously monitor the secondary exit flue gas temperature across the duct. However, due to the high temperature and acidic conditions, the thermocouples frequently shorted and by the end of the test program, only two of the 12 thermocouples remained. However, data from the earlier tests showed that the temperatures were uniform across the duct; therefore, the data are representative of flue gas temperature at the secondary chamber exit.

Radian also collected bottom ash samples before the ash was deposited into an ash truck and landfilled. The bottom ash samples were analyzed for loss-on-ignition as a measure of refuse combustion effectiveness at the different test conditions. In addition, for each test run, a refuse feed load was sorted and weighed, the combustible materials shredded, and a sample composited for analysis. These samples were analyzed for CDD, CDF, and precursors to characterize the amount contained in the samples and to determine if the relative amounts differed between test conditions. Due to interference with organics contained in the samples, the refuse precursor data are not available.

Triplicate test runs were performed under four different operating conditions, as shown in Table 3-2. The two major parameters that were varied are:

- The degree of fouling of the incinerator and heat transfer surfaces, and
- The temperature of the secondary combustion chamber.

The end of campaign tests (Runs 7-9) were performed when the furnace was near the end of the normal cycle between shutdowns for inspection, cleaning and maintenance. The incinerators are typically operated for about two weeks; the boiler tubes are then cleaned and the equipment is inspected. The entire system is cleaned monthly. The three end of campaign runs were conducted just prior to shutdown for maintenance after about two weeks of operation. Testing

## Table 3-2

## SUMMARY OF OPERATING CONDITIONS

| Operating Condition | Maintenance Status | Primary Chamber Temperature Target, °F | Secondary Chamber Temperature Setpoint, °F |
|---|---|---|---|
| Start of campaign (Runs 1-3) | Clean, after major maintenance shutdown | 1450 | 1800 |
| Low secondary chamber temperature (Runs 10-12) | Approximately mid-campaign | 1450 | 1650 |
| Mid-range secondary chamber temperature (Runs 4-6) | Approximately mid-campaign | 1450 | 1750 |
| End of campaign (Runs 7-9) | Fouled, prior to major maintenance shutdown | 1450 | 1800 |

at this condition demonstrates operation with ash buildup in the secondary chamber as well as dirty heat transfer surfaces and ESP plates.

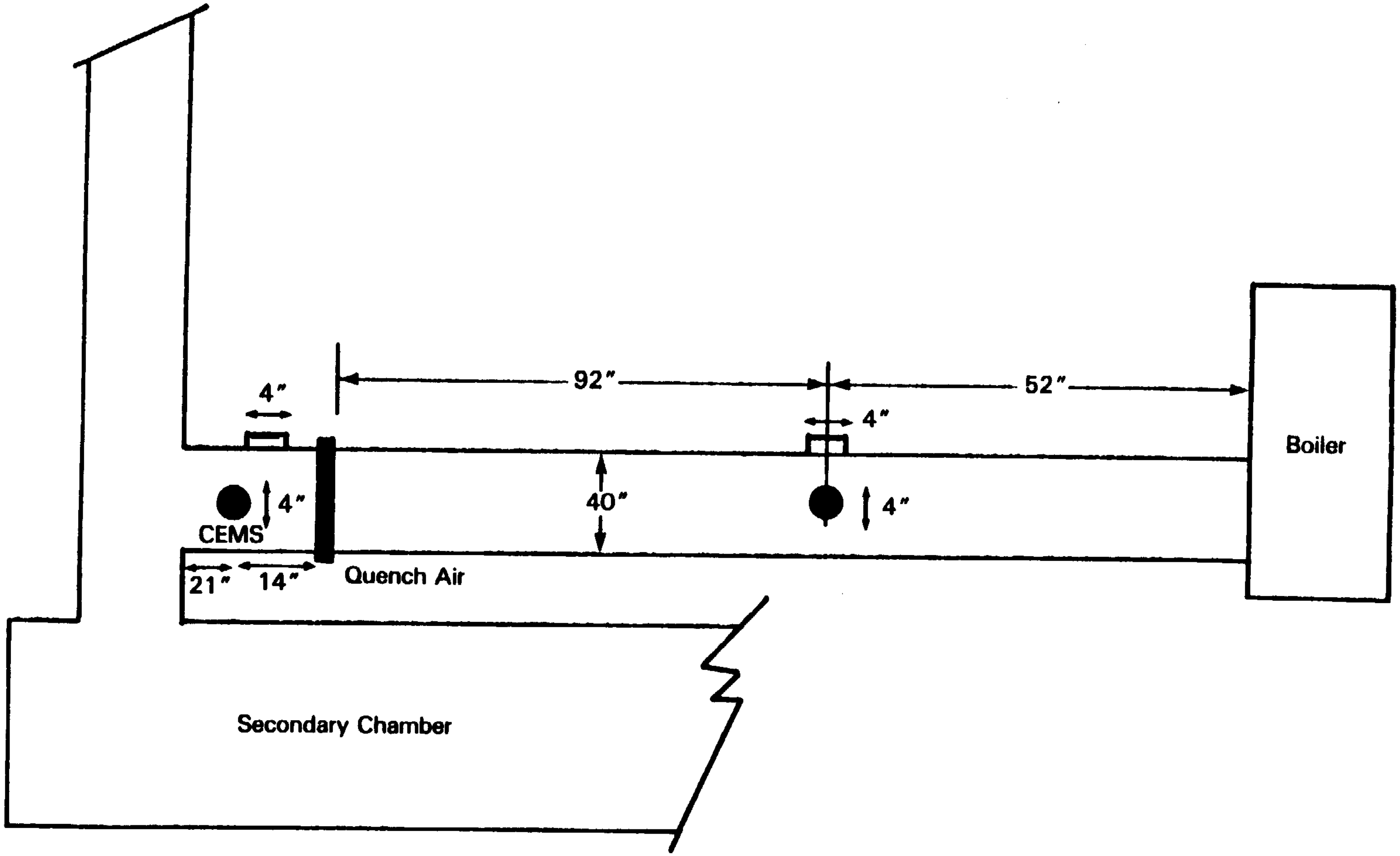
The start of campaign runs (Runs 1-3) were designed to evaluate operation with clean heat transfer surfaces and clean air distribution equipment. The three runs were conducted consecutively starting the day after cleaning and maintenance was completed and the incinerator was exhibiting normal operation.

In order to assess the effect of varying temperature, the remaining two sets of test runs were performed with the primary chamber temperature held near 1450°F (normal setpoint for the primary chamber) and the secondary chamber temperature controlled to 1650°F (Runs 10-12) and 1750°F (Runs 4-6), respectively. The initial setpoints planned for the secondary chamber for these two test series were 1600°F and 1900°F. However, the setpoint planned for the latter series was lowered from 1900°F to 1750°F because the plant operators considered the normal secondary chamber operating temperature setpoint (1800°F) to be high for these units and not much combustion improvement would be expected by raising the temperature further. Also, the facility operators felt they could not maintain the higher temperature without risk of equipment damage.

For these two mid-campaign test conditions, the total air flowrate was adjusted so that the temperature in the secondary chamber would not be affected by variations in excess air. This was necessary because the secondary chamber temperature controls the air split between the primary and secondary chambers. For these tests, a larger fraction of the total combustion air was introduced to the secondary chamber and less was directed to the primary chamber. In addition, feed, transfer, and ash ram cycle intervals for the low secondary chamber temperature tests were increased slightly to maintain primary chamber temperatures; this resulted in a lower feed rate during these tests (see Section 4).

## SAMPLING LOCATIONS

The secondary chamber exit sampling port locations and dimensions are shown in Figure 3-2. The horizontal duct is 40 inches in diameter. Two ports, located



* Not to Scale

Figure 3-2. Location and Dimensions of Sampling Ports, Secondary Chamber Exit

1580025R

92 inches downstream and 52 inches upstream of disturbances (90° orientation), were used for manual sampling of CDD and CDF. These ports are located downstream of the quench air entry. However, no quench air was used during any of the tests since the boiler had been previously retrofitted with refractory-lined tubes.

EPA Method 1 required that 24 points be used for traversing the duct at the secondary chamber exit. Sampling was conducted accordingly with 12-point horizontal and vertical traverses. The sample point layout is given in Figure 3-3.

An identical set of sampling ports, located upstream of the quench air entry, were used for continuous sampling of the combustion gases ($O_2$, $CO_2$, CO, $NO_x$, $SO_2$, and THC). The two 4-inch ports are at a 90° orientation.

The proximity of these ports to the secondary chamber exit indicated the possibility of flue gas stratification. Thus, a sampling probe equipped with a multipoint temperature monitoring system was used to ensure representative measurements of flue gas composition and temperature. However, stratification was not seen during any of the tests.

The ESP inlet sampling location is shown in Figure 3-4. The vertical duct is 30 inches square. The four sample ports are located in a plane two feet upstream and five feet downstream of flow disturbances in the duct. These ports were used for manual CDD, CDF, HCl, and particulate sampling.

The sample point layout of the ESP inlet sampling location is shown in Figure 3-5. As required by EPA Method 1, 24 traverse points were selected for sampling; six sample points per port were used.

The ESP outlet (exhaust stack) sampling location is shown in Figure 3-6. The vertical round duct is 30 inches in diameter. The two sample ports for manual CDD, CDF, HCl and particulate sampling are located in a plane 23.5 feet downstream of a flow disturbance and 63.5 feet upstream of the stack outlet. The ports are at a 90° orientation.

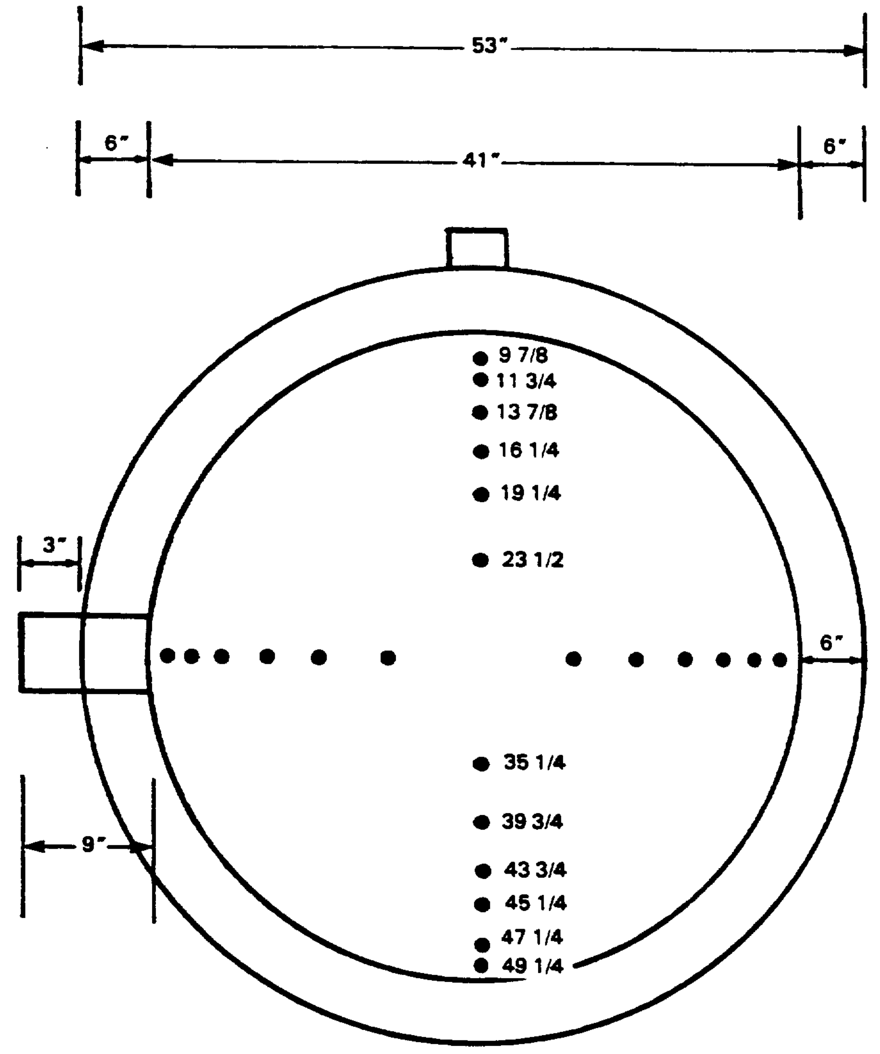


**Figure 3-3. Sampling Point Layout for the MM5 Train, Secondary Chamber Exit**

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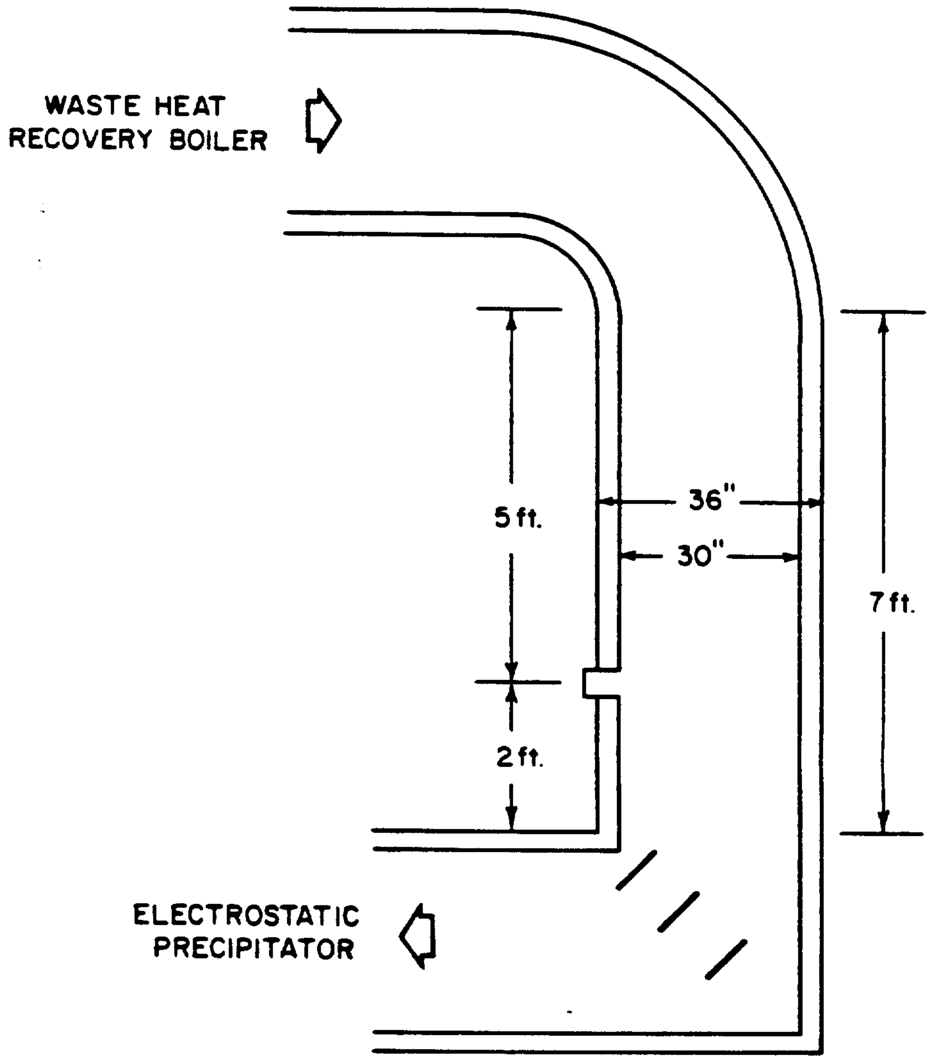
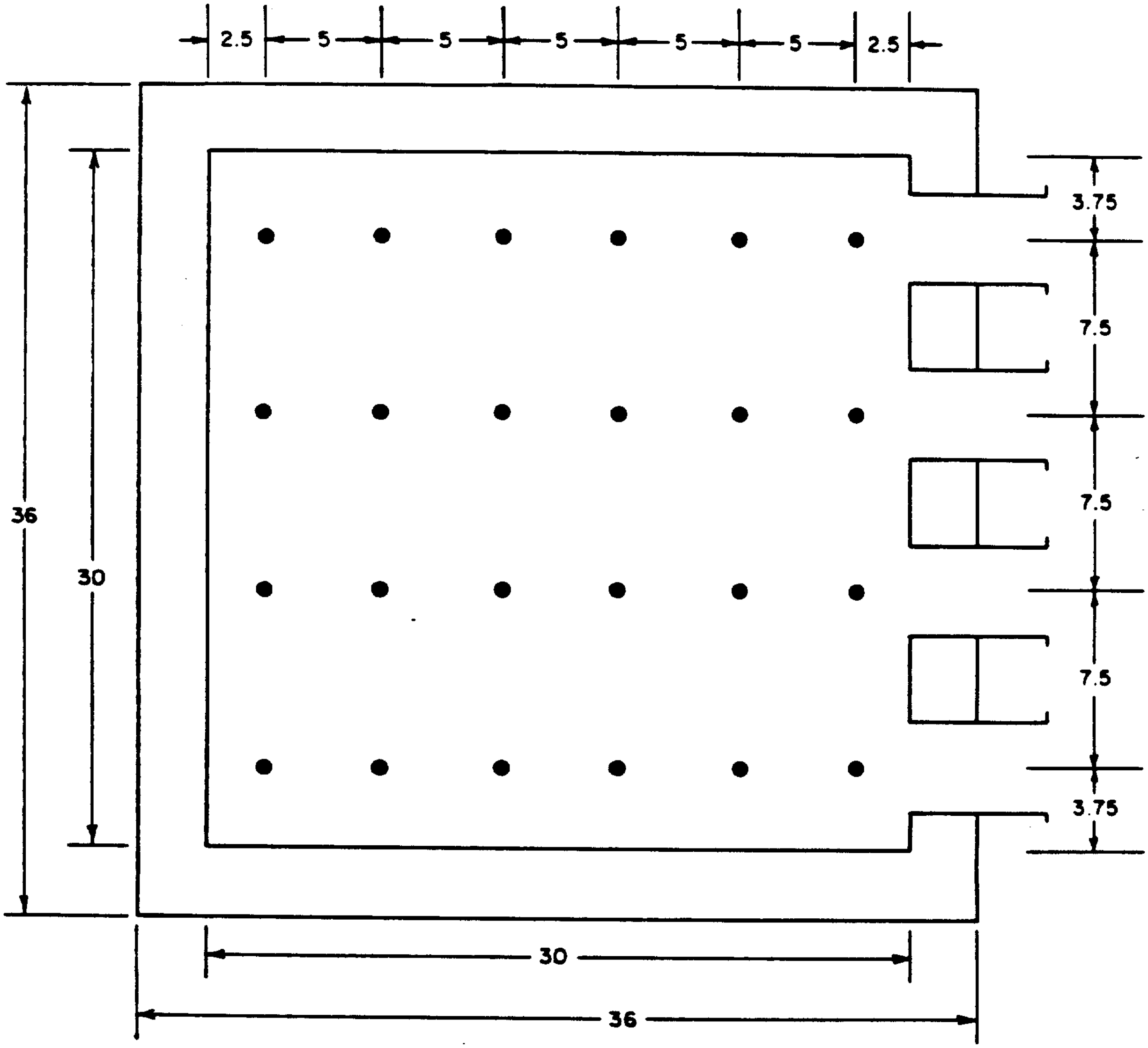


Figure 3-4. Location and Dimensions of Sampling Ports, ESP Inlet



ALL DIMENSIONS IN INCHES

Figure 3-5. Sampling Point Layout for the MM5 Train, ESP Inlet

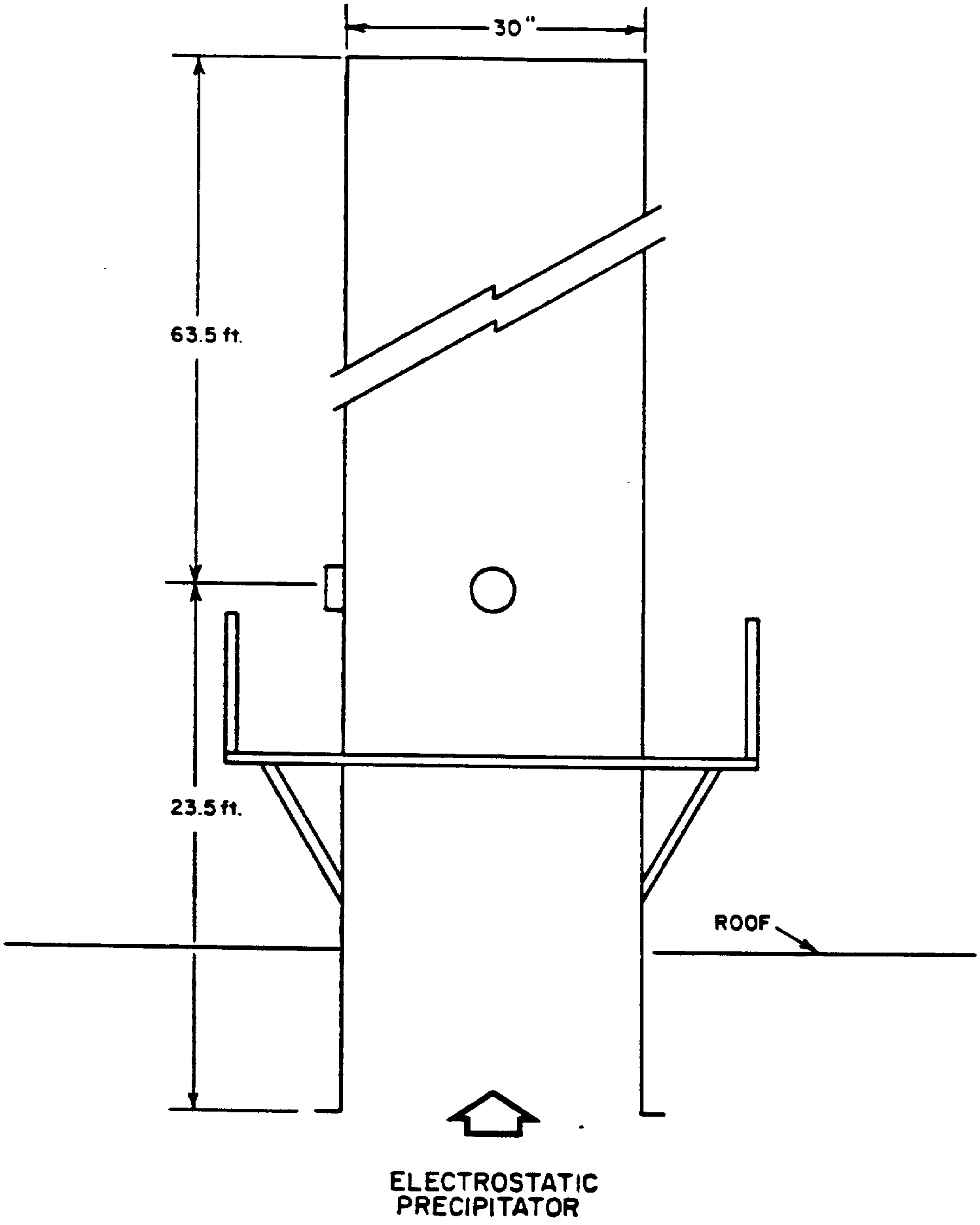
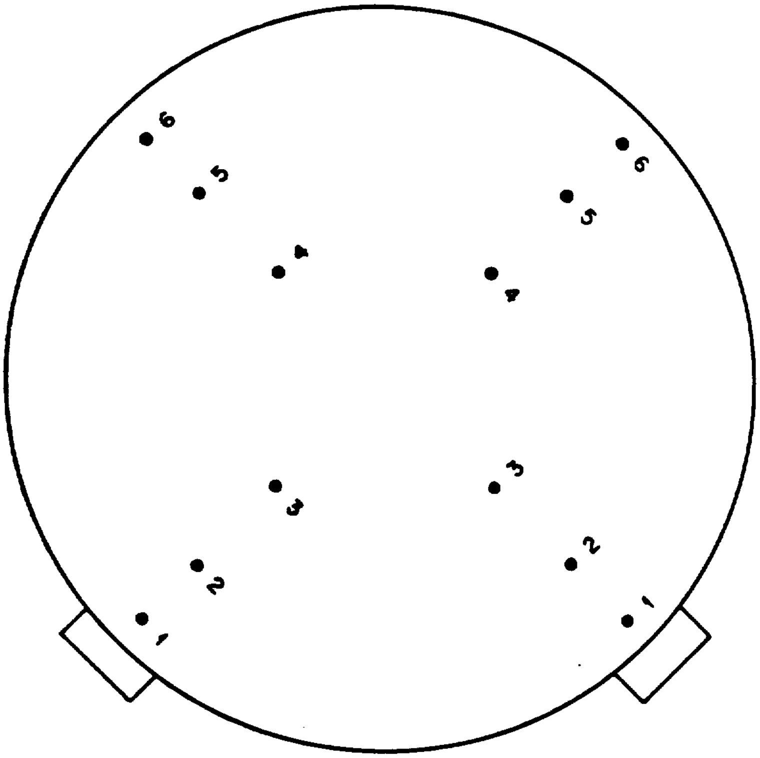


Figure 3-6. Sampling Point Layout for the MM5 Train, ESP Outlet

The sample point layout of the ESP outlet sampling location is shown in Figure 3-7. As required by EPA Method 1, a total of 12 sample points were used to traverse the duct, six points per port.

Near the manual sampling ports, an additional port was used for CEM sampling. At this port, $O_2$, $CO_2$, CO, $NO_x$, and $SO_2$ were monitored.



| POINT NO. | % OF STACK DIAMETER | DISTANCE FROM INSIDE WALL |
|---|---|---|
| 1 | 4.4 | 1.3" |
| 2 | 14.6 | 4.4" |
| 3 | 29.6 | 8.9" |
| 4 | 70.4 | 21.1" |
| 5 | 85.4 | 25.6" |
| 6 | 95.6 | 28.7" |

Figure 3-7. Location and Dimensions of Sampling Ports, ESP Outlet

# Section 4

# SUMMARY OF TEST RESULTS

## INTRODUCTION

This section presents a summary of the data obtained from the testing program at the Oswego County Energy Recovery Facility (ERF); the significance and relationship(s) among the data are discussed in Sections 5, 6 and 7. The results of secondary chamber exit, ESP inlet and ESP outlet flue gas sampling, bottom ash sampling, and refuse sampling are discussed below.

The test runs are labeled as follows: Runs 1-3 are start of campaign test runs (clean heat transfer surfaces), Runs 4-6 are mid-range secondary chamber temperature test runs, Runs 7-9 are end of campaign test runs (dirty heat transfer surfaces) and Runs 10-12 are low secondary chamber temperature test runs. The run sequence used for the graphs presented in this section is: Runs 1-3, 7-9, 4-6, and 10-12. This sequence allows the comparison of start vs. end of campaign and mid-range vs. low secondary chamber temperature.

Figure 4-1 presents a diagram of the facility identifying the locations of the various sampling and monitoring points. Combustion gases were monitored by continuous emission monitors at the secondary chamber exit and ESP outlet. The combustion gases include $O_2$, CO, $CO_2$, $NO_x$, $SO_2$, and THC (secondary chamber exit only). Manual flue gas sampling for CDD, CDF, and precursors was performed at the secondary chamber exit, ESP inlet, and ESP outlet according to a modified version of EPA Method 5 (MM5). Particulates were sampled at the ESP inlet and outlet according to EPA Method 5 (M5); however, these tests were not performed simultaneously with the CDD and CDF tests. Process data were collected to document incinerator operating conditions. These data include: primary and secondary chamber temperature,

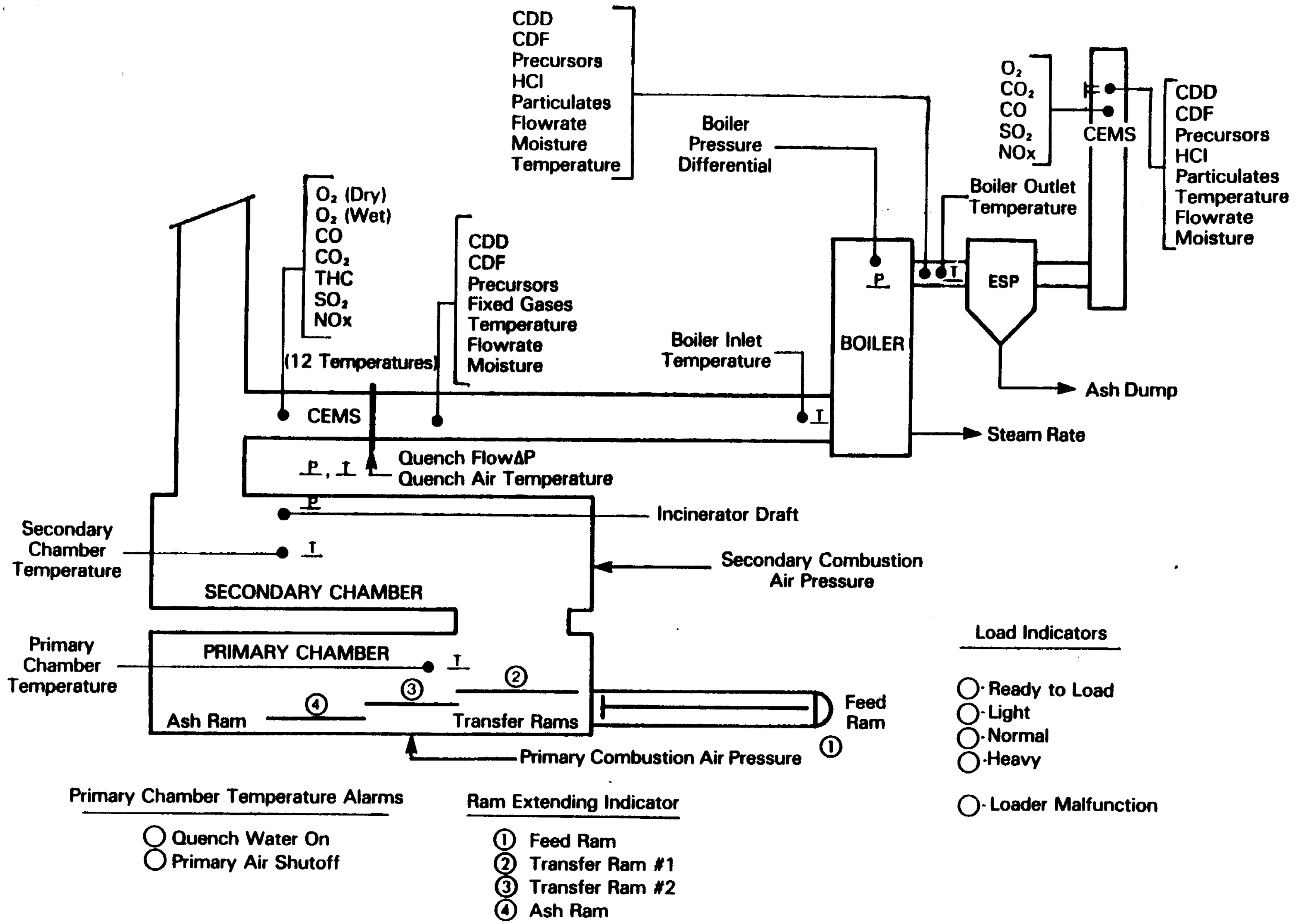


Figure 4-1. Oswego County Process Schematic

secondary chamber exit temperature, boiler inlet and outlet temperature, primary and secondary combustion air pressure, quench air temperature and flow, as well as status indicators of load and ram operation. Figures 4-2 through 4-5 present averaged results for each test condition. the "P" and "T" indicates in the figures represent pressure and temperature, monitoring points, respectively.

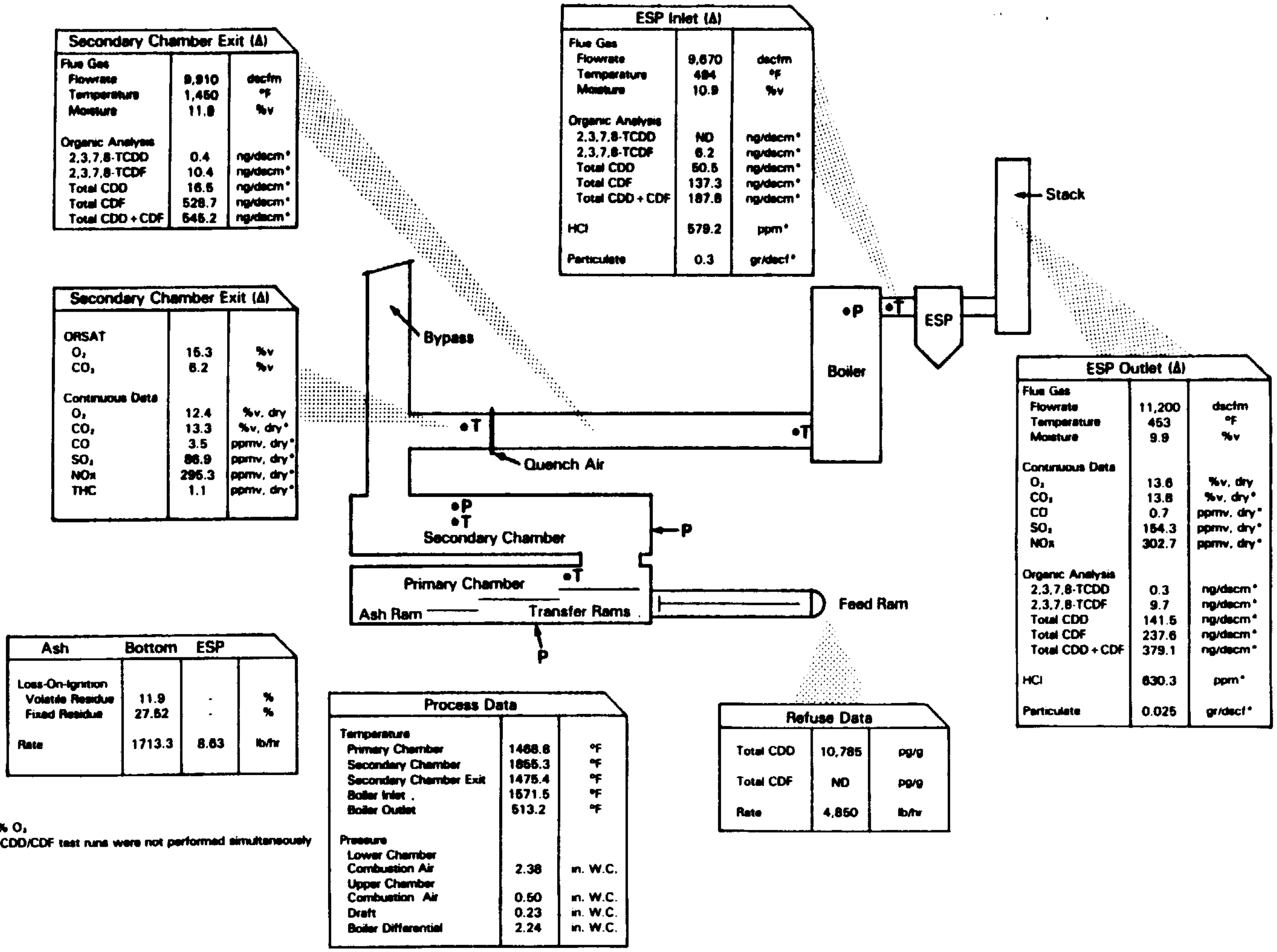
As can be seen in these summary figures, the total CDD increases between the secondary chamber exit and the ESP inlet and again between the ESP inlet and outlet under the operating conditions tested. For all but the low secondary chamber temperature operating condition, CDF concentrations decreased between the secondary chamber exit and ESP inlet and increased between th ESP inlet and outlet; CDF concentrations increased between the secondary chamber exit and ESP inlet and remained unchanged between the ESP inlet and outlet for the low secondary chamber temperature test condition.

## FLUE GAS FLOW AND CONCENTRATION DATA

Tables 4-1, 4-2, and 4-3 present summaries of the flue gas flow and composition results for the secondary chamber exit, ESP inlet, and ESP outlet, respectively. Where available, data are provided for ORSAT results ($O_2$, $CO_2$)j, flue gas moisture, temperature, and flowrate; means and standard deviations are provided for each test series.

Flowrate and temperature were measured using the pitot tubes and thermocouples, respectively, incorporated in both the MM5 and M5 sampling trains. Oxygen and $CO_2$ (secondary chamber exit only) results are from fixed gas sampling; Fyrite$^R$ analyzers were used to analyze the integrated sample. Moisture results were obtained from the weight gain of the impingers in each sampling train. The results summarized below pertain to the MM5 sampling trains.

ORSAT oxygen values measured at the secondary chamber exit ranged from 12.5 to 15.8 percent by volume and carbon dioxide ranged from 5.3 to 8.2 percent by volume. The oxygen levels were slightly higher for the start of campaign and low secondary chamber temperature test conditions.



| Secondary Chamber Exit (Δ) | | |
|---|---|---|
| Flue Gas | | |
| Flowrate | 9,910 | dscfm |
| Temperature | 1,450 | °F |
| Moisture | 11.8 | %v |
| Organic Analyses | | |
| 2,3,7,8-TCDD | 0.4 | ng/dscm* |
| 2,3,7,8-TCDF | 10.4 | ng/dscm* |
| Total CDD | 16.5 | ng/dscm* |
| Total CDF | 528.7 | ng/dscm* |
| Total CDD + CDF | 545.2 | ng/dscm* |

| Secondary Chamber Exit (Δ) | | |
|---|---|---|
| ORSAT | | |
| $O_2$ | 15.3 | %v |
| $CO_2$ | 6.2 | %v |
| Continuous Data | | |
| $O_2$ | 12.4 | %v, dry |
| $CO_2$ | 13.3 | %v, dry* |
| CO | 3.5 | ppmv, dry* |
| $SO_2$ | 86.9 | ppmv, dry* |
| NOx | 295.3 | ppmv, dry* |
| THC | 1.1 | ppmv, dry* |

| ESP Inlet (Δ) | | |
|---|---|---|
| Flue Gas | | |
| Flowrate | 9,670 | dscfm |
| Temperature | 494 | °F |
| Moisture | 10.9 | %v |
| Organic Analysis | | |
| 2,3,7,8-TCDD | ND | ng/dscm* |
| 2,3,7,8-TCDF | 6.2 | ng/dscm* |
| Total CDD | 50.5 | ng/dscm* |
| Total CDF | 137.3 | ng/dscm* |
| Total CDD + CDF | 187.8 | ng/dscm* |
| HCl | 579.2 | ppm* |
| Particulate | 0.3 | gr/dscf* |

| ESP Outlet (Δ) | | |
|---|---|---|
| Flue Gas | | |
| Flowrate | 11,200 | dscfm |
| Temperature | 453 | °F |
| Moisture | 9.9 | %v |
| Continuous Data | | |
| $O_2$ | 13.6 | %v, dry |
| $CO_2$ | 13.8 | %v, dry* |
| CO | 0.7 | ppmv, dry* |
| $SO_2$ | 154.3 | ppmv, dry* |
| NOx | 302.7 | ppmv, dry* |
| Organic Analysis | | |
| 2,3,7,8-TCDD | 0.3 | ng/dscm* |
| 2,3,7,8-TCDF | 9.7 | ng/dscm* |
| Total CDD | 141.5 | ng/dscm* |
| Total CDF | 237.6 | ng/dscm* |
| Total CDD + CDF | 379.1 | ng/dscm* |
| HCl | 630.3 | ppm* |
| Particulate | 0.025 | gr/dscf* |

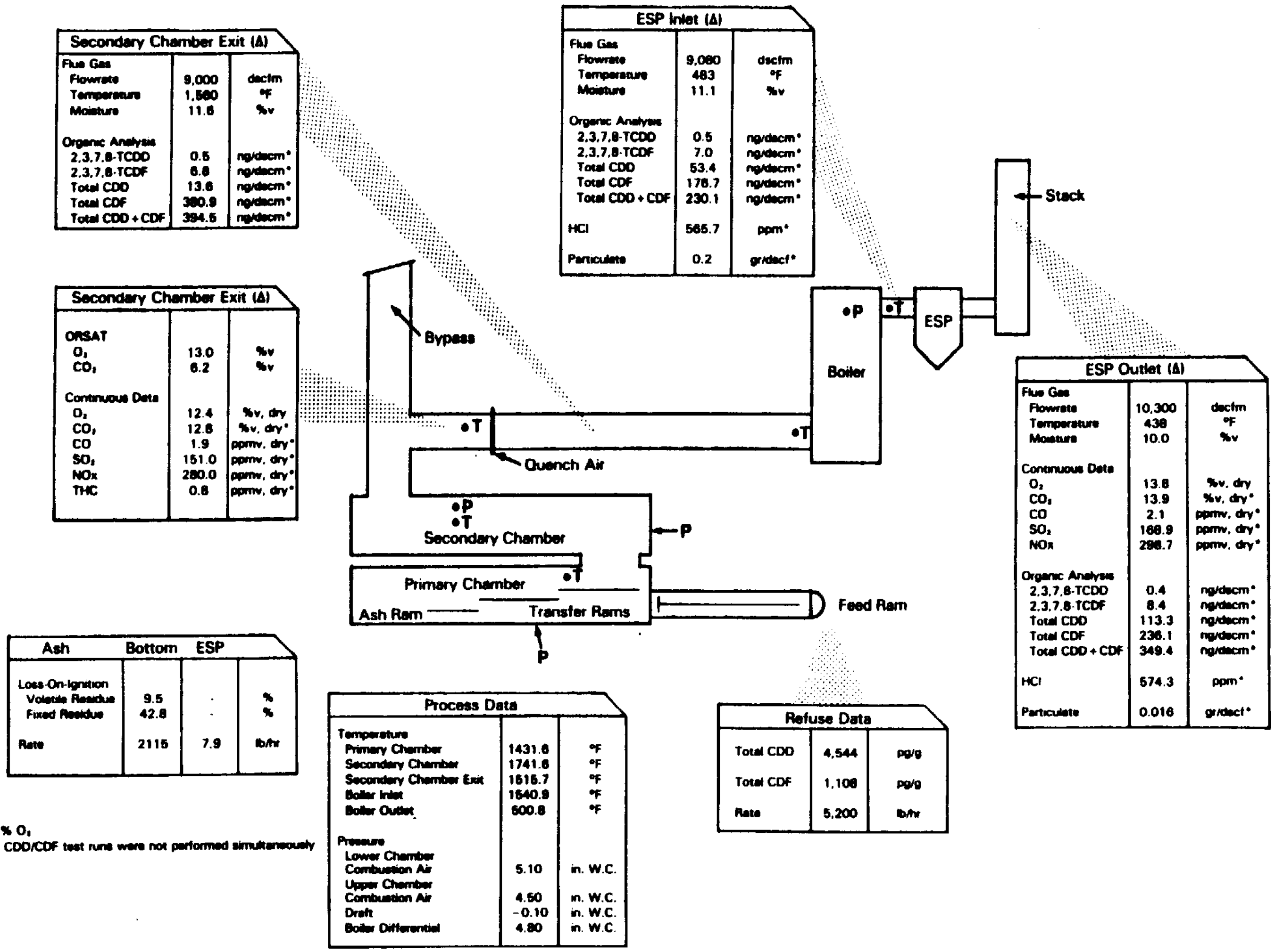
| Ash | Bottom | ESP | |
|---|---|---|---|
| Loss-On-Ignition | | | |
| Volatile Residue | 11.9 | - | % |
| Fixed Residue | 27.52 | - | % |
| Rate | 1713.3 | 8.63 | lb/hr |

| Process Data | | |
|---|---|---|
| Temperature | | |
| Primary Chamber | 1468.8 | °F |
| Secondary Chamber | 1865.3 | °F |
| Secondary Chamber Exit | 1475.4 | °F |
| Boiler Inlet | 1571.5 | °F |
| Boiler Outlet | 513.2 | °F |
| Pressure | | |
| Lower Chamber Combustion Air | 2.38 | in. W.C. |
| Upper Chamber Combustion Air | 0.50 | in. W.C. |
| Draft | 0.23 | in. W.C. |
| Boiler Differential | 2.24 | in. W.C. |

| Refuse Data | | |
|---|---|---|
| Total CDD | 10,785 | pg/g |
| Total CDF | ND | pg/g |
| Rate | 4,850 | lb/hr |

* Corrected to 7% $O_2$
Δ Particulate and CDD/CDF test runs were not performed simultaneously
ND Not Detected

Figure 4-2. Summary Results, Start of Campaign Operating Condition (Runs 1, 2, 3)



**Secondary Chamber Exit (Δ)**

| | | |
|---|---|---|
| Flue Gas | | |
| Flowrate | 9,000 | dscfm |
| Temperature | 1,560 | °F |
| Moisture | 11.6 | %v |
| Organic Analysis | | |
| 2,3,7,8-TCDD | 0.5 | ng/dscm* |
| 2,3,7,8-TCDF | 6.8 | ng/dscm* |
| Total CDD | 13.6 | ng/dscm* |
| Total CDF | 380.9 | ng/dscm* |
| Total CDD + CDF | 394.5 | ng/dscm* |

**Secondary Chamber Exit (Δ)**

| | | |
|---|---|---|
| ORSAT | | |
| $O_2$ | 13.0 | %v |
| $CO_2$ | 6.2 | %v |
| Continuous Data | | |
| $O_2$ | 12.4 | %v, dry |
| $CO_2$ | 12.6 | %v, dry* |
| CO | 1.9 | ppmv, dry* |
| $SO_2$ | 151.0 | ppmv, dry* |
| NOx | 280.0 | ppmv, dry* |
| THC | 0.6 | ppmv, dry* |

**ESP Inlet (Δ)**

| | | |
|---|---|---|
| Flue Gas | | |
| Flowrate | 9,060 | dscfm |
| Temperature | 483 | °F |
| Moisture | 11.1 | %v |
| Organic Analyses | | |
| 2,3,7,8-TCDD | 0.5 | ng/dscm* |
| 2,3,7,8-TCDF | 7.0 | ng/dscm* |
| Total CDD | 53.4 | ng/dscm* |
| Total CDF | 176.7 | ng/dscm* |
| Total CDD + CDF | 230.1 | ng/dscm* |
| HCl | 565.7 | ppm* |
| Particulate | 0.2 | gr/dscf* |

**ESP Outlet (Δ)**

| | | |
|---|---|---|
| Flue Gas | | |
| Flowrate | 10,300 | dscfm |
| Temperature | 438 | °F |
| Moisture | 10.0 | %v |
| Continuous Data | | |
| $O_2$ | 13.8 | %v, dry |
| $CO_2$ | 13.9 | %v, dry* |
| CO | 2.1 | ppmv, dry* |
| $SO_2$ | 168.9 | ppmv, dry* |
| NOx | 298.7 | ppmv, dry* |
| Organic Analyses | | |
| 2,3,7,8-TCDD | 0.4 | ng/dscm* |
| 2,3,7,8-TCDF | 8.4 | ng/dscm* |
| Total CDD | 113.3 | ng/dscm* |
| Total CDF | 236.1 | ng/dscm* |
| Total CDD + CDF | 349.4 | ng/dscm* |
| HCl | 574.3 | ppm* |
| Particulate | 0.016 | gr/dscf* |

| Ash | Bottom | ESP | |
|---|---|---|---|
| Loss-On-Ignition | | | |
| Volatile Residue | 9.5 | - | % |
| Fixed Residue | 42.8 | - | % |
| Rate | 2115 | 7.9 | lb/hr |

**Process Data**

| | | |
|---|---|---|
| Temperature | | |
| Primary Chamber | 1431.6 | °F |
| Secondary Chamber | 1741.6 | °F |
| Secondary Chamber Exit | 1515.7 | °F |
| Boiler Inlet | 1540.9 | °F |
| Boiler Outlet | 500.8 | °F |
| Pressure | | |
| Lower Chamber Combustion Air | 5.10 | in. W.C. |
| Upper Chamber Combustion Air | 4.50 | in. W.C. |
| Draft | -0.10 | in. W.C. |
| Boiler Differential | 4.80 | in. W.C. |

**Refuse Data**

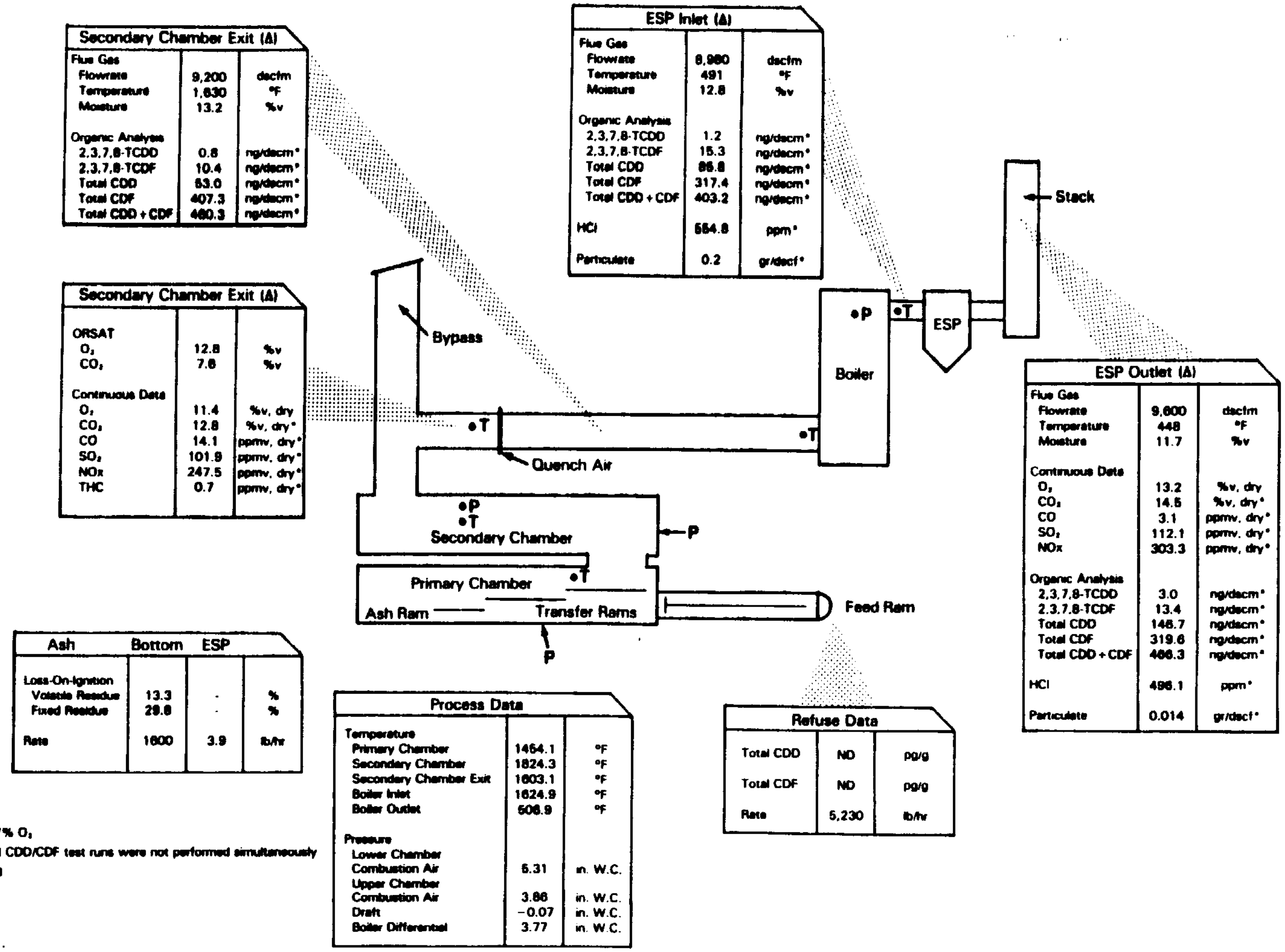
| | | |
|---|---|---|
| Total CDD | 4,544 | pg/g |
| Total CDF | 1,108 | pg/g |
| Rate | 5,200 | lb/hr |

* Corrected to 7% $O_2$

Δ Particulate and CDD/CDF test runs were not performed simultaneously

Figure 4-3. Summary Results, Mid-Range Secondary Chamber Temperature Operating Condition (Runs 4, 5, 6)

1582226R



| Secondary Chamber Exit (Δ) | | |
|---|---|---|
| Flue Gas | | |
| Flowrate | 9,200 | dscfm |
| Temperature | 1,630 | °F |
| Moisture | 13.2 | %v |
| Organic Analyses | | |
| 2,3,7,8-TCDD | 0.8 | ng/dscm* |
| 2,3,7,8-TCDF | 10.4 | ng/dscm* |
| Total CDD | 53.0 | ng/dscm* |
| Total CDF | 407.3 | ng/dscm* |
| Total CDD + CDF | 460.3 | ng/dscm* |

| Secondary Chamber Exit (Δ) | | |
|---|---|---|
| ORSAT | | |
| $O_2$ | 12.8 | %v |
| $CO_2$ | 7.8 | %v |
| Continuous Data | | |
| $O_2$ | 11.4 | %v, dry |
| $CO_2$ | 12.8 | %v, dry* |
| CO | 14.1 | ppmv, dry* |
| $SO_2$ | 101.9 | ppmv, dry* |
| NOx | 247.5 | ppmv, dry* |
| THC | 0.7 | ppmv, dry* |

| ESP Inlet (Δ) | | |
|---|---|---|
| Flue Gas | | |
| Flowrate | 8,980 | dscfm |
| Temperature | 491 | °F |
| Moisture | 12.8 | %v |
| Organic Analysis | | |
| 2,3,7,8-TCDD | 1.2 | ng/dscm* |
| 2,3,7,8-TCDF | 15.3 | ng/dscm* |
| Total CDD | 86.8 | ng/dscm* |
| Total CDF | 317.4 | ng/dscm* |
| Total CDD + CDF | 403.2 | ng/dscm* |
| HCl | 564.8 | ppm* |
| Particulate | 0.2 | gr/dscf* |

| ESP Outlet (Δ) | | |
|---|---|---|
| Flue Gas | | |
| Flowrate | 9,600 | dscfm |
| Temperature | 448 | °F |
| Moisture | 11.7 | %v |
| Continuous Data | | |
| $O_2$ | 13.2 | %v, dry |
| $CO_2$ | 14.5 | %v, dry* |
| CO | 3.1 | ppmv, dry* |
| $SO_2$ | 112.1 | ppmv, dry* |
| NOx | 303.3 | ppmv, dry* |
| Organic Analysis | | |
| 2,3,7,8-TCDD | 3.0 | ng/dscm* |
| 2,3,7,8-TCDF | 13.4 | ng/dscm* |
| Total CDD | 146.7 | ng/dscm* |
| Total CDF | 319.6 | ng/dscm* |
| Total CDD + CDF | 466.3 | ng/dscm* |
| HCl | 496.1 | ppm* |
| Particulate | 0.014 | gr/dscf* |

| Ash | Bottom | ESP | |
|---|---|---|---|
| Loss-On-Ignition | | | |
| Volatile Residue | 13.3 | - | % |
| Fixed Residue | 29.8 | - | % |
| Rate | 1600 | 3.9 | lb/hr |

| Process Data | | |
|---|---|---|
| Temperature | | |
| Primary Chamber | 1464.1 | °F |
| Secondary Chamber | 1824.3 | °F |
| Secondary Chamber Exit | 1603.1 | °F |
| Boiler Inlet | 1624.9 | °F |
| Boiler Outlet | 506.9 | °F |
| Pressure | | |
| Lower Chamber Combustion Air | 5.31 | in. W.C. |
| Upper Chamber Combustion Air | 3.86 | in. W.C. |
| Draft | -0.07 | in. W.C. |
| Boiler Differential | 3.77 | in. W.C. |

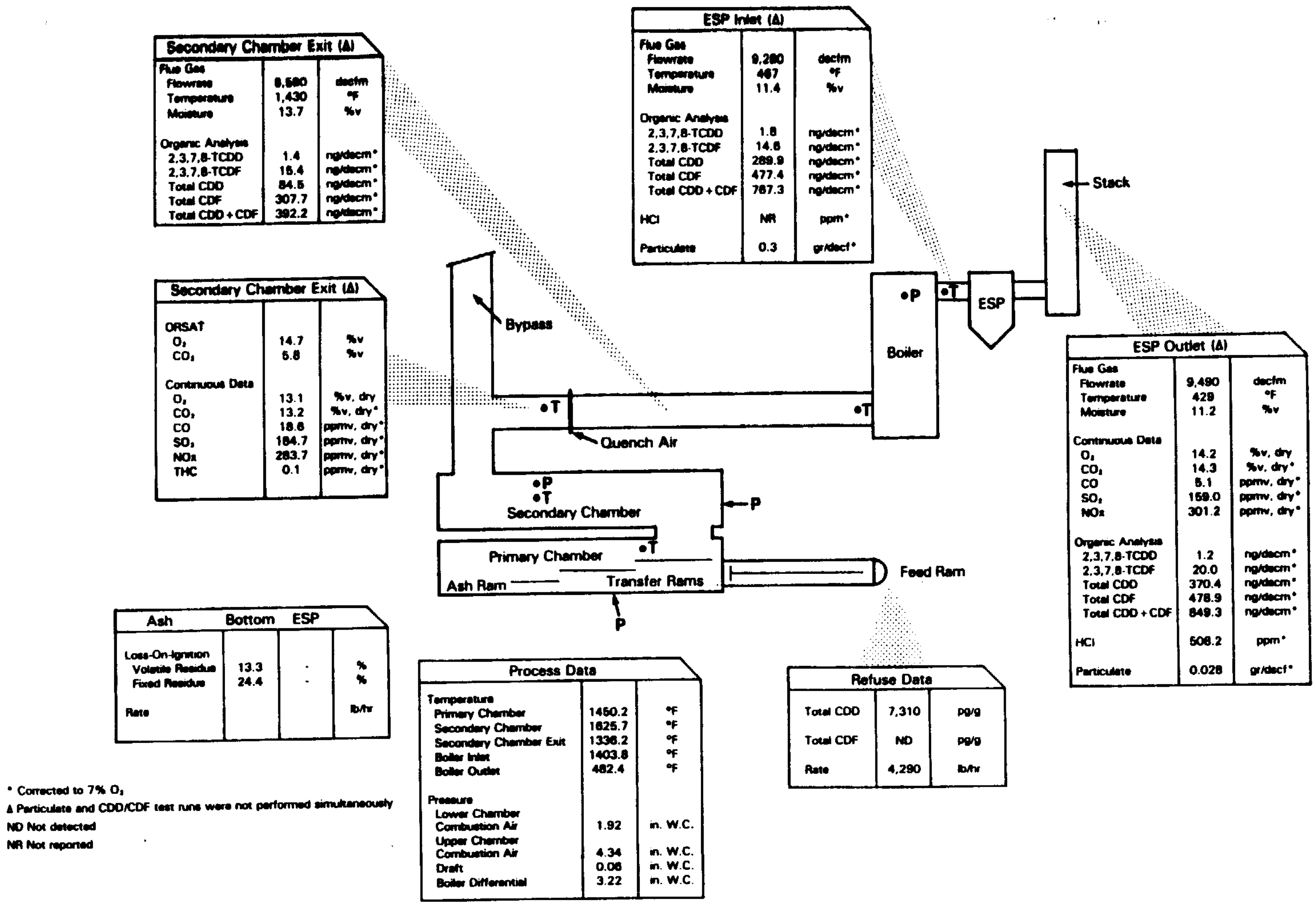
| Refuse Data | | |
|---|---|---|
| Total CDD | ND | pg/g |
| Total CDF | ND | pg/g |
| Rate | 5,230 | lb/hr |

* Corrected to 7% $O_2$

Δ Particulate and CDD/CDF test runs were not performed simultaneously

ND Not detected

Figure 4-4. Summary Results, End of Campaign Operating Condition (Runs 7, 8, 9)



| Secondary Chamber Exit (Δ) | | |
|---|---|---|
| Flue Gas | | |
| Flowrate | 8,580 | dscfm |
| Temperature | 1,430 | °F |
| Moisture | 13.7 | %v |
| Organic Analysis | | |
| 2,3,7,8-TCDD | 1.4 | ng/dscm* |
| 2,3,7,8-TCDF | 15.4 | ng/dscm* |
| Total CDD | 84.5 | ng/dscm* |
| Total CDF | 307.7 | ng/dscm* |
| Total CDD + CDF | 392.2 | ng/dscm* |

| Secondary Chamber Exit (Δ) | | |
|---|---|---|
| ORSAT | | |
| $O_2$ | 14.7 | %v |
| $CO_2$ | 6.8 | %v |
| Continuous Data | | |
| $O_2$ | 13.1 | %v, dry |
| $CO_2$ | 13.2 | %v, dry* |
| CO | 18.6 | ppmv, dry* |
| $SO_2$ | 184.7 | ppmv, dry* |
| $NO_x$ | 283.7 | ppmv, dry* |
| THC | 0.1 | ppmv, dry* |

| ESP Inlet (Δ) | | |
|---|---|---|
| Flue Gas | | |
| Flowrate | 9,280 | dscfm |
| Temperature | 467 | °F |
| Moisture | 11.4 | %v |
| Organic Analyses | | |
| 2,3,7,8-TCDD | 1.8 | ng/dscm* |
| 2,3,7,8-TCDF | 14.6 | ng/dscm* |
| Total CDD | 289.9 | ng/dscm* |
| Total CDF | 477.4 | ng/dscm* |
| Total CDD + CDF | 767.3 | ng/dscm* |
| HCl | NR | ppm* |
| Particulate | 0.3 | gr/dscf* |

| ESP Outlet (Δ) | | |
|---|---|---|
| Flue Gas | | |
| Flowrate | 9,490 | dscfm |
| Temperature | 429 | °F |
| Moisture | 11.2 | %v |
| Continuous Data | | |
| $O_2$ | 14.2 | %v, dry |
| $CO_2$ | 14.3 | %v, dry* |
| CO | 5.1 | ppmv, dry* |
| $SO_2$ | 159.0 | ppmv, dry* |
| $NO_x$ | 301.2 | ppmv, dry* |
| Organic Analysis | | |
| 2,3,7,8-TCDD | 1.2 | ng/dscm* |
| 2,3,7,8-TCDF | 20.0 | ng/dscm* |
| Total CDD | 370.4 | ng/dscm* |
| Total CDF | 478.9 | ng/dscm* |
| Total CDD + CDF | 849.3 | ng/dscm* |
| HCl | 508.2 | ppm* |
| Particulate | 0.028 | gr/dscf* |

| Ash | Bottom | ESP | |
|---|---|---|---|
| Loss-On-Ignition | | | |
| Volatile Residue | 13.3 | - | % |
| Fixed Residue | 24.4 | - | % |
| Rate | | | lb/hr |

| Process Data | | |
|---|---|---|
| Temperature | | |
| Primary Chamber | 1450.2 | °F |
| Secondary Chamber | 1625.7 | °F |
| Secondary Chamber Exit | 1336.2 | °F |
| Boiler Inlet | 1403.8 | °F |
| Boiler Outlet | 482.4 | °F |
| Pressure | | |
| Lower Chamber Combustion Air | 1.92 | in. W.C. |
| Upper Chamber Combustion Air | 4.34 | in. W.C. |
| Draft | 0.06 | in. W.C. |
| Boiler Differential | 3.22 | in. W.C. |

| Refuse Data | | |
|---|---|---|
| Total CDD | 7,310 | pg/g |
| Total CDF | ND | pg/g |
| Rate | 4,290 | lb/hr |

* Corrected to 7% $O_2$

Δ Particulate and CDD/CDF test runs were not performed simultaneously

ND Not detected

NR Not reported

Figure 4-5. Summary Results, Low Secondary Chamber Temperature Operating Condition (Runs 10, 11, 12)

# Table 4-1

## SUMMARY OF FLUE GAS FLOW AND COMPOSITION RESULTS AT THE SECONDARY CHAMBER EXIT

| TEST CONDITION[a] | RUN NUMBER | CDD, CDF AND HCl, MM5 TRAIN | | | | | |
|---|---|---|---|---|---|---|---|
| | | METHOD 3, ORSAT | | | | | |
| | | $O_2$, %V | $CO_2$, %V | $H_2O$, %V | FLUE GAS TEMPERATURE, deg. F | FLUE GAS FLOWRATE, acfm | STANDARD FLUE[b] GAS FLOWRATE, dscfm |
| Start of Campaign, SCE = 1800 deg. F | 1 | 15.8 | 6.0 | 12.5 | 1460 | 42000 | 9840 |
| | 2 | 15.8 | 5.8 | 11.8 | 1410 | 41000 | 10200 |
| | 3 | 14.2 | 6.8 | 11.3 | 1490 | 40600 | 9680 |
| AVERAGE | | 15.3 | 6.2 | 11.9 | 1450 | 41200 | 9910 |
| (STD. DEV.) | | 0.9 | 0.5 | 0.6 | 40 | 720 | 270 |
| Mid-range Secondary Chamber Temperature, SCE = 1750 deg. F | 4 | 13.1 | 6.1 | 10.7 | 1570 | 39200 | 9120 |
| | 5 | 13.5 | 6.0 | 12.5 | 1560 | 40200 | 9170 |
| | 6 | 12.5 | 6.4 | 11.6 | 1560 | 38200 | 8720 |
| AVERAGE | | 13.0 | 6.2 | 11.6 | 1560 | 39200 | 9000 |
| (STD. DEV.) | | 0.5 | 0.2 | 0.9 | 6 | 1000 | 250 |
| End of Campaign, SCE = 1800 deg. F | 7 | 12.5 | 8.2 | 14.3 | 1560 | 41200 | 8650 |
| | 8 | 13.0 | 6.9 | 13.2 | 1680 | 42000 | 9170 |
| | 9 | 13.0 | 7.0 | 12.2 | 1650 | 44700 | 9770 |
| AVERAGE | | 12.8 | 7.6 | 13.2 | 1630 | 42600 | 9200 |
| (STD. DEV.) | | 0.3 | 0.7 | 1.1 | 60 | 1800 | 560 |
| Low Secondary Chamber Temperature, SCE = 1650 deg. F | 10 | 15.3 | 5.3 | 12.9 | 1445 | 38300 | 9060 |
| | 11 | 14.6 | 6.5 | 11.8 | 1435 | 36900 | 8940 |
| | 12 | 14.3 | 5.5 | 16.4 | 1420 | 33500 | 7760 |
| AVERAGE | | 14.7 | 5.8 | 13.7 | 1430 | 36200 | 8590 |
| (STD. DEV.) | | 0.5 | 0.6 | 2.4 | 13 | 2500 | 720 |

[a] SCE = Secondary Chamber Exit; temperatures represent setpoints for condition indicated.

[b] Standard conditions are 68 deg. F (20 deg. C) and 1 atm (101325 Pa).

Table 4-2

SUMMARY OF FLUE GAS FLOW AND COMPOSITION RESULTS AT THE ESP INLET

| | | CDD, CDF AND HCl, MM5 TRAIN | | | | | | PARTICULATE, M5 TRAIN | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | METHOD 3, ORSAT | | | | | | | | | |
| TEST CONDITION[a] | RUN NUMBER | $O_2$, %V[b] | $CO_2$, %V[b] | $H_2O$, %V | FLUE GAS TEMPERATURE, deg. F | FLUE GAS FLOWRATE, acfm | STANDARD FLUE[c] GAS FLOWRATE, dscfm | $H_2O$, %V | FLUE GAS TEMPERATURE, deg. F | FLUE GAS FLOWRATE, acfm | STANDARD FLUE[c] GAS FLOWRATE, dscfm |
| Start of Campaign, SCE = 1800 deg. F | 1 | | | 11.7 | 497 | 20500 | 9780 | 10.8 | 494 | 20600 | 9980 |
| | 2 | | | 11.0 | 489 | 20000 | 9670 | 12.1 | 493 | 20400 | 9640 |
| | 3 | | | 9.9 | 496 | 19500 | 9550 | 9.9 | 502 | 20200 | 9800 |
| AVERAGE | | | | 10.9 | 494 | 20000 | 9670 | 10.9 | 496 | 20400 | 9810 |
| (STD. DEV.) | | | | 0.9 | 4 | 500 | 120 | 1.1 | 5 | 200 | 170 |
| Mid-range Secondary Chamber Temperature, SCE = 1750 deg. F | 4 | | | 11.1 | 483 | 18800 | 9230 | 12.1 | 486 | 19300 | 9380 |
| | 5 | | | 11.2 | 485 | 18600 | 9080 | 10.5 | 492 | 19700 | 9410 |
| | 6 | | | 10.8 | 481 | 18300 | 8930 | 7.7 | 487 | 18400 | 9230 |
| AVERAGE | | | | 11.1 | 483 | 18600 | 9080 | 10.1 | 488 | 19100 | 9340 |
| (STD. DEV.) | | | | 0.2 | 2 | 250 | 150 | 2.2 | 3 | 670 | 100 |
| End of Campaign, SCE = 1800 deg. F | 7 | | | 14.6 | 484 | 17800 | 8380 | 12.3 | 486 | 19700 | 9480 |
| | 8 | | | 12.2 | 490 | 19100 | 9260 | 6.3 | 497 | 20200 | 10300 |
| | 9 | | | 11.6 | 500 | 19400 | 9290 | 11.4 | 506 | 19900 | 9490 |
| AVERAGE | | | | 12.8 | 491 | 18800 | 8980 | 10.0 | 497 | 19900 | 9760 |
| (STD. DEV.) | | | | 1.6 | 8 | 850 | 520 | 3.2 | 10 | 250 | 470 |
| Low Secondary Chamber Temperature, SCE = 1650 deg. F | 10 | | | 11.6 | 465 | 20300 | 9920 | 9.6 | 460 | 17900 | 9010 |
| | 11 | | | 11.0 | 461 | 18300 | 9140 | 10.4 | 472 | 20200 | 9770 |
| | 12 | | | 11.6 | 474 | 17900 | 8770 | 11.1 | 477 | 19800 | 9670 |
| AVERAGE | | | | 11.4 | 467 | 18800 | 9280 | 10.4 | 470 | 19300 | 9480 |
| (STD. DEV.) | | | | 0.3 | 6 | 1300 | 590 | 0.8 | 9 | 1200 | 410 |

[a] SCE = Secondary Chamber Exit; temperatures represent setpoints for condition indicated.

[b] Not reported.

[c] Standard conditions are 68 deg. F (20 deg. C) and 1 atm (101325 Pa).

Table 4-3

SUMMARY OF FLUE GAS FLOW AND COMPOSITION RESULTS AT THE ESP OUTLET

| | | CDD, CDF AND HCl, MM5 TRAIN | | | | | | PARTICULATE, M5 TRAIN | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | METHOD 3, ORSAT | | | | | | | | | |
| TEST CONDITION[a] | RUN NUMBER | O2, %V[b] | CO2, %V[b] | H2O, %V | FLUE GAS TEMPERATURE, deg. F | FLUE GAS FLOWRATE, acfm | STANDARD FLUE[c] GAS FLOWRATE, dscfm | H2O, %V | FLUE GAS TEMPERATURE, deg. F | FLUE GAS FLOWRATE, acfm | STANDARD FLUE[c] GAS FLOWRATE, dscfm |
| Start of Campaign, SCE = 1800 deg. F | 1 | | | 10.0 | 454 | 21400 | 11100 | 9.6 | 438 | 20400 | 10900 |
| | 2 | | | 10.2 | 455 | 21500 | 11000 | 10.7 | 446 | 20900 | 10700 |
| | 3 | | | 9.6 | 449 | 21700 | 11400 | 8.8 | 444 | 21400 | 11400 |
| AVERAGE | | | | 9.9 | 453 | 21500 | 11200 | 9.7 | 443 | 20900 | 11000 |
| (STD. DEV.) | | | | 0.3 | 3 | 150 | 210 | 1.0 | 4 | 500 | 360 |
| Mid-range Secondary Chamber Temperature, SCE = 1750 deg. F | 4 | | | 9.8 | 441 | 20200 | 10700 | 10.8 | 432 | 19200 | 10200 |
| | 5 | | | 10.6 | 439 | 19500 | 10200 | 10.4 | 431 | 17800 | 9460 |
| | 6 | | | 9.6 | 434 | 18600 | 9860 | 10.2 | 428 | 18400 | 9750 |
| AVERAGE | | | | 10.0 | 438 | 19400 | 10300 | 10.5 | 430 | 18500 | 9800 |
| (STD. DEV.) | | | | 0.5 | 4 | 800 | 420 | 0.3 | 2 | 700 | 370 |
| End of Campaign, SCE = 1800 deg. F | 7 | | | 12.3 | 438 | 17800 | 9170 | 10.9 | 425 | 18800 | 9960 |
| | 8 | | | 11.7 | 444 | 18700 | 9680 | 9.8 | 441 | 19500 | 10400 |
| | 9 | | | 11.2 | 461 | 19600 | 9950 | 10.5 | 454 | 19400 | 10000 |
| AVERAGE | | | | 11.7 | 448 | 18700 | 9600 | 10.4 | 440 | 19200 | 10100 |
| (STD. DEV.) | | | | 0.6 | 12 | 900 | 400 | 0.6 | 15 | 380 | 240 |
| Low Secondary Chamber Temperature, SCE = 1650 deg. F | 10 | | | 11.1 | 430 | 19500 | 10100 | 9.1 | 407 | 15900 | 8620 |
| | 11 | | | 10.9 | 430 | 18800 | 9800 | 9.6 | 423 | 18900 | 10100 |
| | 12 | | | 11.7 | 428 | 16900 | 8570 | 10.6 | 430 | 19200 | 10000 |
| AVERAGE | | | | 11.2 | 429 | 18400 | 9490 | 9.8 | 420 | 18000 | 9570 |
| (STD. DEV.) | | | | 0.4 | 2 | 1300 | 810 | 0.8 | 12 | 1800 | 830 |

---

[a] SCE = Secondary Chamber Exit; temperatures represent setpoints for condition indicated.

[b] Not reported.

[c] Standard conditions are 68 deg. F (20 deg. C) and 1 atm (101325 Pa).

The measured flowrate was between 7,760 and 10,200 dscfm at the secondary chamber exit, between 8,770 and 9,920 dscfm at the ESP inlet, and between 8,570 and 11,400 dscfm at the ESP outlet. Figure 4-6 compares these data. As can be seen in the figure, the flue gas flowrate measured at the ESP outlet is greater than that measured at either of the other two locations for all but one test run, and is highest for the start of campaign test runs. The flowrates measured at the secondary chamber exit and ESP inlet do not differ significantly between locations or test runs.

Flue gas moisture ranged from 9.6 to 16.4 percent by volume for all three locations, with the majority of the data between 10 and 13 percent by volume. Figure 4-7 compares the flue gas moisture measured at the three sampling locations. Except for Run 12 at the secondary chamber exit, the flue gas moisture does not vary significantly between locations or test runs. The high moisture measured for Run 12 may be due to sampling error as the ESP inlet and outlet measurements are similar for this test run.

Flue gas temperature ranged from 1410 to 1680 $^{o}$F at the secondary chamber exit, from 461 to 500 $^{o}$F at the ESP inlet and from 428 to 461 $^{o}$F at the ESP outlet. Figures 4-8 and 4-9 present temperature at the secondary chamber exit and ESP inlet and outlet, respectively. As is shown in Figure 4-8, the secondary chamber exit temperature was highest for the end of campaign and mid-range secondary temperature test runs. The temperature drop across the ESP, shown in Figure 4-9, was relatively constant between test runs, averaging about 40 $^{o}$F.

## DILUTION EFFECTS

The emissions data were adjusted to 7 percent $O_2$ to eliminate the effect of possible excess air dilution or inleakage between the flue gas sampling locations. The $O_2$ CEM data measured at the secondary chamber exit were used to adjust the secondary chamber exit emissions data. The emissions data collected at the ESP inlet and outlet were adjusted using the $O_2$ CEM data measured at the ESP outlet location. The following equation was used:

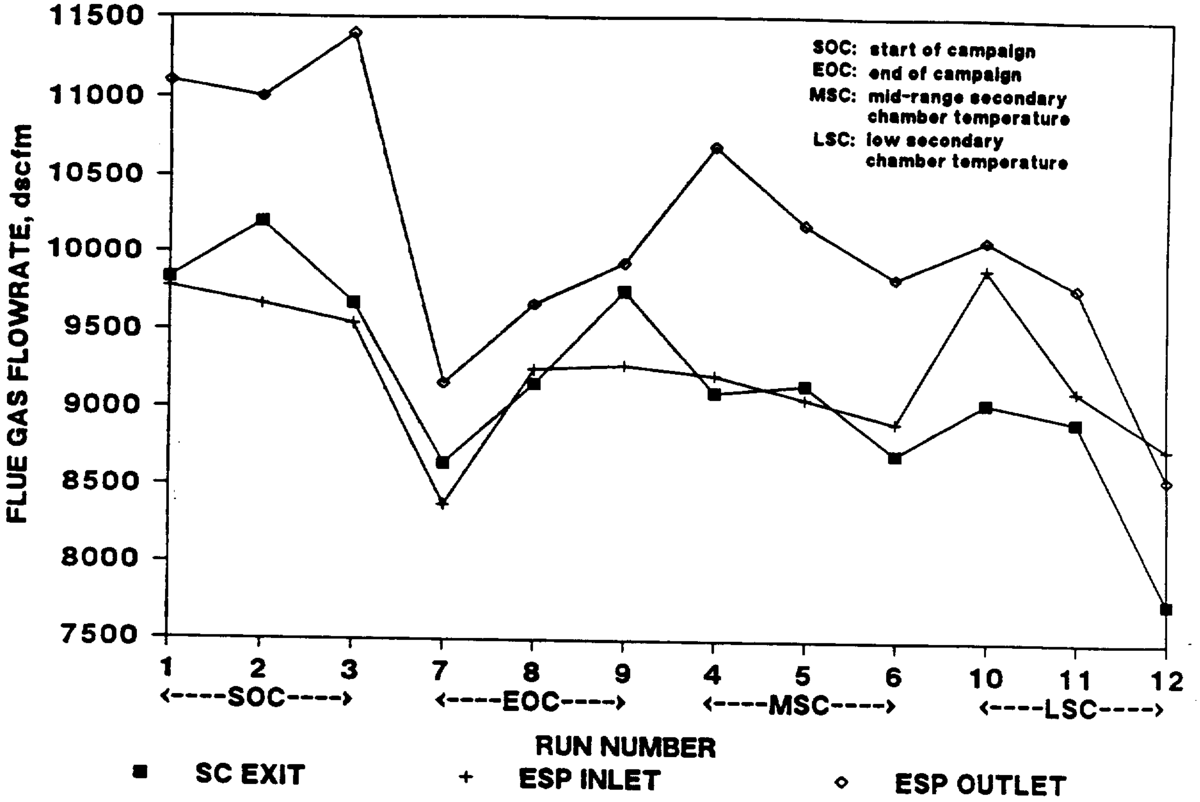


Figure 4-6. Flue Gas Flowrate (MM5) by Run Number

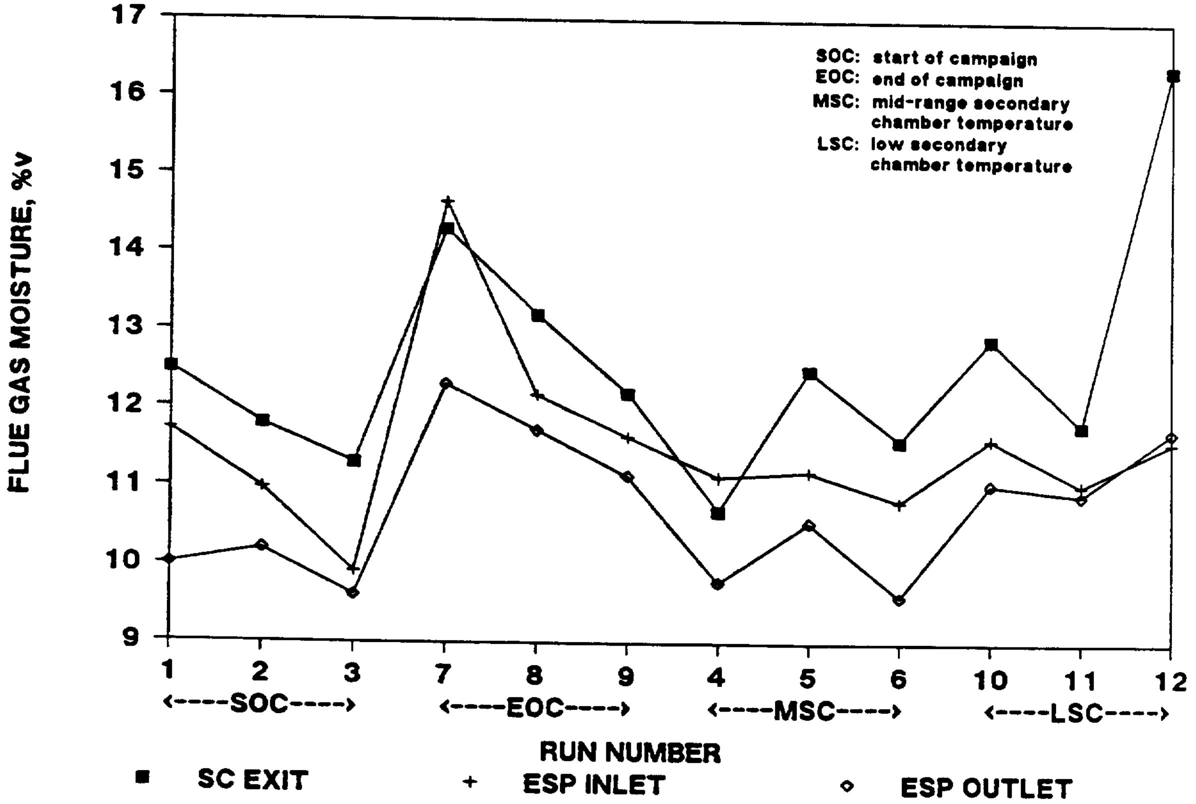


Figure 4-7. Flue Gas Moisture (MM5) by Run Number

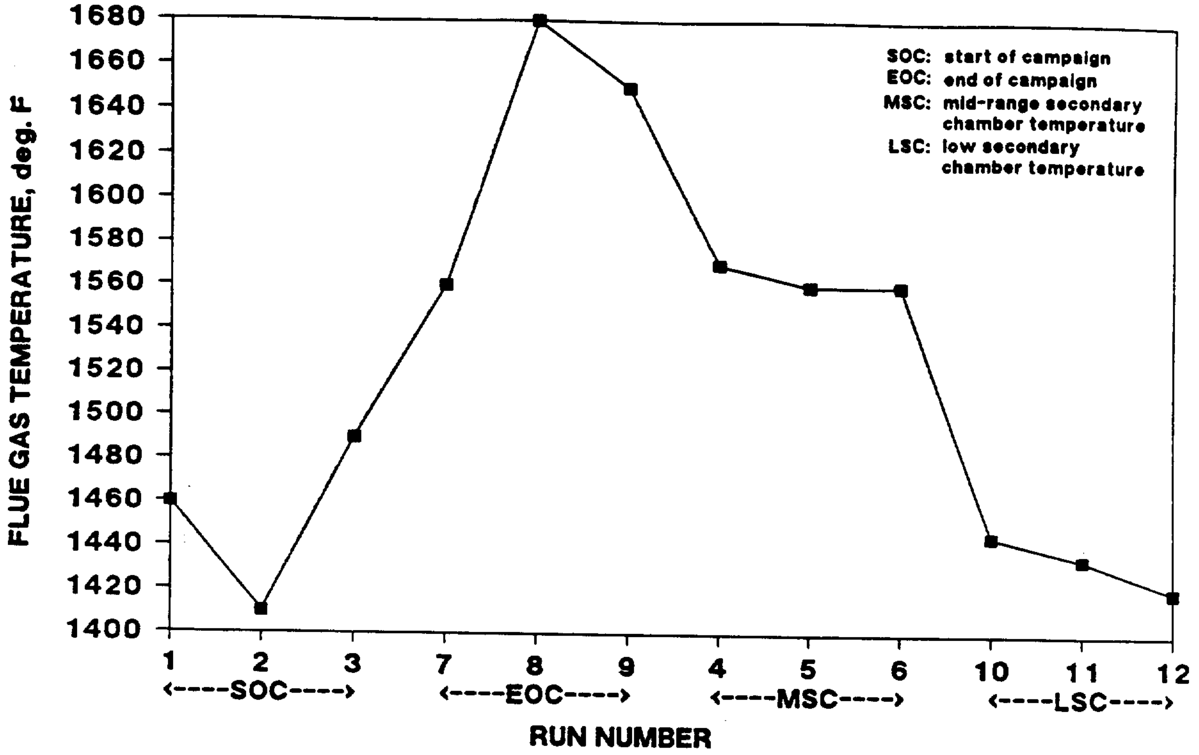


Figure 4-8. Flue Gas Temperature (MM5) Measured at the Secondary Chamber Exit by Run Number

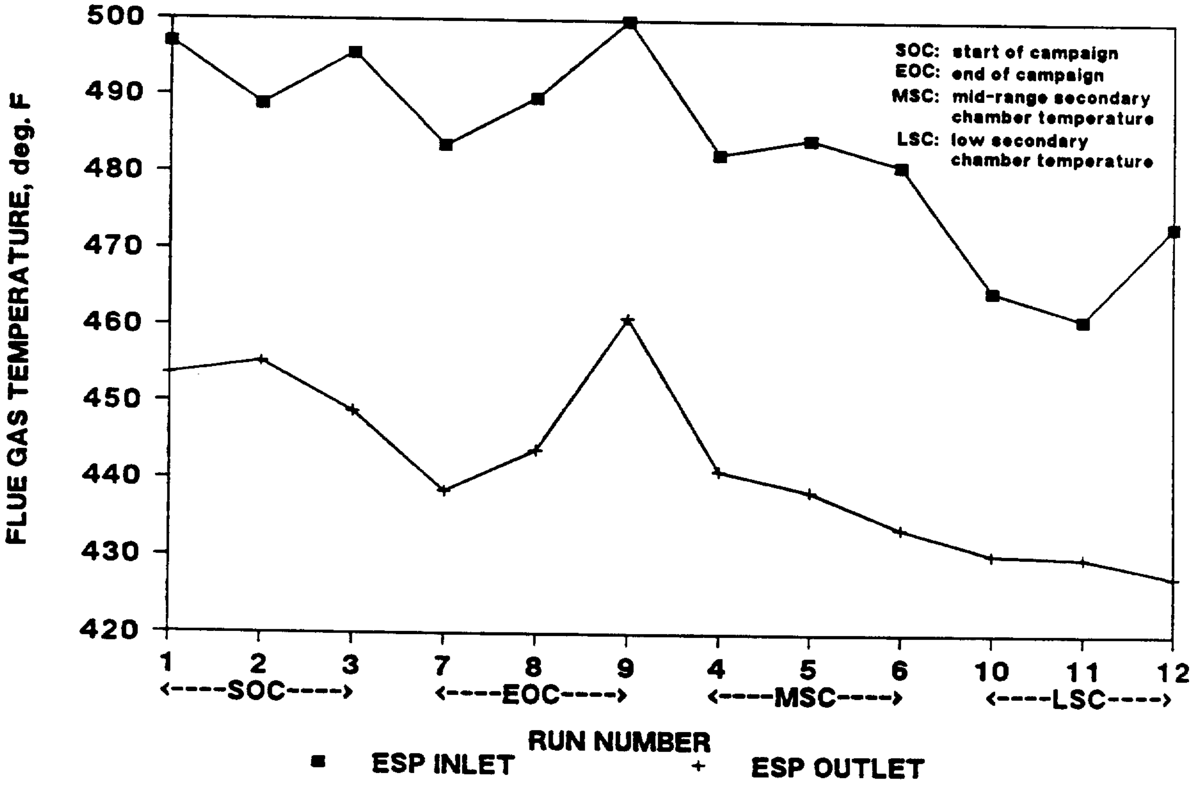


Figure 4-9. Flue Gas Temperature (MM5) Measured at the ESP Inlet and Outlet by Run Number

$$\text{Parameter Concentration @ 7\% } O_2 = \text{Parameter Concentration} \times \{(20.9-7.0)/(20.0-O_2)\}$$

where,

$O_2$ = actual $O_2$ concentration measured, percent by volume, dry basis.

The Run 1 $O_2$ concentration at the secondary chamber exit was invalidated due to equipment problems experienced during the test. For this run, the oxygen concentration was estimated from a best-fit linear regression of the ESP outlet $O_2$ CEM data.

Figure 4-10 compares $O_2$ measured at the secondary chamber exit and the ESP outlet. Assuming no measurement bias, it would be expected that the oxygen concentration would increase from the secondary chamber exit to the ESP outlet, due to the negative pressure on the system as a result of the induced draft fan downstream of the ESP. As is shown in the figure, the oxygen measured at the ESP outlet is consistently higher than the oxygen measured at the secondary chamber exit, as would be expected.

Figures 4-11 through 4-14 present CO and $CO_2$ concentrations unadjusted and adjusted to 7 percent $O_2$ at the secondary chamber exit and ESP outlet. As is shown in the figures, while the adjusted concentrations are larger in magnitude, the general pattern of the data does not change. Therefore, for the purposes of this analysis, either unadjusted or adjusted data may be used to make valid comparisons. The CEM, CDD and CDF data will be presented later in this section both unadjusted and adjusted to 7 percent $O_2$ to allow a comparison of these results to those from other facilities.

## FLUE GAS CDD AND CDF DATA

This section summarizes the flue gas CDD and CDF data collected at the Oswego facility. Tables 4-4, 4-5, and 4-6 present average uncontrolled (secondary chamber exit and ESP inlet) and controlled (ESP outlet) CDD and CDF concentrations. Concentrations are presented unadjusted and adjusted to

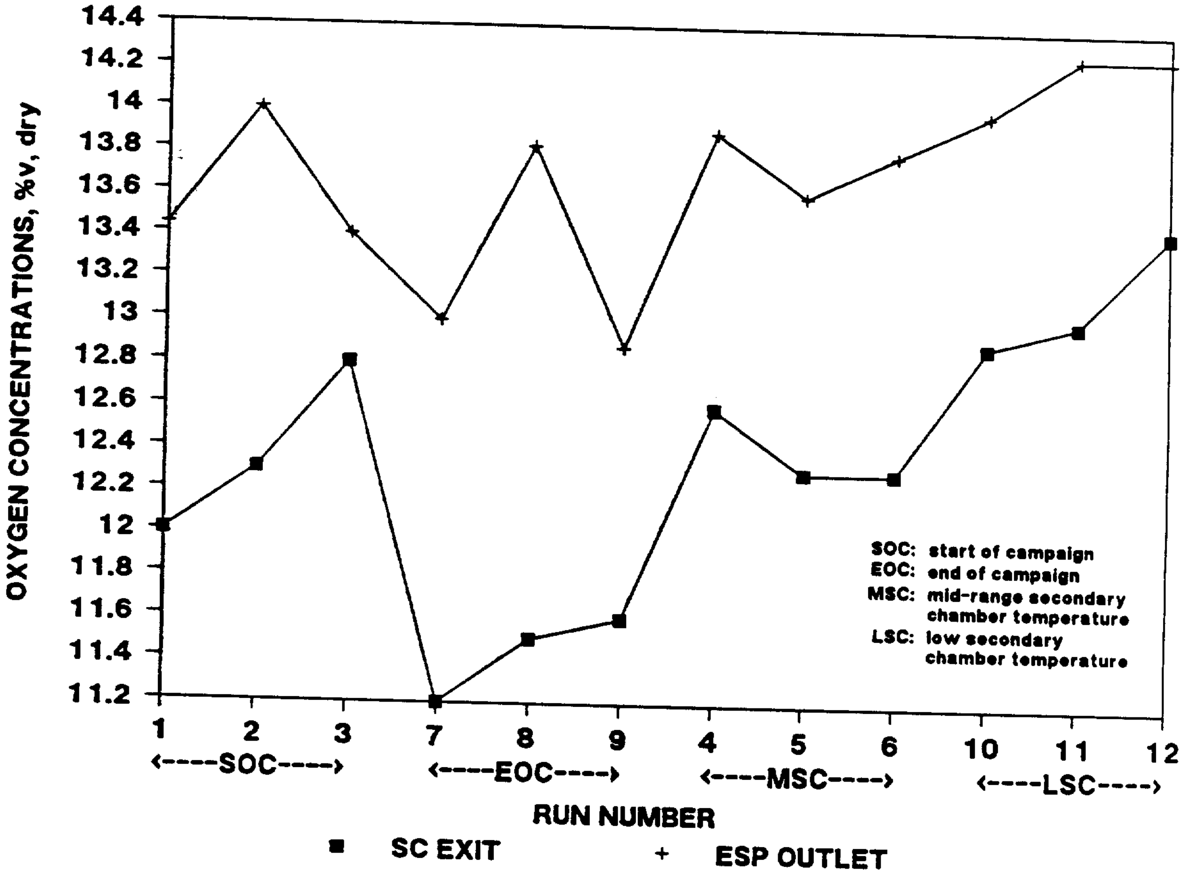


Figure 4-10. Oxygen Concentrations Measured at the Secondary Chamber Exit and ESP Outlet by Run Number

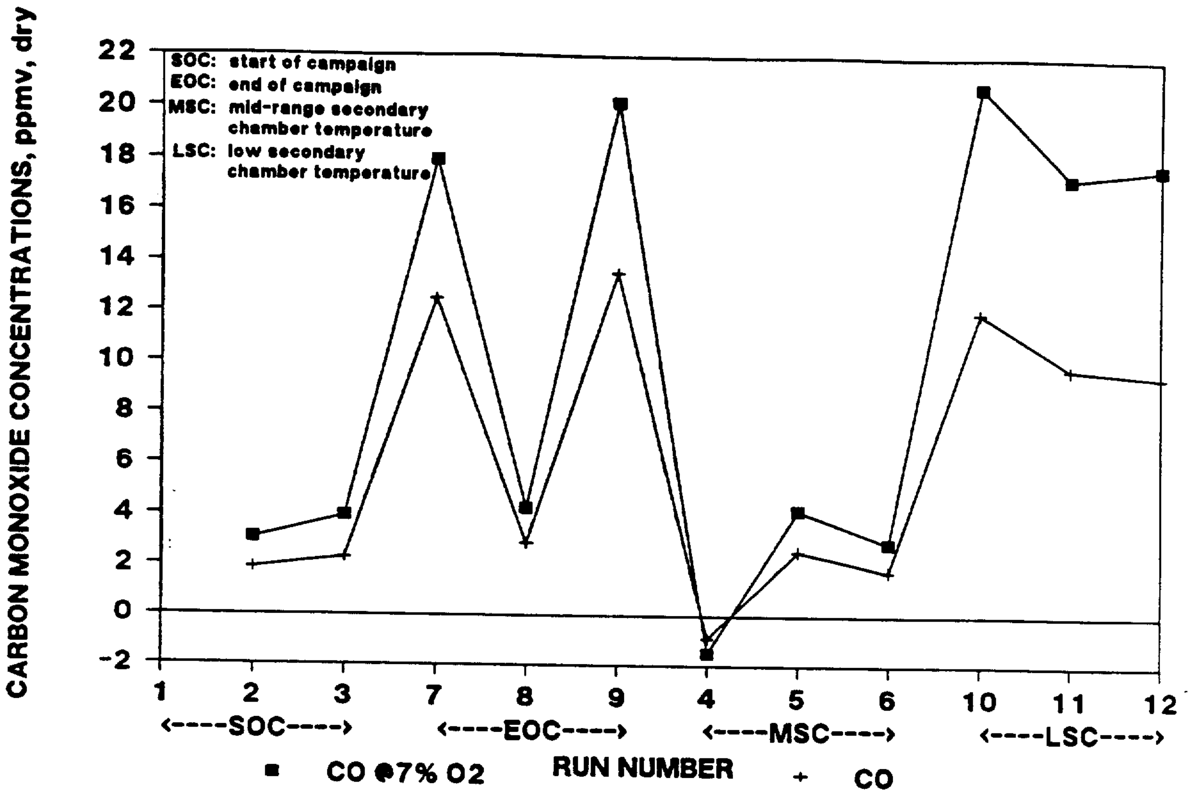


Figure 4-11. Unadjusted and Adjusted Carbon Monoxide Concentrations at the Secondary Chamber Exit by Run Number

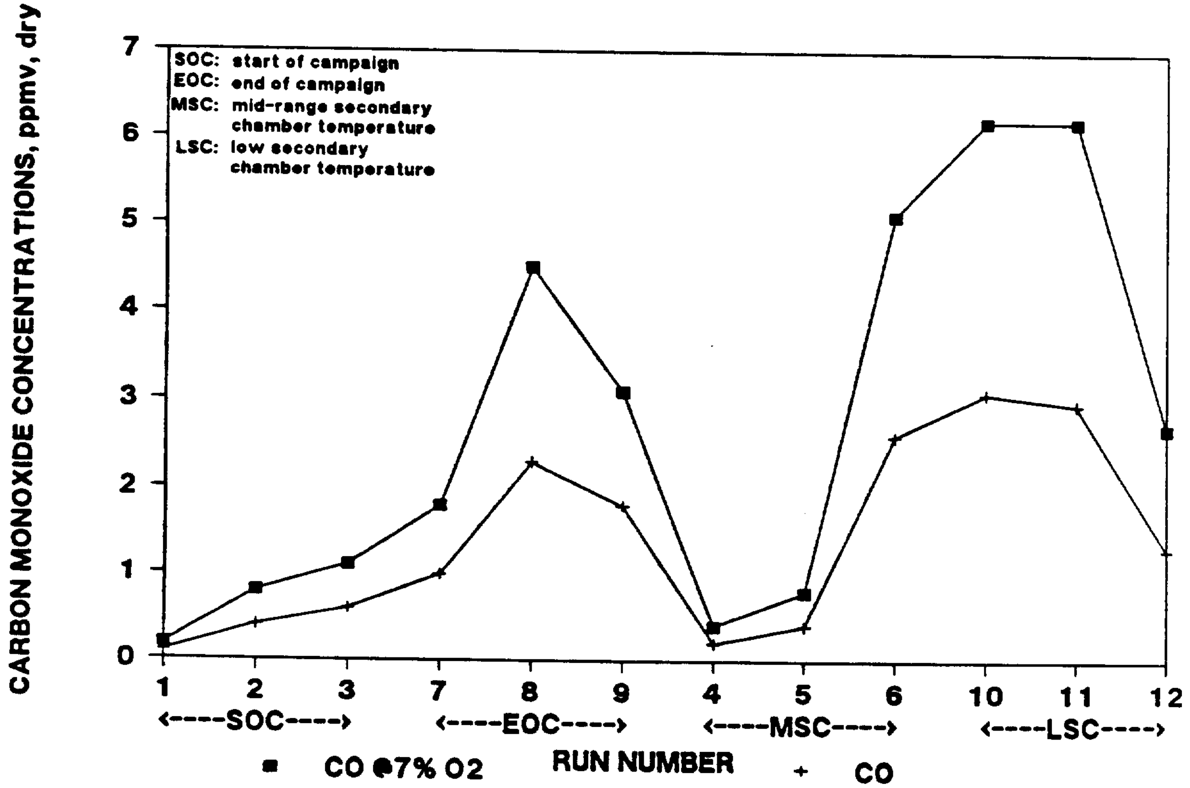


Figure 4-12. Unadjusted and Adjusted Carbon Monoxide Concentrations at the ESP Outlet by Run Number

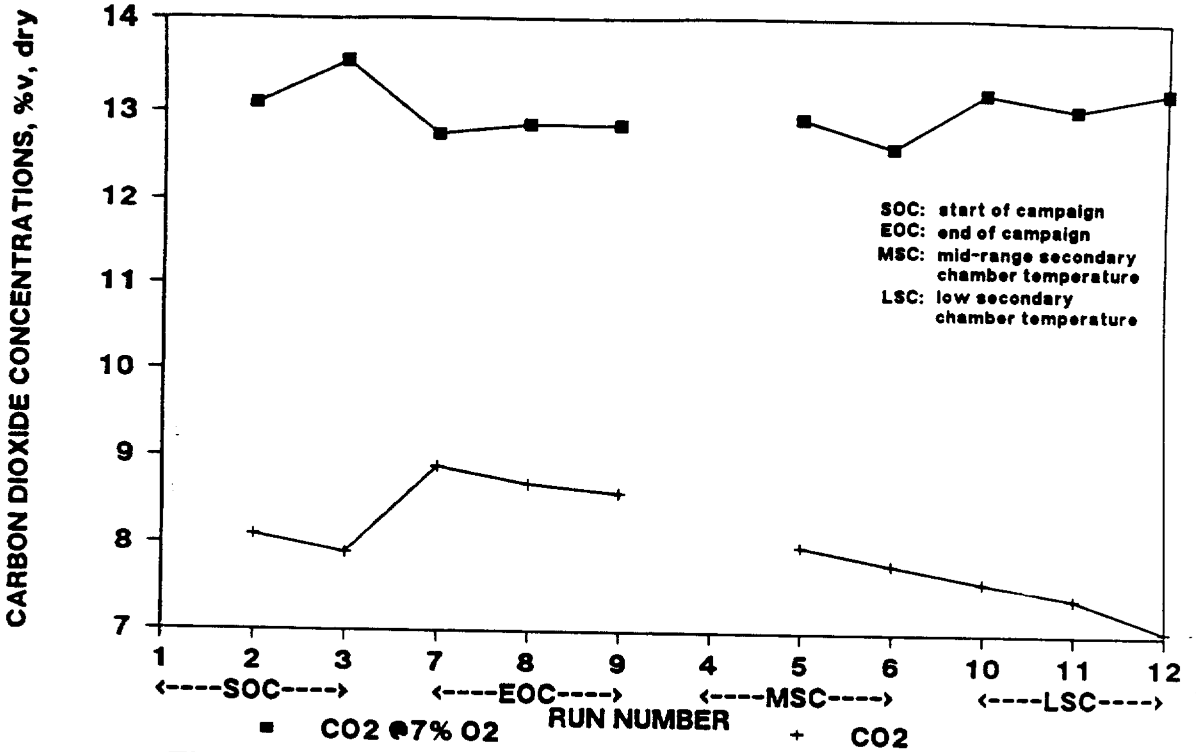


Figure 4-13. Unadjusted and Adjusted Carbon Dioxide Concentrations at the Secondary Chamber Exit by Run Number

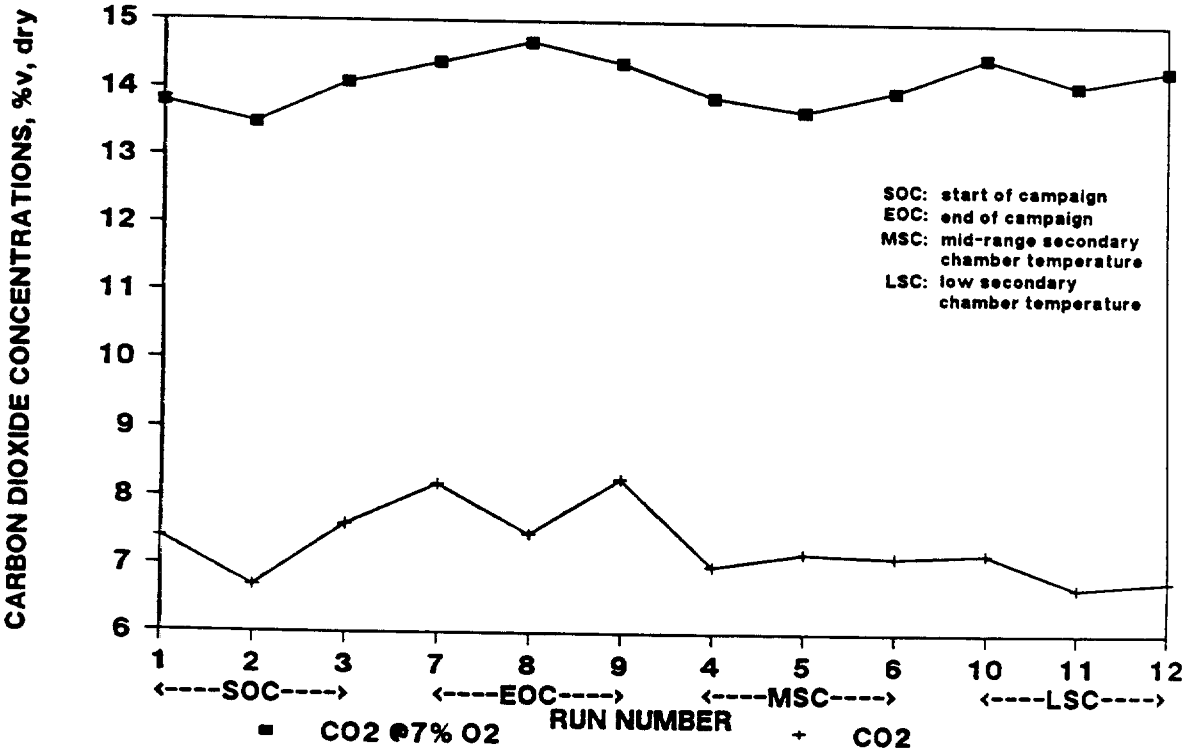


Figure 4-14. Unadjusted and Adjusted Carbon Dioxide Concentrations at the ESP Outlet by Run Number

Table 4-4

SUMMARY OF CDD AND CDF CONCENTRATIONS AT THE SECONDARY CHAMBER EXIT

| Run Number<br>Date | | 1<br>8/26/86 | | | 2<br>8/27/86 | | | 3<br>8/28/86 | | | 4<br>9/3/86 | | | 5<br>9/4/86 | | | 6<br>9/5/86 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Sampling Parameters**[a] | | | | | | | | | | | | | | | | | | |
| Volume gas sampled (dscf) | | 74.7 | | | 75.5 | | | 71.0 | | | 92.3 | | | 86.2 | | | 87.7 | |
| Stack gas flowrate (dscfm) | | 9840 | | | 10200 | | | 9680 | | | 9120 | | | 9170 | | | 8720 | |
| Stack temperature (deg. F) | | 1460 | | | 1410 | | | 1490 | | | 1570 | | | 1560 | | | 1560 | |
| Moisture (percent by volume) | | 12.5 | | | 11.8 | | | 11.3 | | | 10.7 | | | 12.5 | | | 11.6 | |
| Isokinetics (percent) | | 97.3 | | | 106.7 | | | 105.2 | | | 101.5 | | | 99.8 | | | 102.2 | |
| CO (ppm by volume)[b] | | | | | 1.9 | | | 2.3 | | | -0.9 | | | 2.6 | | | 1.8 | |
| $CO_2$ (percent by volume)[b] | | | | | 8.1 | | | 7.9 | | | | | | 8.0 | | | 7.8 | |
| $O_2$ (percent by volume)[b] | | 12.0[c] | | | 12.3 | | | 12.8 | | | 12.6 | | | 12.3 | | | 12.3 | |
| **Process Operations** | | | | | | | | | | | | | | | | | | |
| Steam load (lb/hr) | | 13100 | | | 12700 | | | 13000 | | | 12000 | | | 11600 | | | 11200 | |
| Secondary Chamber Temperature (deg. F) | | 1875 | | | 1851 | | | 1837 | | | 1752 | | | 1741 | | | 1738 | |
| | Front[d] Half | Back[d] Half | Total[d] Train | Front[d] Half | Back[d] Half | Total Train | Front[d] Half | Back[d] Half | Total Train | Front[d] Half | Back[d] Half | Total Train | Front[d] Half | Back[d] Half | Total Train | Front[d] Half | Back[d] Half | Total Train |
| **Dioxin Results**[e] | | | | | | | | | | | | | | | | | | |
| Total CDD (ng/dscm) | | | 18.4 | | | 2.9 | | | 9.5 | | | 3.2 | | | 17.7 | | | 4.3 |
| Total CDD (ng/dscm @ 7% $O_2$) | | | 28.7 | | | 4.7 | | | 16.2 | | | 5.3 | | | 28.7 | | | 6.9 |
| **Furan Results**[e] | | | | | | | | | | | | | | | | | | |
| Total CDF (ng/dscm) | | | 175.7 | | | 545.5 | | | 250.5 | | | 59.0 | | | 127.0 | | | 519.0 |
| Total CDF (ng/dscm @ 7% $O_2$) | | | 274.5 | | | 881.6 | | | 429.9 | | | 98.7 | | | 205.2 | | | 838.8 |
| **Dioxin and Furan Results**[e] | | | | | | | | | | | | | | | | | | |
| Total CDD and CDF (ng/dscm) | | | 194.1 | | | 548.4 | | | 259.9 | | | 62.1 | | | 144.7 | | | 523.3 |
| Total CDD and CDF (ng/dscm @ 7% $O_2$) | | | 303.2 | | | 886.3 | | | 446.1 | | | 104.0 | | | 233.9 | | | 845.7 |

[a] Standard conditions are 68 deg. F (20 deg. C) and 1 atm (101325 Pa).

[b] These values are averages of data (dry basis) taken over the sampling period from continuous emission monitors located at the secondary chamber exit.

[c] Estimated from best-fit linear regression of ESP outlet $O_2$ CEM data.

[d] Not reported.

[e] CDD and CDF concentrations are adjusted for internal standard recoveries.

Table 4-4

SUMMARY OF CDD AND CDF CONCENTRATIONS AT THE SECONDARY CHAMBER EXIT (Continued)

| Run Number<br>Date | 7<br>9/16/86 | | | 8<br>9/17/86 | | | 9<br>9/18/86 | | | 10<br>9/24/86 | | | 11<br>9/25/86 | | | 12<br>9/26/86 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Sampling Parameters[a] | | | | | | | | | | | | | | | | | | |
| Volume gas sampled (dscf) | | 91.1 | | | 93.5 | | | 93.8 | | | 91.3 | | | 88.1 | | | 79.4 | |
| Stack gas flowrate (dscfm) | | 8650 | | | 9170 | | | 9770 | | | 9060 | | | 8940 | | | 7760 | |
| Stack temperature (deg. F) | | 1560 | | | 1680 | | | 1650 | | | 1445 | | | 1435 | | | 1420 | |
| Moisture (percent by volume) | | 14.3 | | | 13.2 | | | 12.2 | | | 12.9 | | | 11.8 | | | 16.4 | |
| Isokinetics (percent) | | 109.0 | | | 105.6 | | | 100.6 | | | 101.0 | | | 102.6 | | | 106.6 | |
| CO (ppm by volume)[b] | | 12.5 | | | 2.9 | | | 13.5 | | | 12.0 | | | 9.8 | | | 9.5 | |
| $CO_2$ (percent by volume)[b] | | 8.9 | | | 8.7 | | | 8.6 | | | 7.6 | | | 7.4 | | | 7.1 | |
| $O_2$ (percent by volume)[b] | | 11.2 | | | 11.5 | | | 11.6 | | | 12.9 | | | 13.0 | | | 13.4 | |
| Process Operations | | | | | | | | | | | | | | | | | | |
| Steam load (lb/hr) | | 12000 | | | 12600 | | | 13100 | | | 10900 | | | 10500 | | | 9300 | |
| Secondary Chamber Temperature (deg. F) | | 1817 | | | 1822 | | | 1834 | | | 1634 | | | 1627 | | | 1617 | |
| | Front[d] Half | Back[d] Half | Total[d] Train | Front[d] Half | Back[d] Half | Total Train | Front[d] Half | Back[d] Half | Total Train | Front[d] Half | Back[d] Half | Total Train | Front[d] Half | Back[d] Half | Total Train | Front[d] Half | Back[d] Half | Total Train |
| Dioxin Results[e] | | | | | | | | | | | | | | | | | | |
| Total CDD (ng/dscm) | 54.7 | 0.0 | 54.7 | 24.1 | 3.1 | 27.2 | | | 27.2 | | | 63.4 | | | 38.5 | | | 40.9 |
| Total CDD (ng/dscm @ 7% $O_2$) | 78.3 | 0.0 | 78.3 | 35.6 | 4.6 | 40.2 | | | 40.6 | | | 110.1 | | | 67.7 | | | 75.8 |
| Furan Results[e] | | | | | | | | | | | | | | | | | | |
| Total CDF (ng/dscm) | 395.5 | 5.1 | 400.5 | 82.9 | 71.6 | 154.5 | | | 280.5 | | | 171.1 | | | 224.1 | | | 125.0 |
| Total CDF (ng/dscm @ 7% $O_2$) | 566.7 | 7.3 | 574.0 | 122.5 | 105.9 | 228.5 | | | 419.3 | | | 297.2 | | | 394.4 | | | 231.6 |
| Dioxin and Furan Results[e] | | | | | | | | | | | | | | | | | | |
| Total CDD and CDF (ng/dscm) | 450.1 | 5.1 | 455.2 | 106.9 | 74.8 | 181.7 | | | 307.7 | | | 234.4 | | | 262.6 | | | 165.9 |
| Total CDD and CDF (ng/dscm @ 7% $O_2$) | 645.0 | 7.3 | 652.3 | 158.1 | 110.6 | 268.7 | | | 459.9 | | | 407.3 | | | 462.1 | | | 307.4 |

[a] Standard conditions are 68 deg. F (20 deg. C) and 1 atm (101325 Pa).

[b] These values are averages of data (dry basis) taken over the sampling period from continuous emission monitors located at the secondary chamber exit.

[c] Estimated from best-fit linear regression of ESP outlet $O_2$ CEM data.

[d] Not reported.

[e] CDD and CDF concentrations are adjusted for internal standard recoveries.

Table 4-5

SUMMARY OF CDD AND CDF CONCENTRATIONS AT THE ESP INLET

| Run Number<br>Date | 1<br>8/26/86 | | | 2<br>8/27/86 | | | 3<br>8/28/86 | | | 4<br>9/3/86 | | | 5<br>9/4/86 | | | 6<br>9/5/86 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Sampling Parameters**[a] | | | | | | | | | | | | | | | | | | |
| Volume gas sampled (dscf) | 99.8 | | | 93.9 | | | 95.7 | | | 89.2 | | | 92.1 | | | 90.5 | | |
| Stack gas flowrate (dscfm) | 9780 | | | 9670 | | | 9550 | | | 9230 | | | 9080 | | | 8930 | | |
| Stack temperature (deg. F) | 497 | | | 489 | | | 496 | | | 483 | | | 485 | | | 481 | | |
| Moisture (percent by volume) | 11.7 | | | 11.0 | | | 9.9 | | | 11.1 | | | 11.2 | | | 10.8 | | |
| Isokinetics (percent) | 103.9 | | | 98.9 | | | 102.1 | | | 98.5 | | | 103.3 | | | 103.2 | | |
| CO (ppm by volume)[b] | 0.1 | | | 0.4 | | | 0.6 | | | 0.2 | | | 0.4 | | | 2.6 | | |
| $CO_2$ (percent by volume)[b] | 7.4 | | | 6.7 | | | 7.6 | | | 7.0 | | | 7.2 | | | 7.2 | | |
| $O_2$ (percent by volume)[b] | 13.4 | | | 14.0 | | | 13.4 | | | 13.9 | | | 13.6 | | | 13.8 | | |
| **Process Operations** | | | | | | | | | | | | | | | | | | |
| Steam load (lb/hr) | 13100 | | | 12700 | | | 13000 | | | 12000 | | | 11600 | | | 11200 | | |
| Secondary Chamber Temperature (deg. F) | 1875 | | | 1851 | | | 1837 | | | 1752 | | | 1741 | | | 1738 | | |
| | Front Half | Back Half | Total Train | Front Half | Back Half | Total Train | Front Half | Back Half | Total Train | Front Half | Back Half | Total Train | Front Half | Back Half | Total Train | Front Half | Back Half | Total Train |
| **Dioxin Results**[c] | | | | | | | | | | | | | | | | | | |
| Total CDD (ng/dscm) | 7.1 | 24.0 | 31.1 | 21.6 | 9.6 | 31.2 | 5.9 | 10.9 | 16.8 | 4.2 | 29.1 | 33.3 | 12.9 | 15.1 | 28.0 | 6.6 | 14.2 | 20.8 |
| Total CDD (ng/dscm @ 7% $O_2$) | 13.2 | 44.5 | 57.7 | 43.5 | 19.4 | 62.8 | 10.9 | 20.2 | 31.1 | 8.3 | 57.8 | 66.1 | 24.6 | 28.7 | 53.3 | 13.0 | 27.7 | 40.7 |
| **Furan Results**[c] | | | | | | | | | | | | | | | | | | |
| Total CDF (ng/dscm) | 10.6 | 73.0 | 83.6 | 54.6 | 29.3 | 83.9 | 8.1 | 39.3 | 47.4 | 16.3 | 85.1 | 101.4 | 18.8 | 67.6 | 86.4 | 18.4 | 65.3 | 83.8 |
| Total CDF (ng/dscm @ 7% $O_2$) | 19.7 | 135.4 | 155.0 | 109.9 | 59.1 | 169.0 | 15.0 | 72.8 | 87.9 | 32.4 | 169.0 | 201.4 | 35.9 | 128.7 | 164.6 | 36.1 | 127.9 | 164.0 |
| **Dioxin and Furan Results**[c] | | | | | | | | | | | | | | | | | | |
| Total CDD and CDF (ng/dscm) | 17.7 | 97.0 | 114.7 | 76.1 | 38.9 | 115.1 | 14.0 | 50.2 | 64.2 | 20.5 | 114.2 | 134.7 | 31.8 | 82.7 | 114.4 | 25.1 | 79.5 | 104.5 |
| Total CDD and CDF (ng/dscm @ 7% $O_2$) | 32.9 | 179.8 | 212.7 | 153.4 | 78.4 | 231.8 | 26.0 | 93.0 | 119.0 | 40.7 | 226.8 | 267.5 | 60.5 | 157.4 | 217.9 | 49.0 | 155.6 | 204.7 |

[a] Standard conditions are 68 deg. F (20 deg. C) and 1 atm (101325 Pa).

[b] These values are averages of data (dry basis) taken over the sampling period from continuous emission monitors located at the ESP outlet.

[c] CDD and CDF concentrations are adjusted for internal standard recoveries.

[d] Not reported.

Table 4-5

SUMMARY OF CDD AND CDF CONCENTRATIONS AT THE ESP INLET (Continued)

| Run Number<br>Date | 7<br>9/16/86 | | | 8<br>9/17/86 | | | 9<br>9/18/86 | | | 10<br>9/24/86 | | | 11<br>9/25/86 | | | 12<br>9/26/86 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Sampling Parameters**[a] | | | | | | | | | | | | | | | | | | |
| Volume gas sampled (dscf) | 87.1 | | | 93.9 | | | 94.2 | | | 98.1 | | | 90.2 | | | 88.8 | | |
| Stack gas flowrate (dscfm) | 8380 | | | 9260 | | | 9290 | | | 9920 | | | 9140 | | | 8770 | | |
| Stack temperature (deg. F) | 484 | | | 490 | | | 500 | | | 465 | | | 461 | | | 474 | | |
| Moisture (percent by volume) | 14.6 | | | 12.2 | | | 11.6 | | | 11.6 | | | 11.0 | | | 11.6 | | |
| Isokinetics (percent) | 105.9 | | | 103.3 | | | 103.3 | | | 101.2 | | | 100.5 | | | 103.3 | | |
| CO (ppm by volume)[b] | 1.0 | | | 2.3 | | | 1.8 | | | 3.1 | | | 3.0 | | | 1.3 | | |
| $CO_2$ (percent by volume)[b] | 8.2 | | | 7.5 | | | 8.3 | | | 7.2 | | | 6.7 | | | 6.8 | | |
| $O_2$ (percent by volume)[b] | 13.0 | | | 13.8 | | | 12.9 | | | 14.0 | | | 14.3 | | | 14.3 | | |
| **Process Operations** | | | | | | | | | | | | | | | | | | |
| Steam load (lb/hr) | 12000 | | | 12600 | | | 13100 | | | 10900 | | | 10500 | | | 9300 | | |
| Secondary Chamber Temperature (deg. F) | 1817 | | | 1822 | | | 1834 | | | 1634 | | | 1627 | | | 1617 | | |
| | Front Half | Back Half | Total Train | Front Half | Back Half | Total Train | Front[d] Half | Back Half | Total Train | Front Half | Back Half | Total Train | Front Half | Back Half | Total Train | Front Half | Back Half | Total Train |
| **Dioxin Results**[e] | | | | | | | | | | | | | | | | | | |
| Total CDD (ng/dscm) | 25.5 | 13.6 | 39.1 | 40.5 | 18.4 | 58.9 | | 42.2 | 42.2 | 97.6 | 76.0 | 173.6 | 42.6 | 78.5 | 121.1 | 61.1 | 64.6 | 125.7 |
| Total CDD (ng/dscm @ 7% $O_2$) | 44.9 | 24.0 | 68.8 | 79.3 | 36.0 | 115.3 | | 73.3 | 73.3 | 196.7 | 153.1 | 349.8 | 89.8 | 165.3 | 255.1 | 128.8 | 136.0 | 264.8 |
| **Furan Results**[e] | | | | | | | | | | | | | | | | | | |
| Total CDF (ng/dscm) | 76.0 | 58.6 | 134.5 | 152.9 | 88.3 | 241.2 | | 140.1 | 140.1 | 150.0 | 145.9 | 295.9 | 70.4 | 133.1 | 203.5 | 84.6 | 108.9 | 193.5 |
| Total CDF (ng/dscm @ 7% $O_2$) | 133.7 | 103.0 | 236.7 | 299.3 | 172.9 | 472.2 | | 243.4 | 243.4 | 302.2 | 294.0 | 596.2 | 148.2 | 280.3 | 428.5 | 178.1 | 229.4 | 407.6 |
| **Dioxin and Furan Results**[e] | | | | | | | | | | | | | | | | | | |
| Total CDD and CDF (ng/dscm) | 101.5 | 72.2 | 173.7 | 193.4 | 106.7 | 300.1 | | 182.3 | 182.3 | 247.6 | 221.9 | 469.6 | 113.0 | 211.6 | 324.6 | 145.7 | 173.5 | 319.2 |
| Total CDD and CDF (ng/dscm @ 7% $O_2$) | 178.6 | 127.0 | 305.6 | 378.6 | 208.9 | 587.5 | | 316.7 | 316.7 | 498.9 | 447.1 | 945.9 | 238.0 | 445.6 | 683.6 | 306.9 | 365.5 | 672.4 |

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[a] Standard conditions are 68 deg. F (20 deg. C) and 1 atm (101325 Pa).

[b] These values are averages of data (dry basis) taken over the sampling period from continuous emission monitors located at the ESP outlet.

[c] CDD and CDF concentrations are adjusted for internal standard recoveries.

[d] Not reported; total train results assume no CDD or CDF detected in front half of sampling train.

## Table 4-6

## SUMMARY OF CDD AND CDF CONCENTRATIONS AT THE ESP OUTLET

| Run Number<br>Date | 1<br>8/26/86 | | | 2<br>8/27/86 | | | 3<br>8/28/86 | | | 4<br>9/3/86 | | | 5<br>9/4/86 | | | 6<br>9/5/86 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Sampling Parameters**[a] | | | | | | | | | | | | | | | | | | |
| Volume gas sampled (dscf) | 136.7 | | | 137.0 | | | 139.3 | | | 132.6 | | | 126.4 | | | 118.9 | | |
| Stack gas flowrate (dscfm) | 11100 | | | 11000 | | | 11400 | | | 10700 | | | 10200 | | | 9860 | | |
| Stack temperature (deg. F) | 454 | | | 455 | | | 449 | | | 441 | | | 439 | | | 434 | | |
| Moisture (percent by volume) | 10.0 | | | 10.2 | | | 9.6 | | | 9.8 | | | 10.6 | | | 9.6 | | |
| Isokinetics (percent) | 98.7 | | | 99.3 | | | 98.1 | | | 98.8 | | | 98.9 | | | 96.6 | | |
| CO (ppm by volume)[b] | 0.1 | | | 0.4 | | | 0.6 | | | 0.2 | | | 0.4 | | | 2.6 | | |
| $CO_2$ (percent by volume)[b] | 7.4 | | | 6.7 | | | 7.6 | | | 7.0 | | | 7.2 | | | 7.2 | | |
| $O_2$ (percent by volume)[b] | 13.4 | | | 14.0 | | | 13.4 | | | 13.9 | | | 13.6 | | | 13.8 | | |
| **Process Operations** | | | | | | | | | | | | | | | | | | |
| Steam load (lb/hr) | 13100 | | | 12700 | | | 13000 | | | 12000 | | | 11600 | | | 11200 | | |
| Secondary Chamber Temperature (deg. F) | 1875 | | | 1851 | | | 1837 | | | 1752 | | | 1741 | | | 1738 | | |
| | Front Half | Back Half | Total Train | Front Half | Back Half | Total Train | Front Half | Back Half | Total Train | Front Half | Back Half | Total Train | Front Half | Back Half | Total Train | Front Half | Back Half | Total Train |
| **Dioxin Results**[c] | | | | | | | | | | | | | | | | | | |
| Total CDD (ng/dscm) | 2.1 | 77.9 | 80.0 | 6.8 | 63.7 | 70.5 | 7.3 | 65.1 | 72.4 | 2.4 | 70.2 | 72.6 | 4.2 | 50.3 | 54.4 | 3.5 | 43.7 | 47.2 |
| Total CDD (ng/dscm @ 7% $O_2$) | 3.9 | 144.4 | 148.3 | 13.7 | 128.3 | 142.1 | 13.6 | 120.6 | 134.2 | 4.8 | 139.4 | 144.1 | 7.9 | 95.7 | 103.6 | 6.8 | 85.5 | 92.3 |
| **Furan Results**[c] | | | | | | | | | | | | | | | | | | |
| Total CDF (ng/dscm) | 0.4 | 129.3 | 129.7 | 3.9 | 119.3 | 123.2 | 4.5 | 116.3 | 120.9 | 0.5 | 124.8 | 125.3 | 1.1 | 101.5 | 102.7 | 0.7 | 134.1 | 134.8 |
| Total CDF (ng/dscm @ 7% $O_2$) | 0.7 | 239.7 | 240.4 | 7.9 | 240.3 | 248.2 | 8.4 | 215.6 | 224.1 | 1.0 | 247.8 | 248.8 | 2.1 | 193.3 | 195.5 | 1.3 | 262.6 | 263.9 |
| **Dioxin and Furan Results**[c] | | | | | | | | | | | | | | | | | | |
| Total CDD and CDF (ng/dscm) | 2.5 | 207.2 | 209.7 | 10.7 | 183.0 | 193.7 | 11.9 | 181.4 | 193.3 | 2.9 | 195.0 | 197.9 | 5.3 | 151.8 | 157.1 | 4.1 | 177.8 | 181.9 |
| Total CDD and CDF (ng/dscm @ 7% $O_2$) | 4.6 | 384.1 | 388.7 | 21.6 | 368.7 | 390.3 | 22.0 | 336.2 | 358.2 | 5.8 | 387.2 | 392.9 | 10.0 | 289.0 | 299.1 | 8.1 | 348.1 | 356.2 |

[a] Standard conditions are 68 deg. F (20 deg. C) and 1 atm (101325 Pa).

[b] These values are averages of data (dry basis) taken over the sampling period from continuous emission monitors located at the ESP outlet.

[c] CDD and CDF concentrations are adjusted for internal standard recoveries.

## Table 4-6

## SUMMARY OF CDD AND CDF CONCENTRATIONS AT THE ESP OUTLET (Continued)

| Run Number<br>Date | | 7<br>9/16/86 | | | 8<br>9/17/86 | | | 9<br>9/18/86 | | | 10<br>9/24/86 | | | 11<br>9/25/86 | | | 12<br>9/26/86 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Sampling Parameters**[a] | | | | | | | | | | | | | | | | | | |
| Volume gas sampled (dscf) | | 115.2 | | | 117.0 | | | 124.5 | | | 121.7 | | | 116.4 | | | 104.9 | |
| Stack gas flowrate (dscfm) | | 9170 | | | 9680 | | | 9950 | | | 10100 | | | 9800 | | | 8570 | |
| Stack temperature (deg. F) | | 438 | | | 444 | | | 461 | | | 430 | | | 430 | | | 428 | |
| Moisture (percent by volume) | | 12.3 | | | 11.7 | | | 11.2 | | | 11.1 | | | 10.9 | | | 11.7 | |
| Isokinetics (percent) | | 100.5 | | | 96.7 | | | 100.1 | | | 96.5 | | | 95.0 | | | 98.0 | |
| CO (ppm by volume)[b] | | 1.0 | | | 2.3 | | | 1.8 | | | 3.1 | | | 3.0 | | | 1.3 | |
| $CO_2$ (percent by volume)[b] | | 8.2 | | | 7.5 | | | 8.3 | | | 7.2 | | | 6.7 | | | 6.8 | |
| $O_2$ (percent by volume)[b] | | 13.0 | | | 13.8 | | | 12.9 | | | 14.0 | | | 14.3 | | | 14.3 | |
| **Process Operations** | | | | | | | | | | | | | | | | | | |
| Steam load (lb/hr) | | 12000 | | | 12600 | | | 13100 | | | 10900 | | | 10500 | | | 9300 | |
| Secondary Chamber Temperature (deg. F) | | 1817 | | | 1822 | | | 1834 | | | 1634 | | | 1627 | | | 1617 | |
| | Front Half | Back Half | Total Train | Front[d] Half | Back Half | Total Train | Front Half | Back Half | Total Train | Front Half | Back Half | Total Train | Front Half | Back Half | Total Train | Front Half | Back Half | Total Train |
| **Dioxin Results**[c] | | | | | | | | | | | | | | | | | | |
| Total CDD (ng/dscm) | 2.6 | 78.2 | 80.8 | | 41.8 | 41.8 | 1.8 | 122.5 | 124.3 | 7.8 | 211.1 | 218.9 | 4.6 | 166.0 | 170.6 | 1.9 | 145.7 | 147.6 |
| Total CDD (ng/dscm @ 7% $O_2$) | 4.5 | 137.6 | 142.1 | | 81.9 | 81.9 | 3.1 | 212.9 | 216.0 | 15.8 | 425.3 | 441.1 | 9.8 | 349.5 | 359.3 | 3.9 | 306.9 | 310.9 |
| **Furan Results**[c] | | | | | | | | | | | | | | | | | | |
| Total CDF (ng/dscm) | 0.3 | 155.8 | 156.2 | | 119.3 | 119.3 | 0.4 | 258.9 | 259.3 | 4.0 | 275.6 | 279.6 | 1.9 | 231.6 | 233.5 | 0.3 | 180.9 | 181.2 |
| Total CDF (ng/dscm @ 7% $O_2$) | 0.6 | 274.2 | 274.8 | | 233.5 | 233.5 | 0.7 | 449.8 | 450.6 | 8.0 | 555.2 | 563.3 | 4.1 | 487.7 | 491.8 | 0.7 | 381.0 | 381.7 |
| **Dioxin and Furan Results**[c] | | | | | | | | | | | | | | | | | | |
| Total CDD and CDF (ng/dscm) | 2.9 | 234.0 | 237.0 | | 161.1 | 161.1 | 2.2 | 381.4 | 383.6 | 11.8 | 486.7 | 498.6 | 6.6 | 397.5 | 404.1 | 2.2 | 326.6 | 328.8 |
| Total CDD and CDF (ng/dscm @ 7% $O_2$) | 5.1 | 411.8 | 416.9 | | 315.4 | 315.4 | 3.8 | 662.7 | 666.5 | 23.8 | 980.5 | 1004.3 | 13.9 | 837.2 | 851.1 | 4.6 | 687.9 | 692.5 |

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[a] Standard conditions are 68 deg. F (20 deg. C) and 1 atm (101325 Pa).

[b] These values are averages of data (dry basis) taken over the sampling period from continuous emission monitors located at the ESP outlet.

[c] CDD and CDF concentrations are adjusted for internal standard recoveries.

[d] Not reported; total train results assume no CDD or CDF detected in front half of sampling train.

a reference oxygen level of 7 percent. Additional supporting data, including sample gas volume, flue gas flowrate, flue gas temperature, flue gas moisture, percent isokinetics, CO, $CO_2$, $O_2$, steam load, and average secondary chamber temperature, are also presented. Homologue-specific CDD and CDF data are included as Appendix G.

As is shown in the tables, total CDD concentrations vary between 4.7 and 110.1 ng/dscm at 7 percent $O_2$ at the secondary chamber exit, between 31.1 and 349.8 ng/dscm at 7 percent $O_2$ at the ESP inlet, and between 81.9 and 441.1 ng/dscm at 7 percent $O_2$ at the ESP outlet. Total CDF concentrations range from 98.7 to 881.6 ng/dscm at 7 percent $O_2$ at the secondary chamber exit, from 87.9 to 596.2 ng/dscm at 7 percent $O_2$ at the ESP inlet, and from 195.5 to 563.3 ng/dscm at 7 percent $O_2$ at the ESP outlet.

Figures 4-15 and 4-16 present total CDD and CDF concentrations, respectively, for the three sampling locations by run number. As is shown in Figure 4-15, except for Runs 7 and 8 (end of campaign test runs), total CDD concentrations increase between the secondary chamber exit and ESP inlet, and again between the ESP inlet and ESP outlet; the concentrations are highest for the low secondary chamber temperature test series. As can be seen from Figure 4-16, for Runs 1, 2, 3, 7, 9, 5, and 6, total CDF concentrations decrease between the secondary chamber and ESP inlet and increase between the ESP inlet and outlet.

## FLUE GAS CDD AND CDF PRECURSOR DATA

Tables 4-7, 4-8, and 4-9 list the flue gas precursor data measured at the secondary chamber exit, ESP inlet, and ESP outlet, respectively. Since the majority of the target precursors were not detected, the chlorobenzene, chlorophenol, and polyaromatic hydrocarbon (PAH) isomers, respectfully, were summed. Figures 4-17, 4-18, and 4-19 show total chlorobenzenes, total chlorophenols, and total PAHs, respectively, by run number. As is shown in Figure 4-17, the chlorobenzene concentrations are fairly consistent between locations, but vary significantly between test runs; the concentrations are lowest for the mid-range secondary chamber temperature test series.

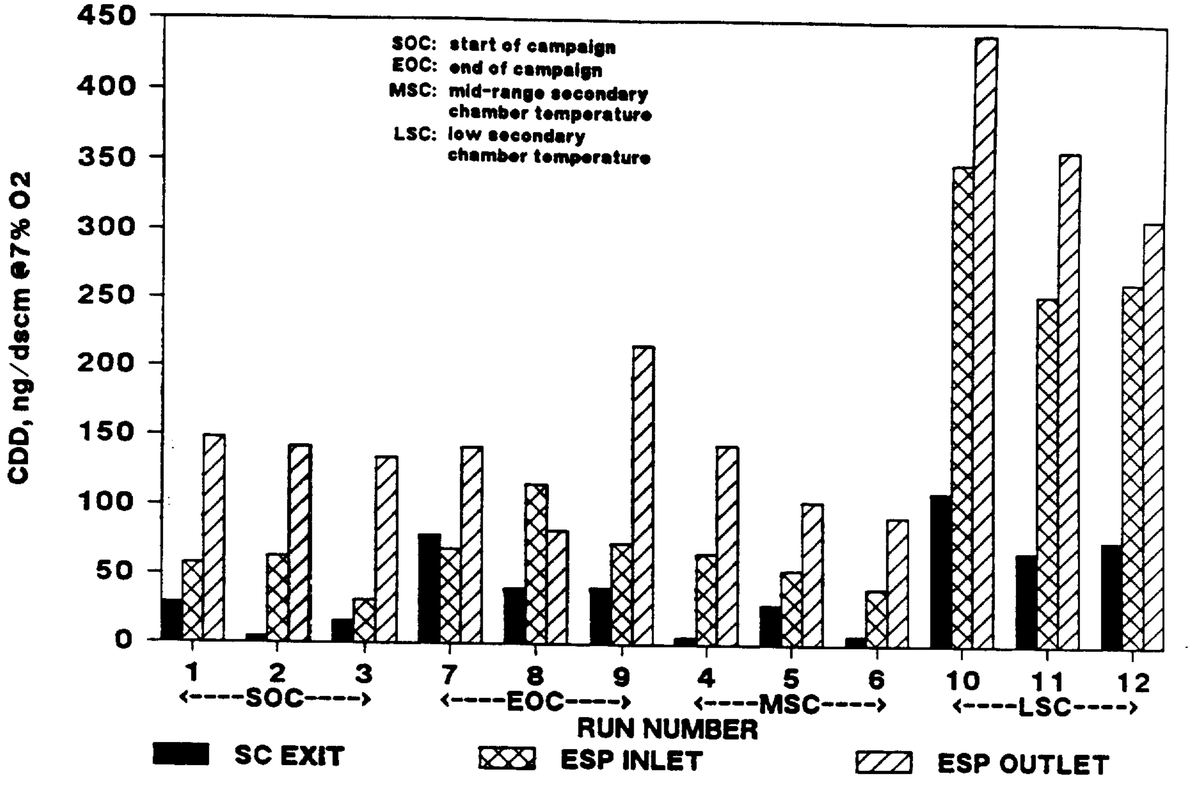


Figure 4-15. CDD Concentrations by Run Number

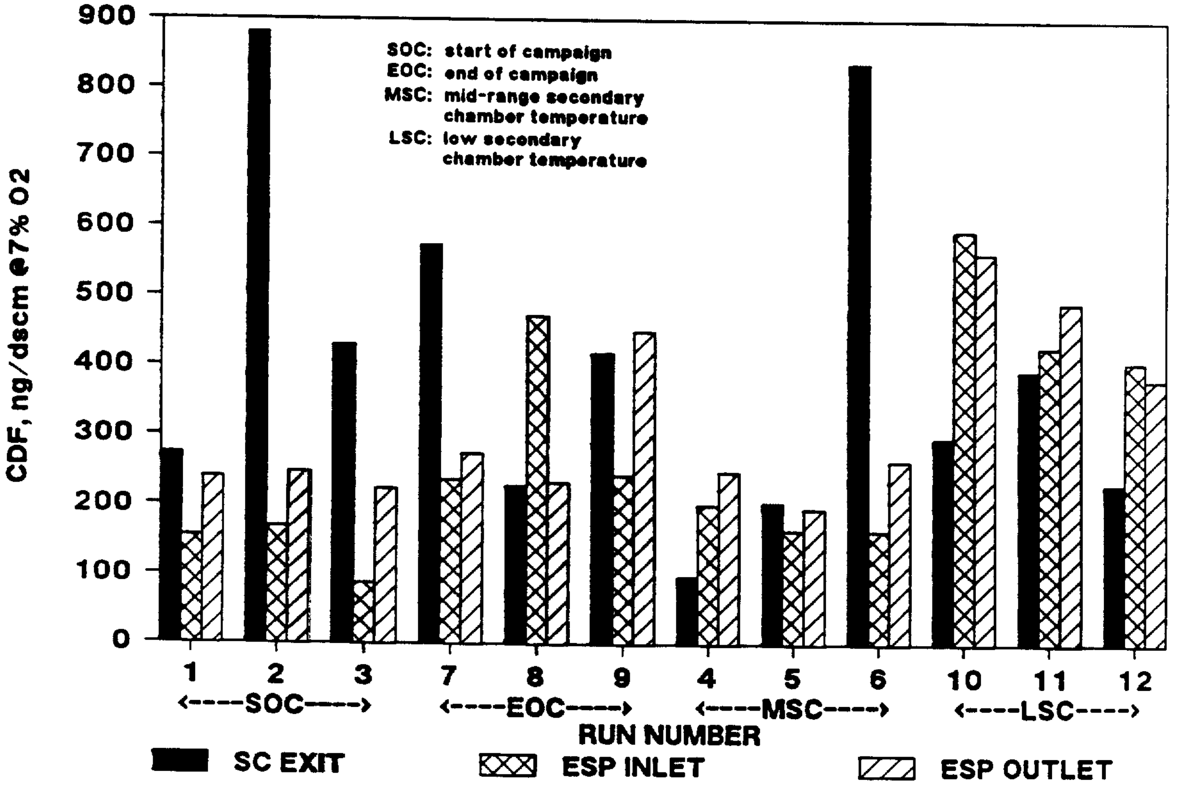


Figure 4-16. CDF Concentrations by Run Number

Table 4-7
SECONDARY CHAMBER EXIT PRECURSOR DATA, ng/dscm @ 7% $O_2$

| | Run 1 | Run 2 | Run 3 | Run 4 | Run 5 | Run 6 | Run 7 | Run 8 | Run 9 | Run 10 | Run 11 | Run 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1,4-Dichlorobenzene | ND | 1396 | 856 | 279 | 493 | 1438 | 1157 | 1180 | | 449 | 824 | 372 |
| 1,3-Dichlorobenzene | ND | 900 | 1248 | 473 | 537 | 1121 | 1834 | 765 | | 411 | 498 | 318 |
| 1,2-Dichlorobenzene | 612 | 1579 | 982 | 382 | 536 | 1813 | 1176 | 1312 | | 407 | 695 | 388 |
| 1,3,5-Trichlorobenzene | ND | 296 | 161 | ND | ND | 239 | 227 | 219 | | 222 | 211 | ND |
| 1,2,3-Trichlorobenzene | ND | 552 | 426 | 206 | ND | 484 | 477 | 407 | | 379 | 344 | 315 |
| 1,2,4-Trichlorobenzene | 617 | 1290 | 782 | 371 | 478 | 997 | 931 | 1017 | | 1010 | 911 | 736 |
| 1,2,4,5-Tetrachlorobenzene | 386 | 454 | 343 | 225 | 337 | 334 | 494 | 525 | | 634 | 505 | 505 |
| 1,2,3,4-Tetrachlorobenzene | 255 | 248 | 236 | 102 | 219 | 215 | 392 | 268 | | 361 | 276 | 279 |
| 1,2,3,4,5-Pentachlorobenzene | 293 | 202 | 207 | 100 | 298 | ND | 311 | 252 | | 528 | 262 | 442 |
| 1,2,3,4,5,6-Hexachlorobenzene | ND | ND | ND | ND | 76 | ND | ND | ND | | 184 | ND | 152 |
| Naphthalene | 4004 | 6083 | 3040 | 2717 | 3004 | 4495 | 15011 | ND | | 1326 | 4240 | 4606 |
| Acenaphthylene | ND | ND | ND | ND | ND | ND | ND | ND | | ND | ND | ND |
| Acenaphthene | ND | ND | ND | ND | ND | ND | ND | ND | | ND | ND | ND |
| Fluorene | ND | ND | ND | ND | ND | 81 | ND | ND | | ND | ND | ND |
| Phenanthrene | ND | ND | ND | ND | 460 | 369 | 1701 | ND | | 55 | 189 | ND |
| Anthracene | ND | ND | ND | ND | ND | ND | ND | ND | | ND | ND | ND |
| Fluoranthene | ND | ND | ND | ND | ND | ND | ND | ND | | ND | ND | ND |
| Pyrene | ND | ND | ND | ND | ND | ND | 176 | ND | | ND | ND | ND |
| Chrysene | ND | ND | ND | ND | ND | ND | ND | ND | | ND | ND | ND |
| Benz(a)anthracene | ND | ND | ND | ND | ND | ND | ND | ND | | ND | ND | ND |
| Benzo(a)pyrene | ND | ND | ND | ND | ND | ND | ND | ND | | ND | ND | ND |
| Dibenzanthracene | ND | ND | ND | ND | ND | ND | ND | ND | | ND | ND | ND |
| Total Dichlorobenzene | 612 | 3983 | 3292 | 1207 | 1836 | 4483 | 4494 | 3315 | | 1314 | 2051 | 1113 |
| Total Trichlorobenzene | 617 | 2116 | 1395 | 600 | 478 | 1773 | 1623 | 1687 | | 1652 | 1504 | 1085 |
| Total Tetrachlorobenzene | 663 | 714 | 598 | 336 | 574 | 566 | 903 | 814 | | 1024 | 803 | 807 |
| Total Pentachlorobenzene | 293 | 202 | 207 | 100 | 298 | ND | 809 | 252 | | 528 | 262 | 442 |
| 1-Chlorophenol | ND | ND | ND | ND | ND | ND | 6811 | ND | | ND | ND | ND |
| 2,4 - or 2,5-Dichlorophenol | ND | ND | ND | 519 | 3979 | ND | 4510 | ND | | 741 | 263 | ND |
| 2,3-Dichlorophenol | ND | ND | ND | ND | ND | ND | ND | 1908 | | 150 | ND | ND |
| 2,6-Dichlorophenol | ND | ND | ND | ND | 725 | ND | ND | ND | | ND | ND | ND |
| 3,4-Dichlorophenol | ND | ND | ND | ND | ND | ND | ND | ND | | ND | ND | ND |
| 3,5-Dichlorophenol | ND | ND | ND | ND | ND | ND | ND | ND | | ND | 603 | ND |
| 2,3,5-Trichlorophenol | ND | ND | ND | ND | ND | ND | 149 | ND | | 217 | 204 | ND |
| 2,4,6-Trichlorophenol | ND | 432 | ND | 575 | 3320 | ND | 12059 | 3831 | | 1045 | 454 | 196 |
| 2,4,5-Trichlorophenol | ND | ND | ND | ND | 633 | ND | ND | 555 | | 901 | 375 | ND |
| 2,3,4-Trichlorophenol | ND | ND | ND | ND | ND | ND | ND | ND | | ND | ND | ND |
| 2,3,6-Trichlorophenol | ND | ND | ND | ND | ND | ND | ND | ND | | 164 | ND | ND |
| 2,3,5,6-Tetrachlorophenol | ND | ND | ND | ND | 182 | ND | 290 | ND | | 181 | 134 | ND |
| 2,3,4,5-Tetrachlorophenol | ND | ND | ND | ND | ND | ND | ND | ND | | 1072 | 574 | ND |
| 2,3,4,6-Tetrachlorophenol | ND | ND | ND | 2423 | 1777 | ND | 2620 | 2663 | | 3234 | 866 | ND |
| 2,3,4,5,6-Pentachlorophenol | ND | ND | ND | ND | 3929 | ND | 5476 | 4679 | | 8459 | 3218 | ND |
| Monochlorobiphenyl | ND | ND | ND | ND | ND | ND | ND | ND | | ND | ND | ND |
| Dichlorobiphenyl | ND | ND | ND | ND | ND | ND | ND | ND | | ND | ND | ND |
| Trichlorobiphenyl | ND | ND | ND | ND | ND | ND | ND | ND | | ND | ND | ND |
| Tetrachlorobiphenyl | ND | ND | ND | ND | ND | ND | ND | ND | | ND | ND | ND |
| Pentachlorobiphenyl | ND | ND | ND | ND | ND | ND | ND | ND | | ND | ND | ND |
| Hexachlorobiphenyl | ND | ND | ND | ND | ND | ND | ND | ND | | ND | ND | ND |
| Heptachlorobiphenyl | ND | ND | ND | ND | ND | ND | ND | ND | | ND | ND | ND |
| Octachlorobiphenyl | ND | ND | ND | ND | ND | ND | ND | ND | | ND | ND | ND |
| Nonachlorobiphenyl | ND | ND | ND | ND | ND | ND | ND | ND | | ND | ND | ND |
| Decachlorobiphenyl | ND | ND | ND | ND | ND | ND | ND | ND | | ND | ND | ND |

## Table 4-8

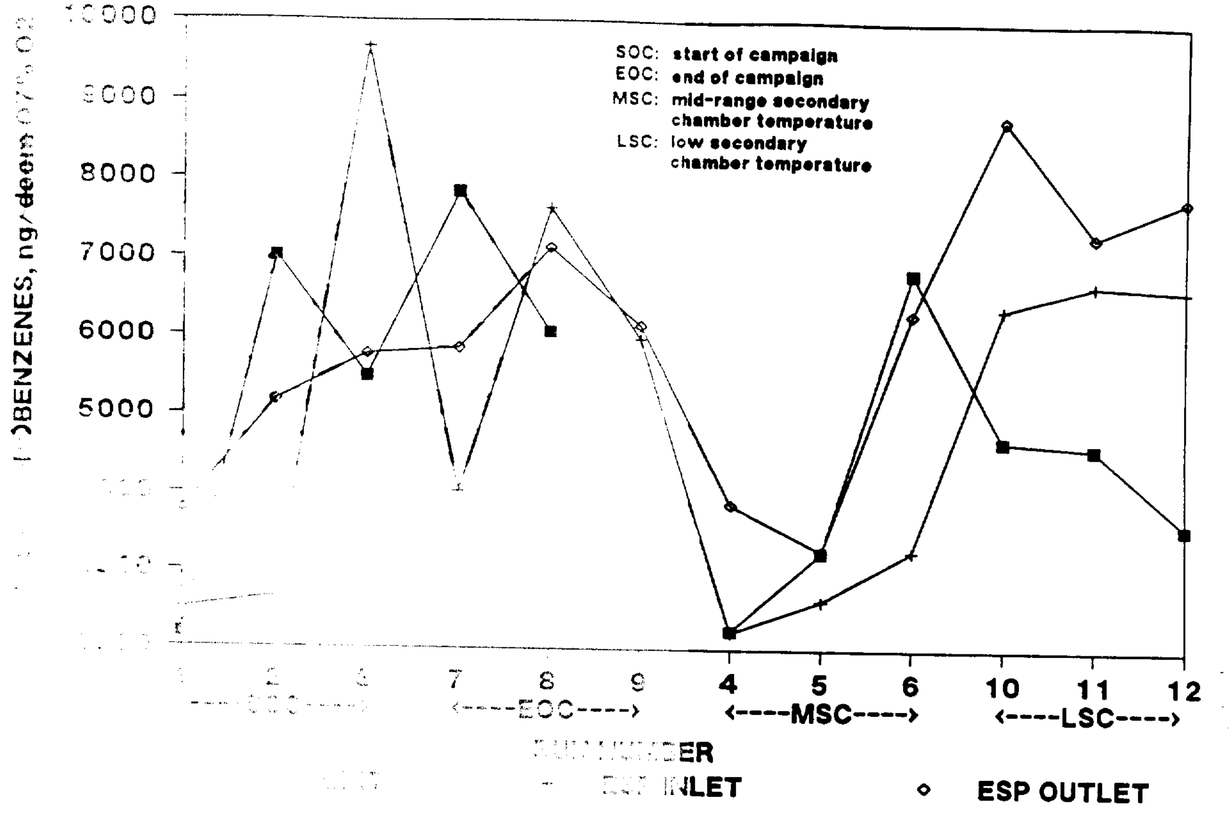
## ESP INLET PRECURSOR DATA, ng/dscm @ 7% $O_2$

| | Run 1 | Run 2 | Run 3 | Run 4 | Run 5 | Run 6 | Run 7 | Run 8 | Run 9 | Run 10 | Run 11 | Run 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1,4-Dichlorobenzene | 135 | 149 | 762 | ND | 247 | ND | 358 | 696 | 548 | ND | 301 | 325 |
| 1,3-Dichlorobenzene | 234 | 222 | 4052 | ND | 355 | 892 | 598 | 751 | 476 | 380 | 347 | 375 |
| 1,2-Dichlorobenzene | ND | 186 | 1663 | ND | 234 | ND | ND | 647 | 417 | 239 | 280 | 238 |
| 1,3,5-Trichlorobenzene | ND | ND | ND | ND | ND | 119 | 262 | 382 | 235 | ND | 338 | 241 |
| 1,2,3-Trichlorobenzene | 150 | 179 | 317 | ND | 156 | 208 | 323 | 564 | 327 | 462 | 486 | 447 |
| 1,2,4-Trichlorobenzene | 543 | 548 | 772 | 469 | 624 | 654 | 823 | 1736 | 1178 | 1259 | 1317 | 1032 |
| 1,2,4,5-Tetrachlorobenzene | 423 | 368 | 362 | ND | 341 | 432 | 580 | 979 | 838 | 1129 | 1214 | 1149 |
| 1,2,3,4-Tetrachlorobenzene | 268 | 228 | 223 | 170 | 171 | 242 | 328 | 580 | 450 | 719 | 727 | 691 |
| 1,2,3,4,5-Pentachlorobenzene | 446 | 446 | 371 | 327 | 282 | 359 | 499 | 846 | 925 | 1208 | 1161 | 1383 |
| 1,2,3,4,5,6-Hexachlorobenzene | 227 | 269 | 311 | 214 | 142 | 177 | 172 | 268 | 454 | 428 | 462 | 614 |
| Naphthalene | 2470 | 812 | 47787 | 3639 | 7042 | 40297 | 6143 | 2999 | 2802 | 2455 | 11892 | 1890 |
| Acenaphthylene | ND | ND | 44816 | ND | ND | ND | ND | ND | ND | ND | ND | ND |
| Acenaphthene | ND | ND | 10251 | ND | ND | ND | ND | ND | ND | ND | ND | ND |
| Fluorene | ND | ND | 14342 | ND | ND | ND | ND | ND | ND | ND | ND | ND |
| Phenanthrene | ND | ND | 28800 | ND | ND | ND | ND | ND | ND | ND | ND | ND |
| Anthracene | ND | ND | 2348 | ND | ND | ND | ND | ND | ND | ND | ND | ND |
| Fluoranthene | ND | ND | 1414 | ND | ND | ND | ND | ND | ND | ND | ND | ND |
| Pyrene | ND | ND | 1277 | ND | ND | ND | ND | ND | ND | ND | ND | ND |
| Chrysene | ND | ND | ND | ND | ND | ND | ND | ND | ND | ND | ND | ND |
| Benz(a)anthracene | ND | ND | 201 | ND | ND | ND | ND | ND | ND | ND | ND | ND |
| Benzo(a)pyrene | ND | ND | 955 | ND | ND | ND | ND | ND | ND | ND | ND | ND |
| Dibenzanthracene | ND | ND | ND | ND | ND | ND | ND | ND | ND | ND | ND | ND |
| Total Dichlorobenzene | 406 | 598 | 7285 | 618 | 898 | 1058 | 1064 | 2212 | 1492 | 1055 | 985 | 1008 |
| Total Trichlorobenzene | 709 | 741 | 1116 | 542 | 792 | 991 | 1375 | 2706 | 1777 | 1772 | 2104 | 1756 |
| Total Tetrachlorobenzene | 713 | 605 | 594 | 517 | 521 | 695 | 923 | 1609 | 1324 | 1906 | 1973 | 1869 |
| Total Pentachlorobenzene | 446 | 446 | 371 | 327 | 282 | 359 | 499 | 846 | 925 | 1208 | 1161 | 1383 |
| 1-Chlorophenol | ND | ND | ND | ND | ND | 388 | 513 | 418 | ND | ND | 391 | ND |
| 2,4 - or 2,5-Dichlorophenol | 365 | 303 | ND | 620 | ND | 698 | 499 | 973 | 1065 | 1128 | 871 | ND |
| 2,3-Dichlorophenol | ND | ND | ND | ND | ND | ND | ND | 208 | 255 | ND | ND | ND |
| 2,6-Dichlorophenol | ND | ND | ND | ND | ND | ND | ND | ND | ND | ND | ND | ND |
| 3,4-Dichlorophenol | ND | ND | ND | ND | ND | ND | ND | ND | ND | ND | ND | ND |
| 3,5-Dichlorophenol | ND | ND | ND | ND | ND | ND | ND | ND | ND | ND | ND | ND |
| 2,3,5-Trichlorophenol | ND | ND | ND | 197 | 175 | 282 | ND | ND | 359 | 378 | ND | 313 |
| 2,4,6-Trichlorophenol | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 4437 |
| 2,4,5-Trichlorophenol | [illegible] | | | [illegible] | [illegible] | [illegible] | | | [illegible] | [illegible] | [illegible] | [illegible] |
| 2,3,4-Trichlorophenol | [illegible] | | | [illegible] | [illegible] | [illegible] | | | [illegible] | [illegible] | ND | [illegible] |
| 2,3,6-Trichlorophenol | | | | [illegible] | | | | | [illegible] | [illegible] | [illegible] | [illegible] |
| 2,3,5,6-Tetrachlorophenol | [illegible] | [illegible] | | [illegible] | [illegible] | | | | [illegible] | [illegible] | 623 | ND |
| 2,3,4,5-Tetrachlorophenol | ND | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | | [illegible] | 1147 | ND | 7194 | ND |
| 2,3,4,6-Tetrachlorophenol | 9330 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 3485 | 10045 | 7918 | ND |
| 2,3,4,5,6-Pentachlorophenol | ND | [illegible] | [illegible] | [illegible] | ND | [illegible] | [illegible] | [illegible] | 6878 | [illegible] | [illegible] | [illegible] |
| Monochlorobiphenyl | ND | [illegible] | [illegible] | [illegible] | [illegible] | ND | [illegible] | ND | ND | ND | ND | ND |
| Dichlorobiphenyl | ND | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | ND | ND | ND | ND | ND |
| Trichlorobiphenyl | ND | [illegible] | [illegible] | ND | [illegible] | [illegible] | [illegible] | ND | ND | ND | ND | [illegible] |
| Tetrachlorobiphenyl | ND | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | ND | ND | ND | ND | ND |
| Pentachlorobiphenyl | ND | [illegible] | [illegible] | [illegible] | | [illegible] | | [illegible] | ND | ND | ND | [illegible] |
| Hexachlorobiphenyl | ND | ND | [illegible] | [illegible] | [illegible] | ND | [illegible] | [illegible] | ND | ND | [illegible] | ND |
| Heptachlorobiphenyl | [illegible] | | | | | | | | [illegible] | ND | [illegible] | [illegible] |
| Octachlorobiphenyl | [illegible] | | | | | | | [illegible] | [illegible] | ND | | [illegible] |
| [illegible] | [illegible] | | | | | | | | [illegible] | [illegible] | | [illegible] |
| [illegible] | [illegible] | | | | | | | | [illegible] | [illegible] | [illegible] | |

Table 4-9

ESP OUTLET PRECURSOR DATA, ng/dscm @ 7% $O_2$

| | Run 1 | Run 2 | Run 3 | Run 4 | Run 5 | Run 6 | Run 7 | Run 8 | Run 9 | Run 10 | Run 11 | Run 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1,4-Dichlorobenzene | 169 | 199 | 179 | 217 | 190 | 394 | 310 | 712 | 439 | 285 | 311 | 291 |
| 1,2-Dichlorobenzene | 199 | 390 | 1165 | 278 | 327 | 1519 | 1031 | 1021 | 527 | 282 | 318 | 244 |
| 1,3-Dichlorobenzene | 143 | ND | 164 | ND | ND | ND | 278 | 529 | ND | ND | ND | 242 |
| 1,3,5-Trichlorobenzene | ND | 158 | 96 | 179 | 99 | 150 | 202 | 295 | 177 | 312 | ND | 272 |
| 1,2,3-Trichlorobenzene | 227 | 258 | 225 | 213 | 151 | 357 | 372 | 487 | 355 | 557 | 451 | 441 |
| 1,2,4-Trichlorobenzene | 457 | 589 | 478 | 536 | 582 | 807 | 840 | 1364 | 956 | 1278 | 1177 | 1145 |
| 1,2,4,5-Tetrachlorobenzene | 570 | 766 | 643 | 571 | 469 | 734 | 750 | 891 | 917 | 1627 | 1259 | 1428 |
| 1,2,3,4-Tetrachlorobenzene | 386 | 563 | 491 | 382 | 277 | 469 | 473 | 497 | 557 | 1116 | 844 | 911 |
| 1,2,3,4,5-Pentachlorobenzene | 1011 | 1462 | 1267 | 941 | 718 | 1017 | 971 | 774 | 1392 | 2259 | 1716 | 1937 |
| 1,2,3,4,5,6-Hexachlorobenzene | 540 | 712 | 800 | 522 | 383 | 522 | 411 | 323 | 674 | 973 | 830 | 808 |
| Naphthalene | ND | 2992 | 1446 | 5455 | 2698 | 2319 | 3889 | 4385 | 3345 | 1382 | 1928 | 3958 |
| Acenaphthylene | ND | ND | ND | ND | ND | ND | ND | ND | ND | ND | ND | ND |
| Acenaphthene | ND | ND | ND | ND | ND | ND | ND | ND | ND | ND | ND | ND |
| Fluorene | ND | ND | ND | ND | ND | 82 | ND | ND | ND | ND | ND | ND |
| Phenanthrene | ND | ND | ND | ND | ND | 630 | ND | ND | ND | ND | ND | ND |
| Anthracene | ND | ND | ND | ND | ND | ND | ND | ND | ND | ND | ND | ND |
| Fluoranthene | ND | ND | ND | ND | ND | ND | ND | ND | ND | ND | ND | ND |
| Pyrene | ND | ND | ND | ND | ND | ND | ND | ND | ND | ND | ND | ND |
| Chrysene | ND | ND | ND | ND | ND | ND | ND | ND | ND | ND | ND | ND |
| Benz(a)anthracene | ND | ND | ND | ND | ND | ND | ND | ND | ND | ND | ND | ND |
| Benzo(a)pyrene | ND | ND | ND | ND | ND | ND | ND | ND | ND | ND | ND | ND |
| Dibenzanthracene | ND | ND | ND | ND | ND | ND | ND | ND | ND | ND | ND | ND |
| Total Dichlorobenzene | 537 | 662 | 1718 | 542 | 572 | 2181 | 1825 | 2412 | 1038 | 613 | 678 | 812 |
| Total Trichlorobenzene | 709 | 990 | 812 | 905 | 839 | 1335 | 1400 | 2198 | 1526 | 2148 | 1904 | 1832 |
| Total Tetrachlorobenzene | 988 | 1355 | 1176 | 971 | 769 | 1243 | 1245 | 1428 | 1518 | 2789 | 2175 | 2381 |
| Total Pentachlorobenzene | 1011 | 1462 | 1267 | 941 | 718 | 1017 | 971 | 774 | 1392 | 2259 | 1716 | 1937 |
| 1-Chlorophenol | ND | 405 | ND | ND | 204 | ND | 274 | ND | ND | 506 | 257 | 259 |
| 2,4 - or 2,5-Dichlorophenol | 600 | 739 | 580 | 510 | 539 | 1007 | 747 | 1182 | 1322 | 2192 | 1253 | 791 |
| 2,3-Dichlorophenol | ND | ND | ND | ND | ND | ND | ND | 199 | 270 | 422 | ND | ND |
| 2,6-Dichlorophenol | ND | ND | ND | ND | ND | ND | 114 | ND | 150 | ND | ND | ND |
| 3,4-Dichlorophenol | ND | ND | ND | ND | ND | ND | ND | ND | ND | ND | ND | ND |
| 3,5-Dichlorophenol | ND | ND | ND | ND | ND | ND | ND | ND | ND | ND | ND | ND |
| 2,3,5-Trichlorophenol | 194 | ND | 136 | ND | 151 | 231 | 232 | 271 | 390 | 534 | 474 | 283 |
| 2,4,6-Trichlorophenol | 2163 | 2046 | 1729 | 1468 | 1076 | 1830 | 2691 | 1689 | 1861 | 4705 | 3388 | 4450 |
| 2,4,5-Trichlorophenol | 793 | 977 | 908 | 697 | 680 | 1155 | 1351 | 1139 | 1557 | 2554 | 2504 | 2073 |
| 2,3,4-Trichlorophenol | 348 | 395 | 348 | 212 | 247 | 421 | 447 | ND | 589 | 1086 | 926 | 718 |
| 2,3,6-Trichlorophenol | ND | ND | ND | ND | ND | 234 | 255 | 243 | ND | 434 | ND | 269 |
| 2,3,5,6-Tetrachlorophenol | 408 | ND | ND | ND | ND | 293 | 396 | ND | 507 | 2914 | 659 | 366 |
| 2,3,4,5-Tetrachlorophenol | 1679 | ND | ND | ND | ND | 966 | 1290 | ND | ND | ND | 2497 | ND |
| 2,3,4,6-Tetrachlorophenol | 6899 | 11157 | 26429 | 6033 | 15331 | 4722 | 5633 | 17998 | 6886 | 55399 | 9036 | 10115 |
| 2,3,4,5,6-Pentachlorophenol | 18424 | ND | ND | ND | ND | 10829 | 10847 | ND | 8652 | ND | 21280 | ND |
| Monochlorobiphenyl | ND | ND | ND | ND | ND | ND | ND | ND | ND | ND | ND | ND |
| Dichlorobiphenyl | ND | ND | ND | ND | ND | ND | ND | ND | ND | ND | ND | ND |
| Trichlorobiphenyl | ND | ND | ND | ND | ND | 117 | ND | ND | ND | ND | ND | ND |
| Tetrachlorobiphenyl | ND | ND | ND | ND | ND | ND | ND | ND | ND | ND | ND | ND |
| Pentachlorobiphenyl | ND | ND | ND | ND | ND | ND | ND | ND | ND | ND | ND | ND |
| Hexachlorobiphenyl | ND | ND | ND | ND | ND | ND | ND | ND | ND | ND | ND | ND |
| Heptachlorobiphenyl | ND | ND | ND | ND | ND | ND | ND | ND | ND | ND | ND | ND |
| Octachlorobiphenyl | ND | ND | ND | ND | ND | ND | ND | ND | ND | ND | ND | ND |
| Nonachlorobiphenyl | ND | ND | ND | ND | ND | ND | ND | ND | ND | ND | ND | ND |
| Decachlorobiphenyl | ND | ND | ND | ND | ND | ND | ND | ND | ND | ND | ND | ND |



[illegible] Total Chlorobenzene Concentrations by Run Number

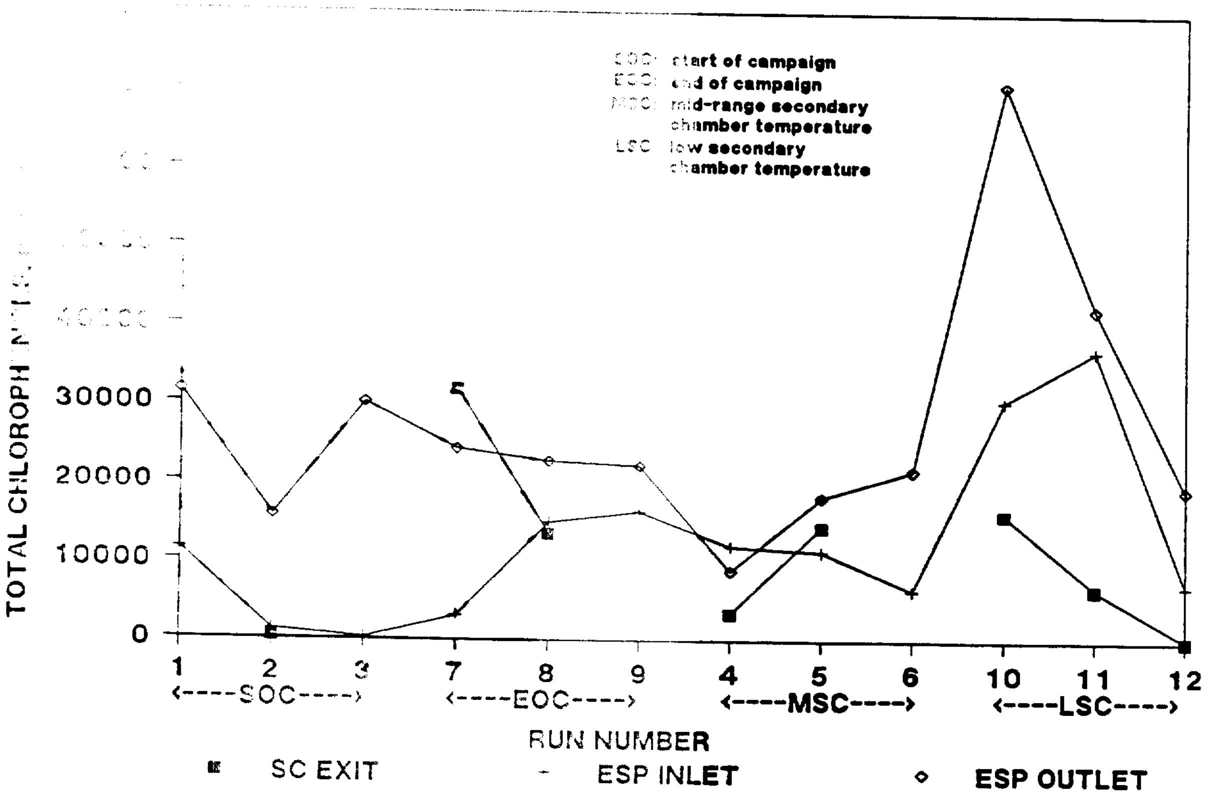


Figure 4-18. Total Chlorophenol Concentrations by Run Number

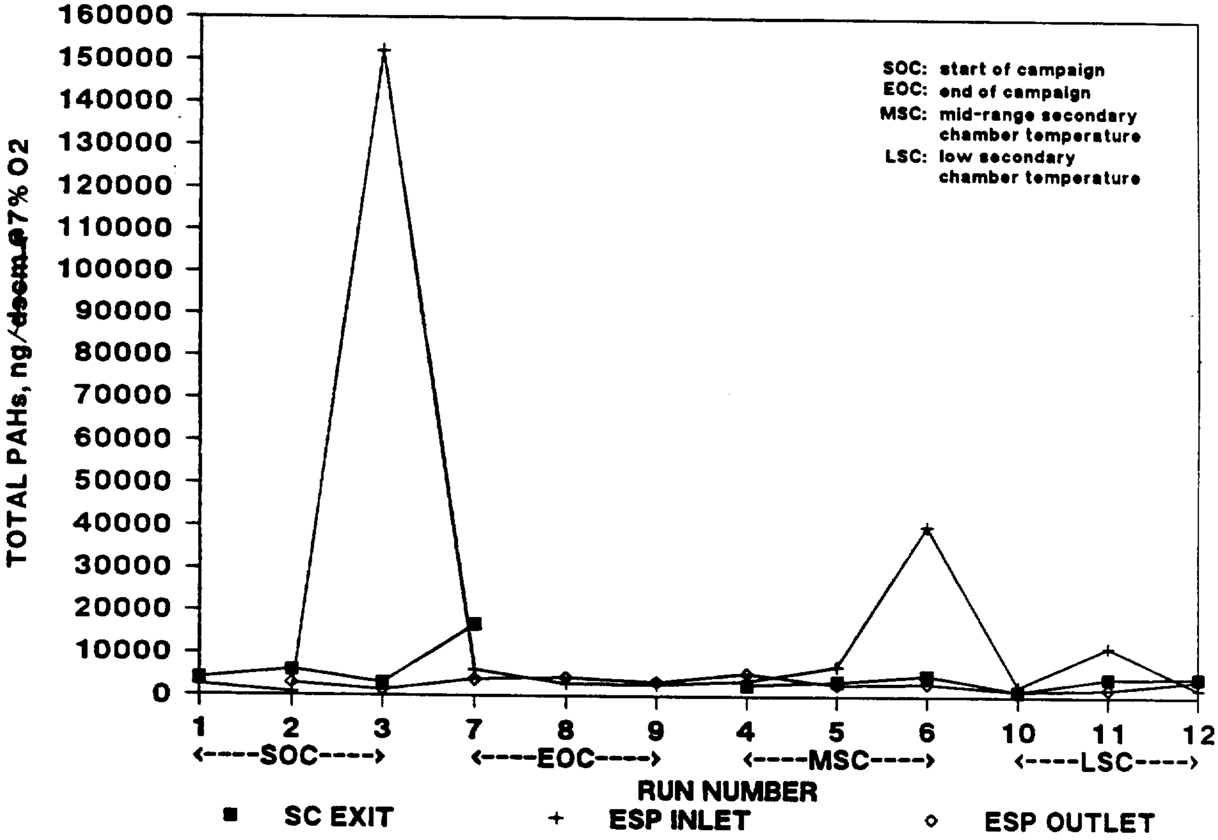


Figure 4-19. Total Polyaromatic Hydrocarbon Concentrations by Run Number

Figure 4-18 shows that the majority of the chlorophenols were measured at the ESP outlet rather than at the ESP inlet or secondary chamber exit, indicating there may have been formation occurring between the sampling locations. Excluding Runs 3 and 6 at the ESP inlet, the PAH concentrations were consistent between locations and test runs (Figure 4-19). There are no known reasons for the observed high PAH results for Runs 3 and 6 at the ESP inlet. The relationship(s) between these potential CDD and CDF precursors and total CDD and CDF concentrations are presented in Section 7.

## CEM DATA

The means and standard deviations of the unadjusted concentrations of combustion gases measured at the secondary chamber exit and ESP outlet are summarized in Tables 4-10 and 4-11. The adjusted means are presented in Tables 4-12 and 4-13. The values are compared on an as-measured basis to yield qualitative information about how good the measurements are and how much air leakage there may have been.

Secondary chamber exit mean oxygen concentrations ranged from 11.2 to 13.4 percent by volume and ESP outlet mean oxygen concentrations ranged between 12.9 and 14.3 percent by volume. Figure 4-10, presented earlier in this section, compares oxygen concentrations measured at the secondary chamber exit and ESP outlet. Since the incinerator is under negative pressure, and thus potential air inleakage, the oxygen concentrations measured at the ESP outlet should logically be larger than those measured at the secondary chamber exit. This pattern is shown in the figure. In addition, the oxygen concentrations are highest for the low secondary chamber temperature test series. The majority of the data fall between 12 and 14 percent by volume, which is typical of this type of incinerator.

Carbon monoxide concentrations were between -0.9 (zero) and 13.5 ppmv at the secondary chamber exit and between 0.1 and 3.1 ppmv at the ESP outlet. Figure 4-20 shows the CO concentrations measured at the two locations. No data are presented for Run 1 at the secondary chamber exit due to equipment failure. As can be seen in the figure, there is no distinct pattern in the data between test runs; the CO concentrations measured at the secondary

Table 4-10

## MEAN VALUES AND STANDARD DEVIATIONS OF CONTINUOUSLY MONITORED COMBUSTION GAS VARIABLES AT THE SECONDARY CHAMBER EXIT

| | | Continuous Monitoring Results (Standard Deviation) | | | | | |
|---|---|---|---|---|---|---|---|
| Test[a] Condition | Run Number | Oxygen % V, dry | Carbon Monoxide ppmv, dry | Carbon Dioxide % V, dry | Nitrogen Oxides ppmv, dry | Sulfur Dioxide ppmv, dry | Total Hydrocarbons ppmv, dry |
| Start of Campaign, SCE = 1800 deg. F | 1[b] | 12.0 (--)[c] | -- (--) | -- (--) | -- (--) | -- (--) | -- (--) |
| | 2 | 12.3 (0.5) | 1.9 (12.8) | 8.1 (0.5) | 178.6 (15.8) | 63.3 (20.6) | 0.7 (0.3) |
| | 3 | 12.8 (0.7) | 2.3 (10.5) | 7.9 (0.6) | 176.0 (21.6) | 41.7 (21.1) | 0.6 (0.1) |
| | Average | 12.6 | 2.1 | 8.0 | 177.3 | 52.4 | 0.7 |
| Mid-range Secondary Chamber Temperature, SCE = 1750 deg. F | 4 | 12.6 (0.6) | -0.9 (4.2) | -- (--)[d] | 175.1 (15.3) | -- (--)[d] | -- (--)[d] |
| | 5 | 12.3 (0.6) | 2.6 (11.1) | 8.0 (0.6) | 180.4 (22.0) | 111.4 (24.1) | 0.5 (0.1) |
| | 6 | 12.3 (0.7) | 1.8 (8.2) | 7.8 (0.6) | 158.0 (14.4) | 75.5 (31.0) | 0.5 (0.1) |
| | Average | 12.4 | 1.2 | 7.9 | 169.4 | 93.5 | 0.5 |
| End of Campaign, SCE = 1800 deg. F | 7 | 11.2 (1.3) | 12.5 (51.4) | 8.9 (1.1) | 179.8 (15.9) | 36.4 (35.6) | 0.4 (4.9) |
| | 8 | 11.5 (1.2) | 2.9 (17.4) | 8.7 (1.1) | 178.0 (16.7) | 57.9 (21.6) | 0.6 (0.1) |
| | 9 | 11.6 (1.2) | 13.5 (54.6) | 8.6 (1.1) | 148.2 (16.9) | 112.4 (80.9) | 1.3 (6.8) |
| | Average | 11.4 | 9.6 | 8.7 | 168.6 | 68.9 | 0.8 |
| Low Secondary Chamber Temperature, SCE = 1650 deg. F | 10 | 12.9 (1.1) | 12.0 (26.6) | 7.6 (1.0) | 160.6 (28.2) | 84.8 (52.7) | -0.5 (0.2) |
| | 11 | 13.0 (0.7) | 9.8 (9.7) | 7.4 (0.6) | 149.2 (13.4) | 125.4 (32.5) | 0.3 (0.1) |
| | 12 | 13.4 (0.6) | 9.5 (14.0) | 7.1 (0.6) | 166.0 (13.7) | 99.7 (22.5) | 0.3 (0.1) |
| | Average | 13.1 | 10.4 | 7.4 | 158.6 | 103.3 | 0.0 |

[a] SCE = Secondary Chamber Exit; temperatures represent setpoints for condition indicated.

[b] CEM data were invalidated due to equipment failure.

[c] Estimated from best-fit linear regression of ESP outlet $O_2$ CEM data.

[d] Not reported.

## Table 4-11

### MEAN VALUES AND STANDARD DEVIATIONS OF CONTINUOUSLY MONITORED COMBUSTION GAS VARIABLES AT THE ESP OUTLET

| | | Continuous Monitoring Results (Standard Deviation) | | | | |
|---|---|---|---|---|---|---|
| Test[a] Condition | Run Number | Oxygen % Vol, dry | Carbon Monoxide ppmv, dry | Carbon Dioxide % V, dry | Nitrogen Oxides ppmv, dry | Sulfur Dioxide ppmv, dry |
| Start of Campaign, SCE = 1800 deg. F | 1 | 13.4 (0.5) | 0.1 (0.7) | 7.4 (0.5) | 154.8 (17.1) | 68.4 (24.0) |
| | 2 | 14.0 (0.5) | 0.4 (3.2) | 6.7 (0.5) | 151.0 (16.8) | 99.7 (31.8) |
| | 3 | 13.4 (0.6) | 0.6 (7.5) | 7.6 (0.6) | 170.3 (19.6) | 72.7 (64.6) |
| | Average | 13.6 | 0.4 | 7.2 | 158.7 | 80.3 |
| Mid-range Secondary Chamber Temperature, SCE = 1750 deg. F | 4 | 13.9 (0.5) | 0.2 (1.3) | 7.0 (0.5) | 149.8 (14.1) | -- ( -- )[b] |
| | 5 | 13.6 (0.5) | 0.4 (3.2) | 7.2 (0.5) | 163.1 (20.0) | 75.1 (26.9) |
| | 6 | 13.8 (0.7) | 2.6 (31.8) | 7.2 (0.6) | 147.1 (16.9) | 99.5 (47.5) |
| | Average | 13.8 | 1.1 | 7.1 | 153.3 | 87.3 |
| End of Campaign, SCE = 1800 deg. F | 7 | 13.0 (1.0) | 1.0 (11.6) | 8.2 (0.9) | 179.4 (17.9) | -- ( -- )[b] |
| | 8 | 13.8 (1.5) | 2.3 (22.3) | 7.5 (1.5) | 152.8 (23.0) | 61.1 (58.7) |
| | 9 | 12.9 (0.9) | 1.8 (23.9) | 8.3 (0.9) | 169.6 (22.6) | 60.1 (68.0) |
| | Average | 13.2 | 1.7 | 8.0 | 167.3 | 60.6 |
| Low Secondary Chamber Temperature, SCE = 1650 deg. F | 10 | 14.0 (0.6) | 3.1 (13.2) | 7.2 (0.6) | 150.0 (22.4) | 98.1 (29.3) |
| | 11 | 14.3 (0.5) | 3.0 (5.0) | 6.7 (0.5) | 129.9 (11.6) | 63.1 (25.3) |
| | 12 | 14.3 (0.5) | 1.3 (7.7) | 6.8 (0.5) | 156.6 (15.8) | 70.0 (41.2) |
| | Average | 14.2 | 2.5 | 6.9 | 145.5 | 77.1 |

---

[a] SCE = Secondary Chamber Exit; temperatures represent setpoints for condition indicated.

[b] Data invalidated.

Table 4-12

## MEAN NORMALIZED VALUES OF CONTINUOUSLY MONITORED COMBUSTION GAS VARIABLES AT THE SECONDARY CHAMBER EXIT

| | | Continuous Monitoring Results | | | | | |
|---|---|---|---|---|---|---|---|
| Test[a] Condition | Run Number | Oxygen % V, dry | Carbon Monoxide ppmv, dry @ 7% $O_2$ | Carbon Dioxide % V, dry @ 7% $O_2$ | Nitrogen Oxides ppmv, dry @ 7% $O_2$ | Sulfur Dioxide ppmv, dry @ 7% $O_2$ | Total Hydrocarbons ppmv, dry @ 7% $O_2$ |
| Start of Campaign, SCE = 1800 deg. F | 1[b] | 12.0[c] | -- | -- | -- | -- | -- |
| | 2 | 12.3 | 3.1 | 13.1 | 288.7 | 102.3 | 1.1 |
| | 3 | 12.8 | 3.9 | 13.6 | 302.0 | 71.6 | 1.0 |
| | **Average** | 12.4 | 3.5 | 13.3 | 295.3 | 86.9 | 1.1 |
| Mid-range Secondary Chamber Temperature, SCE = 1750 deg. F | 4 | 12.6 | -1.5 | --[d] | 293.2 | --[d] | --[d] |
| | 5 | 12.3 | 4.2 | 12.9 | 291.6 | 180.1 | 0.8 |
| | 6 | 12.3 | 2.9 | 12.6 | 255.4 | 122.0 | 0.8 |
| | **Average** | 12.4 | 1.9 | 12.8 | 280.0 | 151.0 | 0.8 |
| End of Campaign, SCE = 1800 deg. F | 7 | 11.2 | 17.9 | 12.8 | 257.7 | 52.2 | 0.6 |
| | 8 | 11.5 | 4.3 | 12.9 | 263.2 | 85.6 | 0.9 |
| | 9 | 11.6 | 20.2 | 12.9 | 221.5 | 168.0 | 1.9 |
| | **Average** | 11.4 | 14.1 | 12.8 | 247.5 | 101.9 | 0.7 |
| Low Secondary Chamber Temperature, SCE = 1650 deg. F | 10 | 12.9 | 20.9 | 13.2 | 279.0 | 147.3 | -0.9 |
| | 11 | 13.0 | 17.3 | 13.0 | 262.8 | 220.9 | 0.5 |
| | 12 | 13.4 | 17.7 | 13.2 | 309.3 | 185.8 | 0.6 |
| | Average | 13.1 | 18.6 | 13.2 | 283.7 | 184.7 | 0.1 |

[a] SCE = Secondary Chamber Exit; temperatures represent setpoints for condition indicated.

[b] CEM data invalidated due to equipment failure.

[c] Estimated from best-fit linear regression of ESP outlet $O_2$ CEM data.

[d] Not reported.

Table 4-13

MEAN NORMALIZED VALUES OF CONTINUOUSLY MONITORED COMBUSTION GAS VARIABLES AT THE ESP OUTLET

| Test[a] Condition | Run Number | Continuous Monitoring Results | | | | |
|---|---|---|---|---|---|---|
| | | Oxygen % V, dry | Carbon Monoxide ppmv, dry @ 7% $O_2$ | Carbon Dioxide % V, dry @ 7% $O_2$ | Nitrogen Oxides ppmv, dry @ 7% $O_2$ | Sulfur Dioxide ppmv, dry @ 7% $O_2$ |
| Start of Campaign, SCE = 1800 deg. F | 1 | 13.4 | 0.2 | 13.8 | 288.4 | 127.4 |
| | 2 | 14.0 | 0.8 | 13.5 | 304.2 | 200.8 |
| | 3 | 13.4 | 1.1 | 14.1 | 315.6 | 134.7 |
| | Average | 13.6 | 0.7 | 13.8 | 302.7 | 154.3 |
| Mid-range Secondary Chamber Temperature, SCE = 1750 deg. F | 4 | 13.9 | 0.4 | 13.9 | 297.5 | --[b] |
| | 5 | 13.6 | 0.8 | 13.7 | 310.6 | 143.0 |
| | 6 | 13.8 | 5.1 | 14.0 | 288.0 | 194.8 |
| | Average | 13.8 | 2.1 | 13.9 | 298.7 | 168.9 |
| End of Campaign, SCE = 1800 deg. F | 7 | 13.0 | 1.8 | 14.4 | 315.7 | --[b] |
| | 8 | 13.8 | 4.5 | 14.7 | 300.4 | 120.1 |
| | 9 | 12.9 | 3.1 | 14.4 | 293.9 | 104.2 |
| | Average | 13.2 | 3.1 | 14.5 | 303.3 | 112.1 |
| Low Secondary Chamber Temperature, SCE = 1650 deg. F | 10 | 14.0 | 6.2 | 14.5 | 302.2 | 197.6 |
| | 11 | 14.3 | 6.2 | 14.1 | 272.8 | 132.5 |
| | 12 | 14.3 | 2.7 | 14.3 | 328.8 | 147.0 |
| | Average | 14.2 | 5.1 | 14.3 | 301.2 | 159.6 |

[a] SCE = Secondary Chamber Exit; temperatures represent setpoints for condition indicated.

[b] Data invalidated.

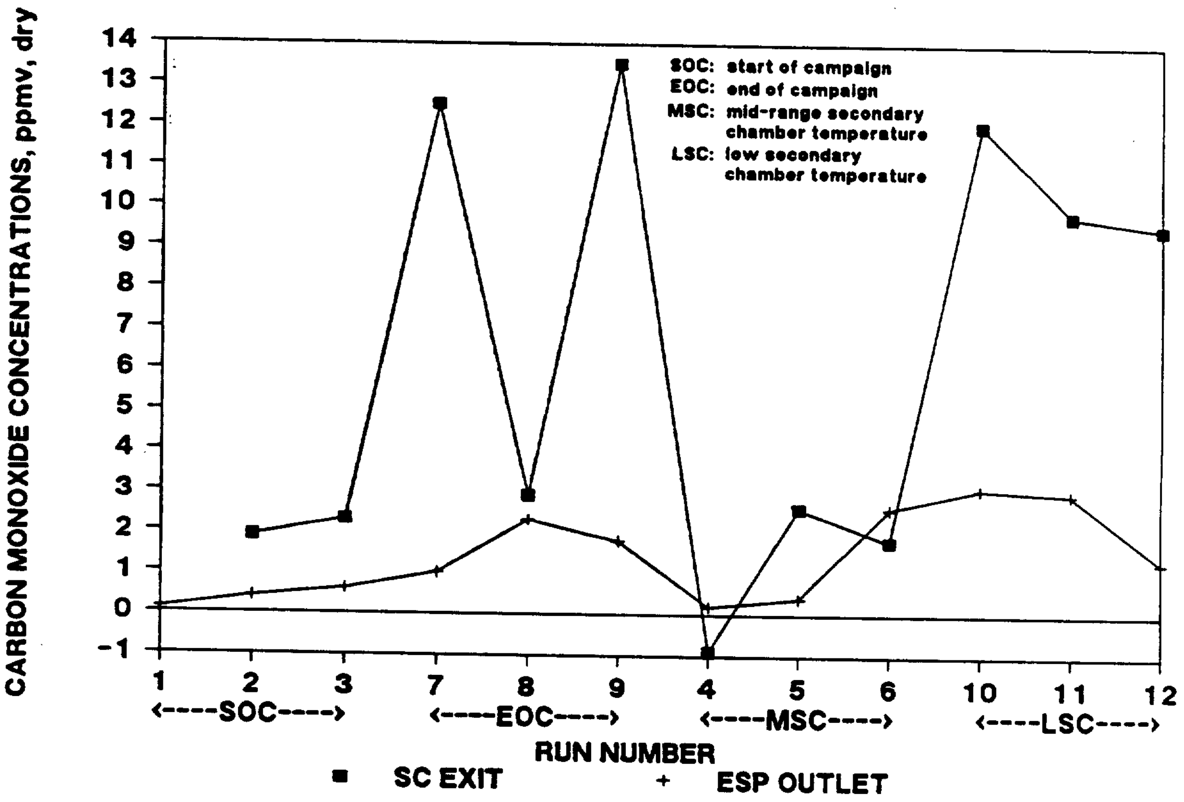


Figure 4-20. Unadjusted Carbon Monoxide Concentrations by Run Number

chamber exit are generally higher than those measured at the ESP outlet. However, since all of the mean CO concentrations are below 20 ppmv, the analyzers may have sensitivity limitations in this low concentration range.

Mean carbon dioxide concentrations were between 7.1 and 8.9 percent by volume at the secondary chamber exit and between 6.7 and 8.3 percent by volume at the ESP outlet. Figure 4-21 presents carbon dioxide concentrations measured at the two locations by run number. Carbon dioxide levels are highest for the end of campaign test series and lowest for the low secondary chamber temperature test series. No data are presented for Runs 1 and 4 at the secondary chamber exit as these data were invalidated due to equipment failure.

Nitrogen oxide emissions ranged from 148.2 to 180.4 ppmv at the secondary chamber exit and from 129.9 to 179.4 ppmv at the ESP outlet. Figure 4-22 presents the data graphically. As is shown in the figure, the measurements made at the two locations were very similar across test runs and, in general, did not vary more than about 20 ppmv between the two sampling locations. No data are presented for Run 1 at the secondary chamber exit due to equipment failure.

Sulfur dioxide concentrations ranged from 36.4 to 125.4 ppmv at the secondary chamber exit and from 60.1 to 99.7 ppmv at the ESP outlet. Figure 4-23 compares the sulfur dioxide concentrations between the two locations by run number. As can be seen in the figure, there is no distinct pattern to the data between test runs or sampling locations. Sulfur dioxide concentrations are not presented for Runs 1 and 4 at the secondary chamber exit and for Runs 4 and 7 at the ESP outlet due to equipment problems experienced during sampling.

Total hydrocarbons were measured at the secondary chamber exit only and ranged between -0.5 (zero) and 1.3 ppmv. The data were invalidated for Runs 1 and 4 due to equipment failures. Typical of combustors of this type,

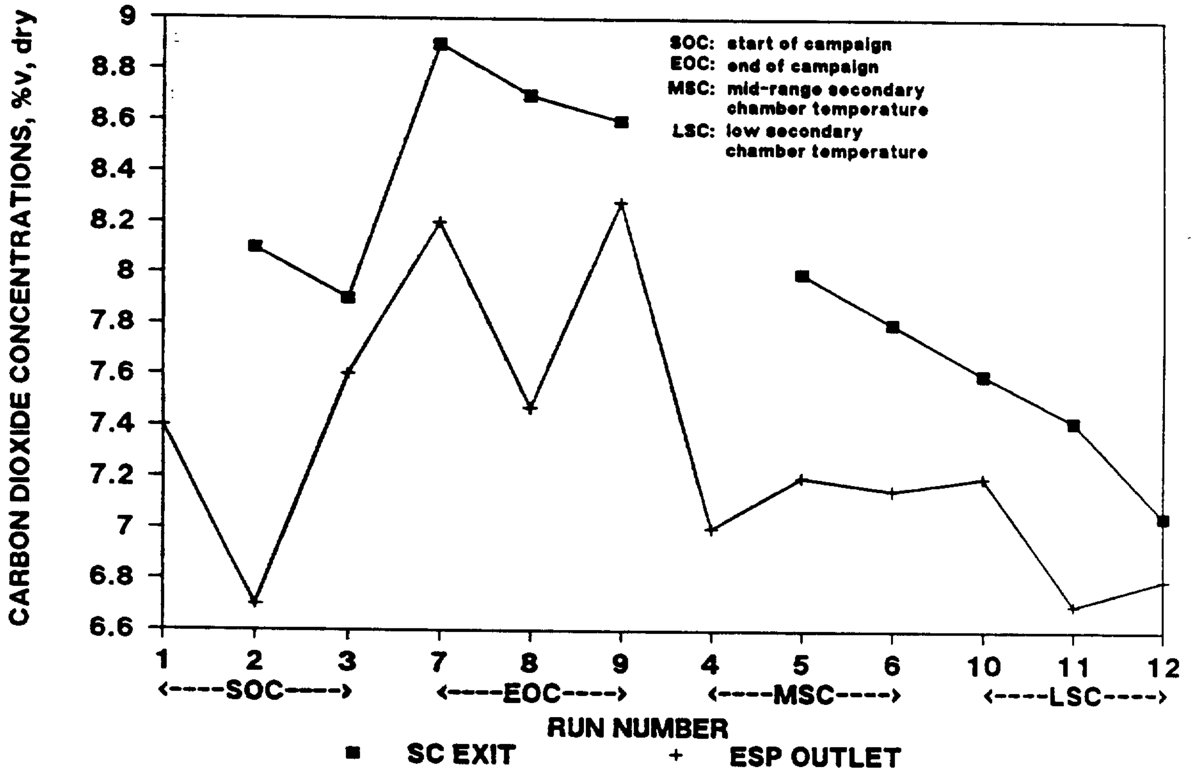


Figure 4-21. Unadjusted Carbon Dioxide Concentrations by Run Number

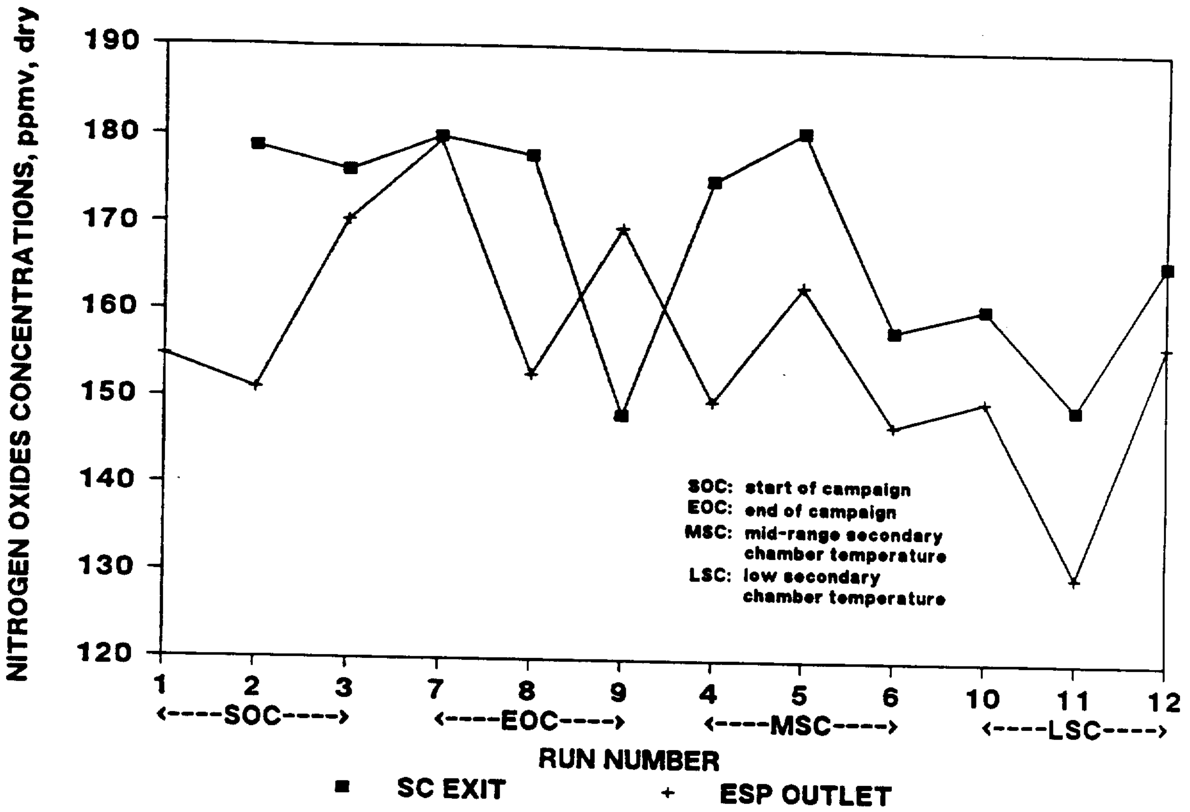


Figure 4-22. Unadjusted Nitrogen Oxides Concentrations by Run Number

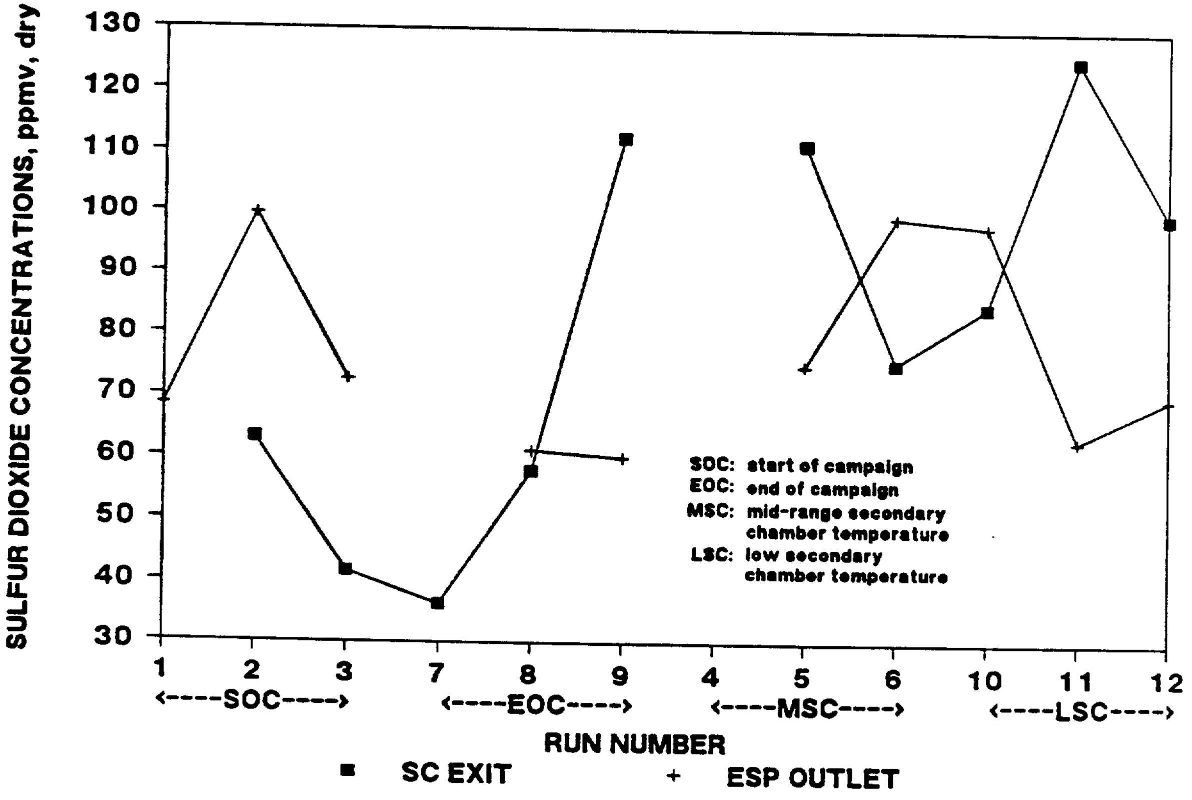


Figure 4-23. Unadjusted Sulfur Dioxide Concentrations by Run Number

THC concentrations are low and may be considered to be essentially zero, since these values are so low as to be at the limits of detection for the analyzer.

## PARTICULATE AND HCl DATA

Tables 4-14, 4-15, 4-16, and 4-17 present summary tables of particulate and HCl concentrations and mass rates at the ESP inlet and outlet. The particulate tests were not performed concurrently with the CDD and CDF test runs and, therefore, the CDD and CDF results should not be compared directly to the particulate results. Additional supporting data, including volume of gas sampled, flue gas flowrate, flue gas temperature, flue gas moisture, steam load, and average secondary chamber temperature are also shown.

Uncontrolled (ESP inlet) particulate concentrations ranged between 0.079 and 0.253 gr/dscf. Controlled (ESP outlet) particulate concentrations ranged between 0.006 and 0.020 gr/dscf. Figure 4-24 compares the uncontrolled and controlled particulate emissions. As is shown in the figure, ESP inlet particulate concentrations were lowest for the end of campaign and mid-range secondary chamber temperature test series. ESP outlet particulate concentrations did not vary significantly between test runs.

Hydrogen chloride concentrations were between 485 and 648 ppm at 7 percent $O_2$ at the ESP inlet and between 356 and 693 ppm at 7 percent $O_2$ at the ESP outlet. Figure 4-25 compares the HCl concentrations from the two sampling locations by test run. As is shown in the figure, HCl concentrations did not vary significantly between test runs or sampling locations. HCl concentrations were not obtained for the secondary chamber exit or for Runs 2, 3, 10, 11, and 12 at the ESP inlet.

## PROCESS DATA

Test run averages for several process variables including key temperatures and pressures, as well as estimates of bottom ash and ESP dust generation rates are presented in Table 4-18. These data were collected to characterize incinerator performance during each test run. The process data

Table 4-14

## SUMMARY OF UNCONTROLLED PARTICULATE CONCENTRATIONS MEASURED AT THE ESP INLET

| Run Number<br>Date | 1<br>8/26/86 | 2<br>8/27/86 | 3<br>8/28/86 | 4<br>9/3/86 | 5<br>9/4/86 | 6<br>9/5/86 | 7<br>9/16/86 | 8<br>9/17/86 | 9<br>9/18/86 | 10<br>9/24/86 | 11<br>9/25/86 | 12<br>9/25/86 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Sampling Parameters**[a] | | | | | | | | | | | | |
| Volume gas sampled (dscf) | 33.5 | 32.3 | 32.4 | 31.9 | 31.6 | 30.9 | 32.2 | 33.9 | 33.2 | 30.1 | 31.6 | 31.6 |
| Stack gas flowrate (dscfm) | 9980 | 9640 | 9800 | 9380 | 9410 | 9230 | 9480 | 10300 | 9490 | 9010 | 9770 | 9670 |
| Stack temperature (deg. F) | 494 | 493 | 502 | 486 | 492 | 487 | 487 | 497 | 506 | 460 | 472 | 477 |
| Moisture (percent by volume) | 10.8 | 12.1 | 9.9 | 12.1 | 10.5 | 7.7 | 12.3 | 6.3 | 11.4 | 9.6 | 10.4 | 11.1 |
| Isokinetics (percent) | 102.7 | 103.4 | 101.0 | 103.8 | 102.7 | 102.2 | 104.0 | 100.4 | 106.9 | 102.0 | 98.8 | 100.1 |
| CO (ppm by volume)[b] | 0.1 | NR[d] | 0.0 | NR | 0.3 | 0.3 | NR | 0.6 | NR | 0.6 | 3.2 | 3.1 |
| $CO_2$ (percent by volume)[b] | 6.8 | NR | 6.8 | NR | 7.0 | 6.8 | NR | 7.4 | NR | 6.5 | 6.5 | 6.5 |
| $O_2$ (percent by volume)[b] | 13.8 | 13.8[e] | 13.7 | 13.7[e] | 13.6 | 13.7 | 13.6[e] | 13.6 | 13.6[e] | 14.2 | 14.3 | 14.8 |
| **Process Operations** | | | | | | | | | | | | |
| Steam load (lb/hr) | 13100 | 12700 | 13000 | 12000 | 11600 | 11200 | 12000 | 12600 | 13100 | 10900 | 10500 | 9300 |
| **Particulate Results**[c] | | | | | | | | | | | | |
| (front-half catch probe and filter) mg (mass) | 551.0 | 354.0 | 221.6 | 195.1 | 241.4 | 161.0 | 331.2 | 174.4 | 206.1 | 248.8 | 387.6 | 335.8 |
| gr/dscf | 0.253 | 0.169 | 0.105 | 0.094 | 0.118 | 0.080 | 0.158 | 0.079 | 0.096 | 0.127 | 0.189 | 0.163 |
| gr/dscf @ 7% $O_2$ | 0.495 | 0.331 | 0.203 | 0.182 | 0.224 | 0.155 | 0.301 | 0.151 | 0.183 | 0.264 | 0.398 | 0.372 |
| mg/dscm | 579.1 | 386.5 | 241.0 | 215.9 | 269.0 | 183.8 | 362.0 | 181.3 | 219.7 | 291.6 | 432.3 | 374.0 |
| mg/dscm @ 7% $O_2$ | 1133.8 | 756.6 | 465.3 | 416.7 | 512.1 | 354.9 | 689.3 | 345.2 | 418.3 | 604.9 | 910.4 | 852.3 |
| lb/hr | 21.6 | 14.0 | 8.8 | 7.6 | 9.5 | 6.4 | 12.9 | 7.0 | 7.8 | 9.8 | 15.8 | 13.5 |
| kg/hr | 9.8 | 6.3 | 4.0 | 3.4 | 4.3 | 2.9 | 5.8 | 3.2 | 3.5 | 4.5 | 7.2 | 6.1 |

[a] Standard Conditions are 68 deg. F (20 deg. C) and 1 atm (101325 Pa).

[b] These values are averages of data (dry basis) taken over the sampling period from continuous emission monitors located at the ESP outlet.

[c] Particulate results are adjusted for blank results.

[d] NR = Not reported.

[e] Estimated.

## Table 4-15

## SUMMARY OF CONTROLLED PARTICULATE CONCENTRATIONS MEASURED AT THE ESP OUTLET

| Run Number<br>Date | 1<br>8/26/86 | 2<br>8/27/86 | 3<br>8/28/86 | 4<br>9/3/86 | 5<br>9/4/86 | 6<br>9/5/86 | 7<br>9/16/86 | 8<br>9/17/86 | 9<br>9/18/86 | 10<br>9/24/86 | 11<br>9/25/86 | 12<br>9/25/86 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Sampling Parameters**[a] | | | | | | | | | | | | |
| Volume gas sampled (dscf) | 44.0 | 44.6 | 46.6 | 43.2 | 39.1 | 40.3 | 41.5 | 41.6 | 41.3 | 34.5 | 40.1 | 40.2 |
| Stack gas flowrate (dscfm) | 10900 | 10700 | 11400 | 10200 | 9460 | 9750 | 9960 | 10400 | 10000 | 8620 | 10100 | 10000 |
| Stack temperature (deg. F) | 438 | 446 | 444 | 432 | 431 | 428 | 425 | 441 | 454 | 407 | 423 | 430 |
| Moisture (percent by volume) | 9.6 | 10.7 | 8.8 | 10.8 | 10.4 | 10.2 | 10.9 | 9.8 | 10.5 | 9.1 | 9.6 | 10.6 |
| Isokinetics (percent) | 97.4 | 100.0 | 98.2 | 101.6 | 99.2 | 101.2 | 100.0 | 96.2 | 99.0 | 95.9 | 95.3 | 96.1 |
| CO (ppm by volume)[b] | 0.1 | NR[d] | 0.0 | NR | 0.3 | 0.3 | NR | 0.6 | NR | 0.6 | 3.2 | 3.1 |
| $CO_2$ (percent by volume)[b] | 6.8 | NR | 6.8 | NR | 7.0 | 6.8 | NR | 7.4 | NR | 6.5 | 6.5 | 6.5 |
| $O_2$ (percent by volume)[b] | 13.8 | 13.8[e] | 13.7 | 13.7[e] | 13.6 | 13.7 | 13.6[e] | 13.6 | 13.6[e] | 14.2 | 14.3 | 14.8 |
| **Process Operations** | | | | | | | | | | | | |
| Steam load (lb/hr) | 13100 | 12700 | 13000 | 12000 | 11600 | 11200 | 12000 | 12600 | 13100 | 10900 | 10500 | 9300 |
| **Particulate Results**[c] | | | | | | | | | | | | |
| (front-half catch probe and filter) mg (mass) | 38.6 | 30.0 | 43.6 | 19.5 | 15.9 | 30.5 | 18.6 | 15.8 | 16.1 | 20.4 | 51.5 | 28.0 |
| gr/dscf | 0.014 | 0.010 | 0.014 | 0.007 | 0.006 | 0.012 | 0.007 | 0.006 | 0.006 | 0.009 | 0.020 | 0.011 |
| gr/dscf @ 7% $O_2$ | 0.026 | 0.020 | 0.028 | 0.013 | 0.012 | 0.023 | 0.013 | 0.011 | 0.011 | 0.019 | 0.042 | 0.024 |
| mg/dscm | 30.9 | 23.7 | 33.0 | 15.9 | 14.3 | 26.7 | 15.8 | 13.4 | 13.7 | 20.8 | 45.3 | 24.5 |
| mg/dscm @ 7% $O_2$ | 60.5 | 46.4 | 63.7 | 30.7 | 27.3 | 51.5 | 30.1 | 25.5 | 26.1 | 43.3 | 95.4 | 55.9 |
| lb/hr | 1.3 | 0.9 | 1.4 | 0.6 | 0.5 | 1.0 | 0.6 | 0.5 | 0.5 | 0.7 | 1.7 | 0.9 |
| kg/hr | 0.6 | 0.4 | 0.6 | 0.3 | 0.2 | 0.4 | 0.3 | 0.2 | 0.2 | 0.3 | 0.8 | 0.4 |

[a] Standard Conditions are 68 deg. F (20 deg. C) and 1 atm (101325 Pa).

[b] These values are averages of data (dry basis) taken over the sampling period from continuous emission monitors located at the ESP outlet.

[c] Particulate results are adjusted for blank results.

[d] NR = Not reported.

[e] Estimated.

## Table 4-16

## SUMMARY OF HCl CONCENTRATIONS MEASURED AT THE ESP INLET

| Run Number<br>Date | 1<br>8/26/86 | 2<br>8/27/86 | 3<br>8/28/86 | 4<br>9/3/86 | 5<br>9/4/86 | 6<br>9/5/86 | 7<br>9/16/86 | 8<br>9/17/86 | 9<br>9/18/86 | 10<br>9/24/86 | 11<br>9/25/86 | 12<br>9/26/86 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Sampling Parameters[a] | | | | | | | | | | | | |
| Volume gas sampled (dscf) | 99.8 | 93.9 | 95.7 | 89.2 | 92.1 | 90.5 | 87.1 | 93.9 | 94.2 | 98.1 | 90.2 | 88.8 |
| Stack gas flowrate (dscfm) | 9780 | 9670 | 9550 | 9230 | 9080 | 8930 | 8380 | 9260 | 9290 | 9920 | 9140 | 8770 |
| Stack temperature (deg. F) | 497 | 489 | 496 | 483 | 485 | 481 | 484 | 490 | 500 | 465 | 461 | 474 |
| Moisture (percent by volume) | 11.7 | 11.0 | 9.9 | 11.1 | 11.2 | 10.8 | 14.6 | 12.2 | 11.6 | 11.6 | 11.0 | 11.6 |
| Isokinetics (percent) | 103.9 | 98.9 | 102.1 | 98.5 | 103.3 | 103.2 | 105.9 | 103.3 | 103.3 | 101.2 | 100.5 | 103.3 |
| CO (ppm by volume)[b] | 0.1 | 0.4 | 0.6 | 0.2 | 0.4 | 2.6 | 1.0 | 2.3 | 1.8 | 3.1 | 3.0 | 1.3 |
| $CO_2$ (percent by volume)[b] | 7.4 | 6.7 | 7.6 | 7.0 | 7.2 | 7.2 | 8.2 | 7.5 | 8.3 | 7.2 | 6.7 | 6.8 |
| $O_2$ (percent by volume)[b] | 13.4 | 14.0 | 13.4 | 13.9 | 13.6 | 13.8 | 13.0 | 13.8 | 12.9 | 14.0 | 14.3 | 14.3 |
| Process Operations | | | | | | | | | | | | |
| Steam load (lb/hr) | 13100 | 12700 | 13000 | 12000 | 11600 | 11200 | 12000 | 12600 | 13100 | 10900 | 10500 | 9300 |
| HCl Results[c] | | | | | | | | | | | | |
| gr/dscf | 0.201 | NR[d] | NR | 0.190 | 0.184 | 0.187 | 0.195 | 0.213 | 0.180 | NR | NR | NR |
| gr/dscf @ 7% $O_2$ | 0.373 | NR | NR | 0.377 | 0.350 | 0.366 | 0.342 | 0.418 | 0.313 | NR | NR | NR |
| mg/dscm | 460.9 | NR | NR | 434.5 | 420.9 | 428.3 | 445.1 | 488.2 | 411.8 | NR | NR | NR |
| mg/dscm @ 7% $O_2$ | 854.1 | NR | NR | 862.7 | 801.4 | 838.5 | 783.2 | 955.7 | 715.4 | NR | NR | NR |
| ppm | 312.5 | NR | NR | 294.6 | 285.4 | 290.4 | 301.8 | 331.0 | 279.2 | NR | NR | NR |
| ppm @ 7% $O_2$ | 579.2 | NR | NR | 585.0 | 543.4 | 568.6 | 531.1 | 648.1 | 485.2 | NR | NR | NR |
| lb/hr | 16.9 | NR | NR | 15.0 | 14.3 | 14.3 | 14.0 | 16.9 | 14.3 | NR | NR | NR |
| kg/hr | 7.7 | NR | NR | 6.8 | 6.5 | 6.5 | 6.3 | 7.7 | 6.5 | NR | NR | NR |

[a] Standard Conditions are 68 deg. F (20 deg. C) and 1 atm (101325 Pa).

[b] These values are averages of data (dry basis) taken over the sampling period from continuous emission monitors located at the ESP outlet.

[c] HCl results reported as chlorides.

[d] NR = Not reported.

## Table 4-17

## SUMMARY OF HCl CONCENTRATIONS MEASURED AT THE ESP OUTLET

| Run Number | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Date | 8/26/86 | 8/27/86 | 8/28/86 | 9/3/86 | 9/4/86 | 9/5/86 | 9/16/86 | 9/17/86 | 9/18/86 | 9/24/86 | 9/25/86 | 9/26/86 |
| **Sampling Parameters**[a] | | | | | | | | | | | | |
| Volume gas sampled (dscf) | 136.7 | 137.0 | 139.3 | 132.6 | 126.4 | 118.9 | 115.2 | 117.0 | 124.5 | 121.7 | 116.4 | 104.9 |
| Stack gas flowrate (dscfm) | 11100 | 11000 | 11400 | 10700 | 10200 | 9860 | 9170 | 9680 | 9950 | 10100 | 9800 | 8570 |
| Stack temperature (deg. F) | 454 | 455 | 449 | 441 | 439 | 434 | 438 | 444 | 461 | 430 | 430 | 428 |
| Moisture (percent by volume) | 10.0 | 10.2 | 9.6 | 9.8 | 10.6 | 9.6 | 12.3 | 11.7 | 11.2 | 11.1 | 10.9 | 11.7 |
| Isokinetics (percent) | 98.7 | 99.3 | 98.1 | 98.8 | 98.9 | 96.6 | 100.5 | 96.7 | 100.1 | 96.5 | 95.0 | 98.0 |
| CO (ppm by volume)[b] | 0.1 | 0.4 | 0.6 | 0.2 | 0.4 | 2.6 | 1.0 | 2.3 | 1.8 | 3.1 | 3.0 | 1.3 |
| $CO_2$ (percent by volume)[b] | 7.4 | 6.7 | 7.6 | 7.0 | 7.2 | 7.2 | 8.2 | 7.5 | 8.3 | 7.2 | 6.7 | 6.8 |
| $O_2$ (percent by volume)[b] | 13.4 | 14.0 | 13.4 | 13.9 | 13.6 | 13.8 | 13.0 | 13.8 | 12.9 | 14.0 | 14.3 | 14.3 |
| **Process Operations** | | | | | | | | | | | | |
| Steam load (lb/hr) | 13100 | 12700 | 13000 | 12000 | 11600 | 11200 | 12000 | 12600 | 13100 | 10900 | 10500 | 9300 |
| **HCl Results**[c] | | | | | | | | | | | | |
| gr/dscf | 0.235 | 0.166 | 0.241 | 0.189 | 0.219 | 0.162 | 0.176 | 0.170 | 0.182 | 0.114 | 0.187 | 0.171 |
| gr/dscf @ 7% $O_2$ | 0.436 | 0.335 | 0.447 | 0.376 | 0.418 | 0.317 | 0.310 | 0.332 | 0.316 | 0.229 | 0.393 | 0.360 |
| mg/dscm | 538.9 | 380.8 | 551.7 | 433.1 | 501.8 | 370.4 | 403.8 | 388.6 | 416.3 | 260.7 | 426.9 | 391.2 |
| mg/dscm @ 7% $O_2$ | 998.7 | 767.0 | 1022.5 | 860.1 | 955.5 | 725.1 | 710.5 | 760.8 | 723.2 | 525.2 | 899.1 | 823.9 |
| ppm | 365.4 | 258.2 | 374.1 | 293.7 | 340.3 | 251.2 | 273.8 | 263.5 | 282.3 | 176.8 | 289.5 | 265.3 |
| ppm @ 7% $O_2$ | 677.3 | 520.2 | 693.4 | 583.3 | 647.9 | 491.7 | 481.8 | 515.9 | 490.5 | 356.1 | 609.7 | 558.7 |
| lb/hr | 22.4 | 15.7 | 23.6 | 17.4 | 19.2 | 13.7 | 13.9 | 14.1 | 15.5 | 9.9 | 15.7 | 12.6 |
| kg/hr | 10.2 | 7.1 | 10.7 | 7.9 | 8.7 | 6.2 | 6.3 | 6.4 | 7.0 | 4.5 | 7.1 | 5.7 |

[a] Standard Conditions are 68 deg. F (20 deg. C) and 1 atm (101325 Pa).

[b] These values are averages of data (dry basis) taken over the sampling period from continuous emission monitors located at the ESP outlet.

[c] HCl results reported as chlorides.

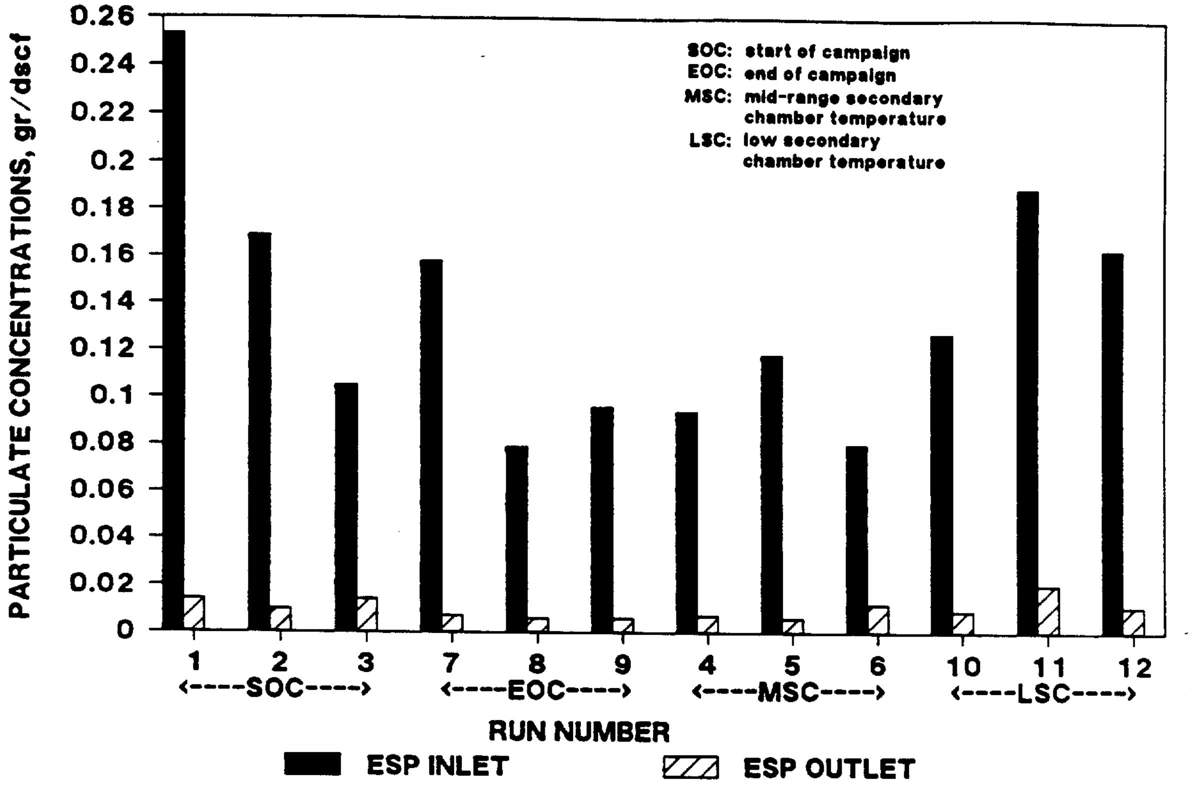


Figure 4-24. Particulate Concentrations by Run Number

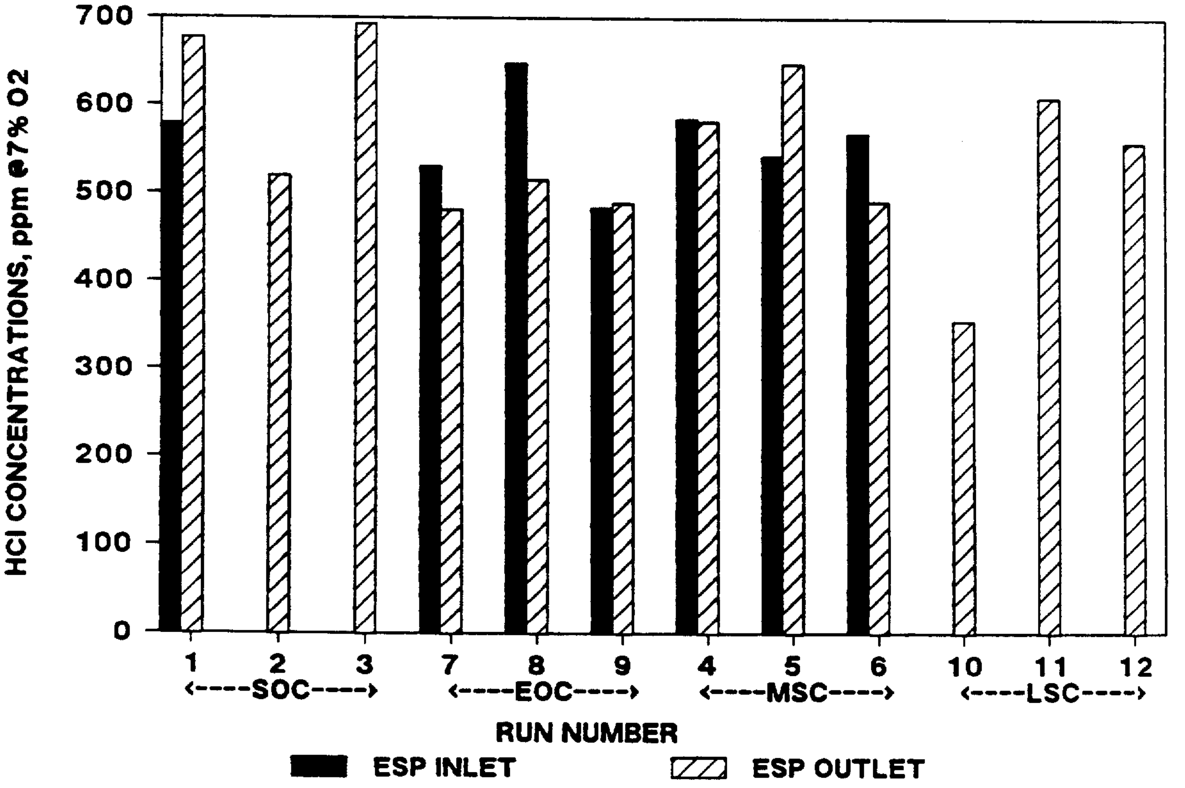


Figure 4-25. HCl Concentrations by Run Number

Table 4-18

PROCESS DATA SUMMARY

| Run Number | Average SCE Temp., °F | Secondary Chamber Temp., °F | Primary Chamber Temp., °F | Boiler Outlet Temp., °F | Boiler Inlet Temp., °F | Incinerator Draft Pressure, in. W.C. | Upper Chamber Combustion Air Pressure, in. W.C. | Lower Chamber Combustion Air Pressure, in. W.C. | Boiler Differential Pressure, in. W.C. | ESP Dust, lb/hr | Bottom Ash, lb/hr |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1516.4 | 1877.3 | 1513.0 | 513.6 | 1565.6 | 0.88 | (a) | 2.64 | 2.91 | 7.5 | 1440 |
| 2 | 1450.6 | 1851.1 | 1441.1 | 513.7 | 1546.6 | -0.10 | (a) | 2.10 | 1.90 | 10.0 | 1850 |
| 3 | 1459.2 | 1837.6 | 1452.3 | 512.4 | 1602.2 | -0.10 | 0.50 | 2.40 | 1.90 | 8.4 | 1850 |
| 4 | (a) | 1751.7 | 1419.8 | 504.6 | 1543.9 | (a) | (a) | (a) | (a) | 8.4 | 1700 |
| 5 | 1516.0 | 1735.0 | 1450.7 | 500.6 | 1540.9 | -0.10 | 4.30 | 5.30 | 4.70 | 8.5 | 2530[b] |
| 6 | 1515.3 | 1738.1 | 1424.3 | 497.3 | 1538.0 | 0.00 | 4.70 | 4.90 | 4.90 | 6.7 | (a) |
| 7 | 1573.8 | 1816.9 | 1445.3 | 499.4 | 1610.5 | -0.10 | 3.20 | 5.70 | 3.30 | (a) | 1740 |
| 8 | 1584.0 | 1822.4 | 1434.9 | 502.9 | 1610.8 | -0.10 | 3.80 | 5.40 | 3.60 | 2.5 | 1840 |
| 9 | 1651.4 | 1833.6 | 1482.2 | 518.3 | 1653.5 | -0.01 | 4.57 | 4.84 | 4.41 | 5.2 | 1220 |
| 10 | 1341.2 | 1633.6 | 1462.5 | 482.1 | 1423.6 | 0.00 | 4.70 | 1.60 | 3.60 | 4.2 | 1030 |
| 11 | 1317.0 | 1626.5 | 1472.2 | 480.6 | 1405.5 | 0.04 | 4.44 | 1.91 | 3.16 | 10.1 | 1370 |
| 12 | 1350.4 | 1616.9 | 1415.8 | 484.5 | 1382.4 | 0.07 | 3.87 | 2.26 | 2.91 | 8.0 | 1040 |

[a] Not Reported.

[b] Ash may have contained a large amount of water.

were recorded continuously at 10-second intervals. The bottom ash and ESP dust generation rates were calculated from manual weight measurements before and after each CDD and CDF test run. The bottom ash was collected as it was discharged from the quench tank and the ESP dust was collected at the screw conveyor before it was discharged to the quench tank.

As is shown in the table, the secondary chamber temperature averaged about 1840°F for the start and end of campaign test series, 1740°F for the mid-range secondary chamber test series, and 1625°F for the low secondary chamber test series. The primary chamber temperature did not vary significantly between test conditions because this parameter was controlled to 1450°F (setpoint) for all test runs.

The boiler inlet temperature varied significantly between the start of campaign runs (average temperature ~1570°F) and the end of campaign test runs (average temperature ~1625°F). This is due to the increased thickness of ash deposits on the refractory-lined secondary chamber and ductwork. The ash deposits act as insulation to reduce heat losses.

Figures 4-26 and 4-27 present the temperatures throughout the incinerator system: primary chamber, secondary chamber, secondary chamber exit, boiler inlet, and boiler outlet. In general, the secondary chamber is the hottest section of the incinerator system, followed by the boiler inlet, secondary chamber exit, and primary chamber. For the low secondary chamber test runs, the primary chamber temperature is higher than the secondary chamber exit or boiler inlet temperature. The secondary chamber exit and the boiler inlet are separated by ducting only; therefore, the boiler inlet temperature should logically be lower than the temperature at the secondary chamber exit due to convective heat loss. However, as is shown in Figure 4-26, the boiler inlet temperature is higher than the secondary chamber exit temperature for all test runs. This is attributed to consistent measurement bias in the secondary chamber exit temperature since the thermocouples were positioned near a water-cooled probe which probably produced a temperature gradient near the thermocouple junction.

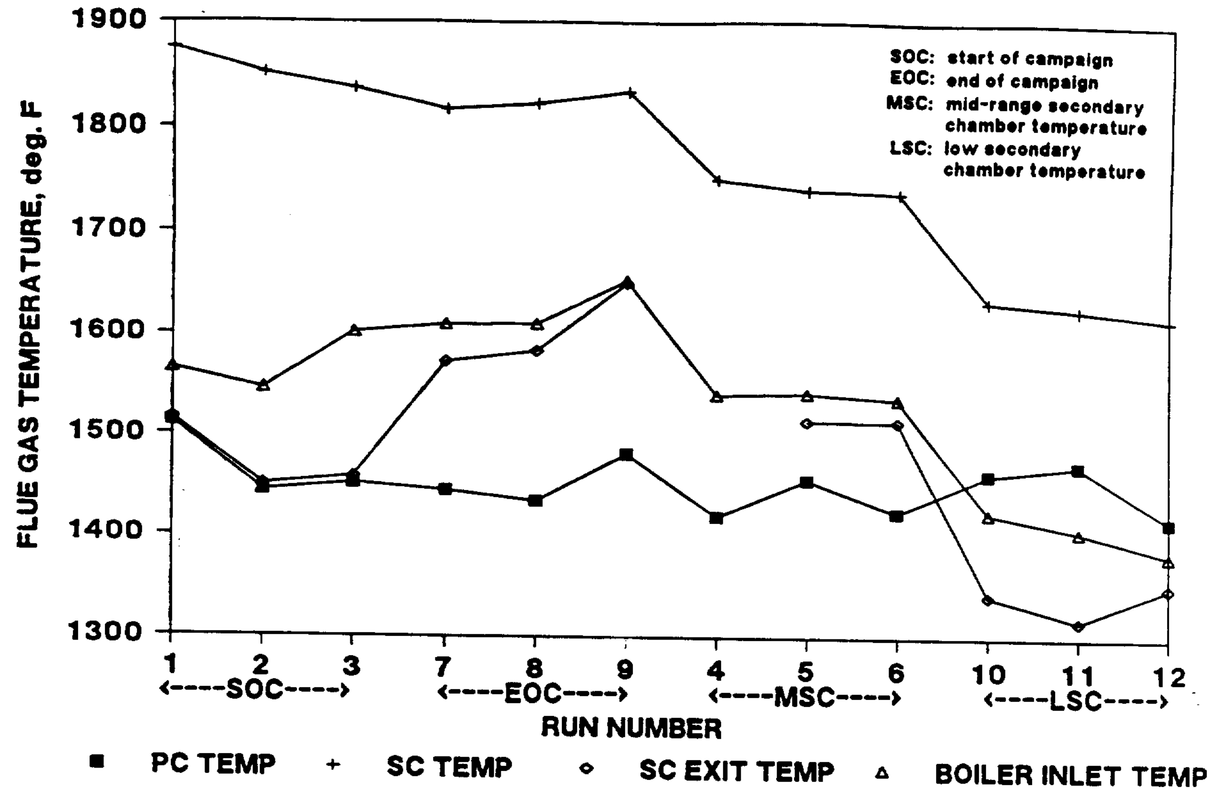


Figure 4-26. Continuously Monitored Flue Gas Temperature by Run Number

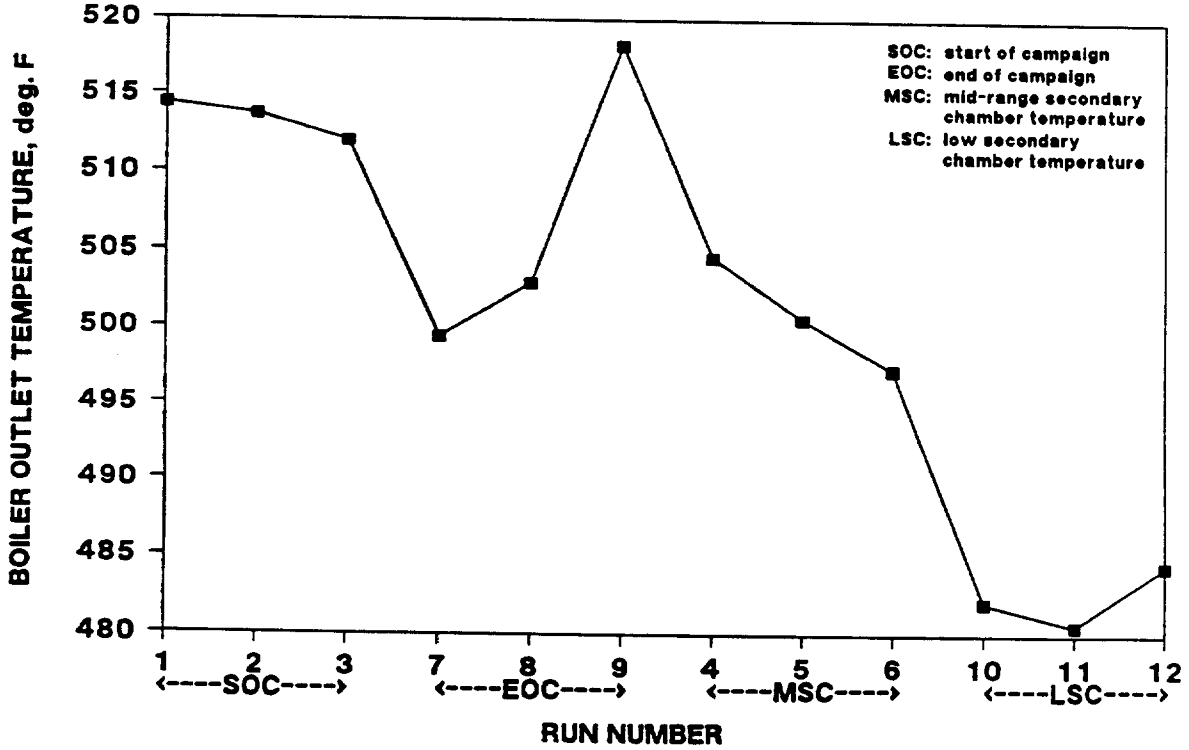


Figure 4-27. Continuously Monitored Boiler Outlet Temperature by Run Number

Figure 4-28 presents the upper (secondary) and lower (primary) chamber combustion air pressures by test run. As is shown in the figure, the lower chamber air pressure is higher than the upper chamber air pressure for all but the low secondary chamber temperature test series. This is expected since the total air flowrate and thus, air pressures were changed for this test condition (see Section 3).

Figures 4-29 and 4-30 show bottom ash and ESP dust rates, respectively, by run number. As is shown in the first figure, the bottom ash rate measured for Run 5 was unusually high. This is probably due to an excessive amount of water retained in the ash truck. The lowest bottom ash rates occurred for the low secondary chamber temperature test runs. This is most likely due to the larger feed cycle intervals (lower feed rate) that were required to achieve the setpoint for the primary chamber. The ESP dust rate varied considerably between test runs and was lowest for the end of campaign test runs. In addition, the ESP inlet and outlet particulate rates were usually not similar to the measured ESP dust rate; no obvious reason could be found to explain this difference.

## BOTTOM ASH LOSS-ON-IGNITION RESULTS

Table 4-19 presents the bottom ash loss-on-ignition results. Samples were collected each time the ash ram operated during the CDD and CDF test runs and were composited at the end of each run to provide a single daily sample.

As is shown in the table, the moisture content of the bottom ash for Runs 3 and 5 was significantly lower than for the other runs. Figures 4-31 and 4-32 present the bottom ash volatile and fixed residue results graphically. Except for Run 5, the volatile residue does not vary significantly between test runs or test series indicating there was no positive or negative impact on the ash burnout caused by the variation in combustion conditions. However, the fixed residue does vary significantly between test runs and test series, ranging from 15.2 to 54.7 percent.

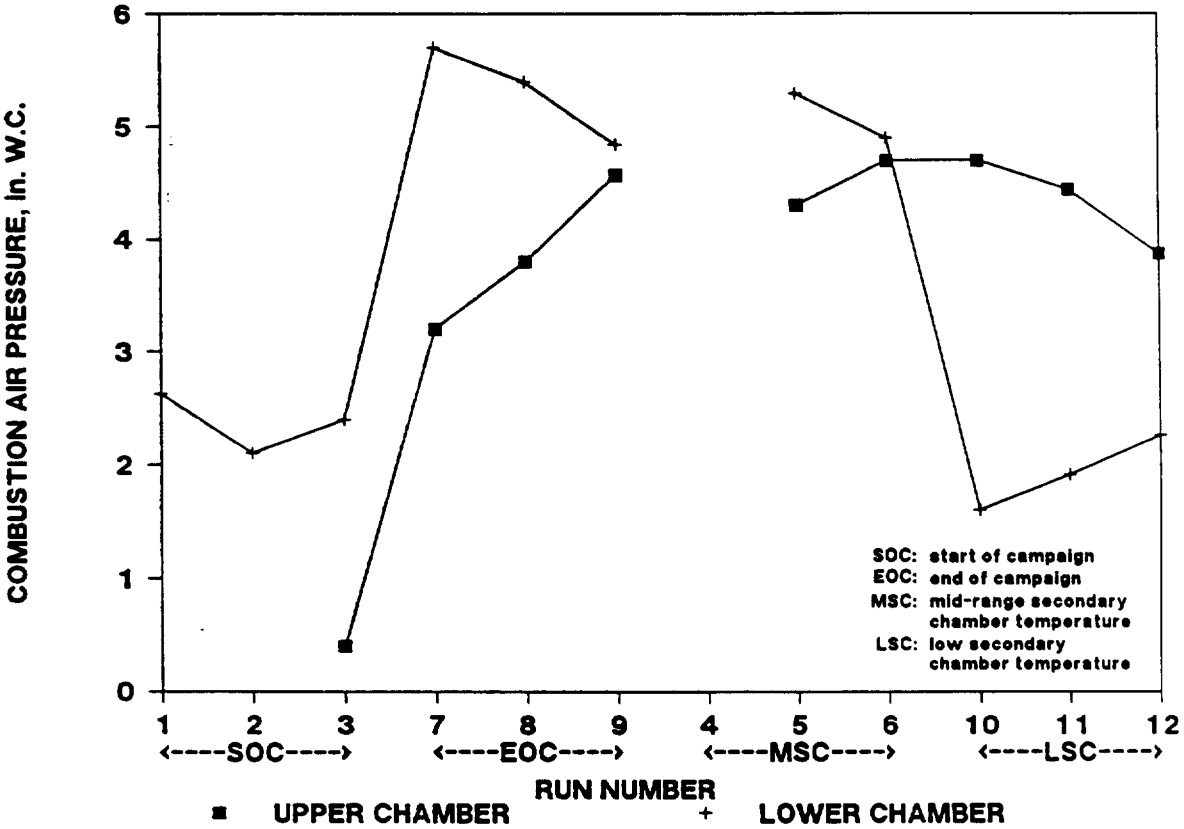


Figure 4-28. Continuously Monitored Upper and Lower Chamber Combustion Air Pressure by Run Number

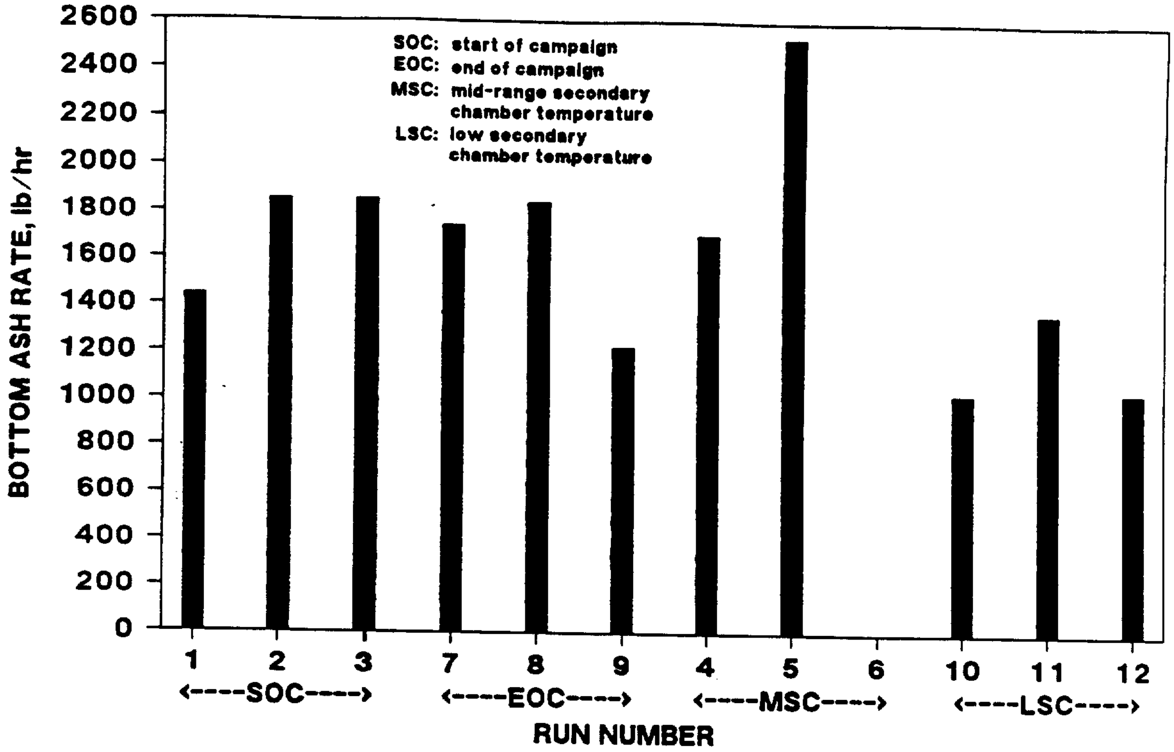


Figure 4-29. Bottom Ash Generation Rate by Run Number

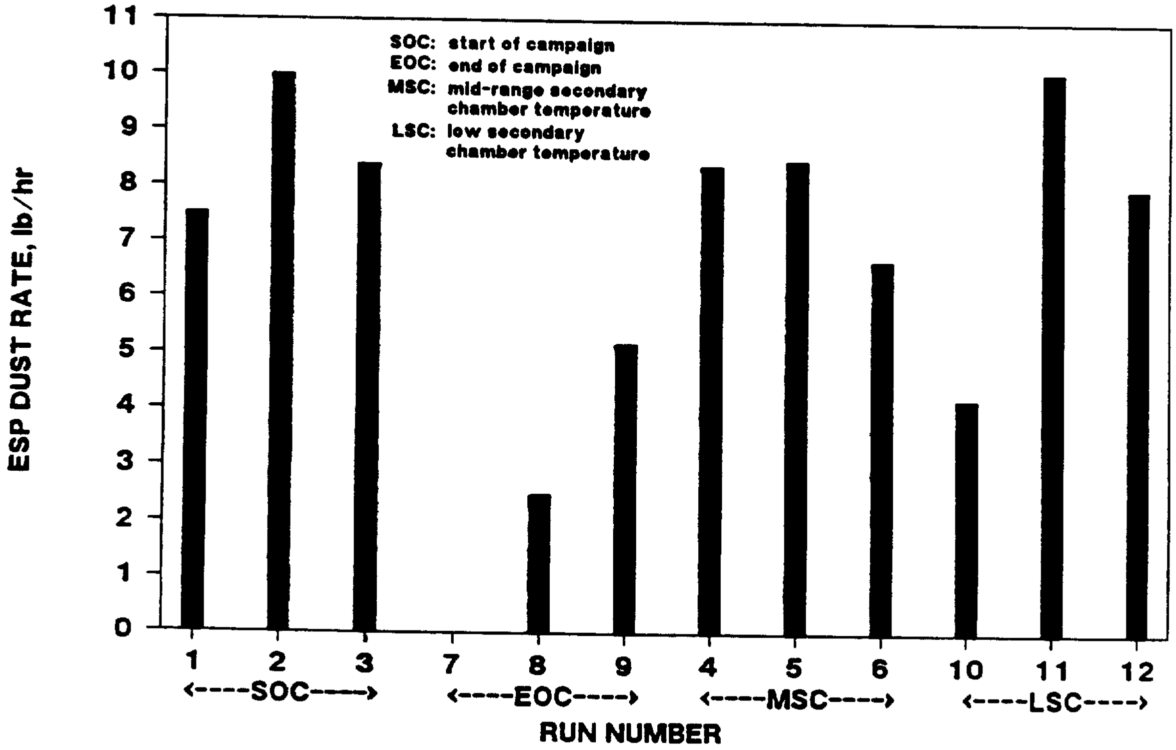


Figure 4-30. ESP Dust Generation Rate by Run Number

## Table 4-19

## INCINERATOR BOTTOM ASH LOSS-ON-IGNITION RESULTS

| Run Number | Moisture, Percent | Total Residue, Percent | Volatile[a] Residue, Percent | Fixed[a] Residue, Percent |
|---|---|---|---|---|
| 1 | 70.7 | 29.3 | 12.7 | 16.5 |
| 1 | 70.9 | 29.1 | 11.2 | 17.9 |
| Average | 70.8 | 29.2 | 12.0 | 17.2 |
| (Percent Diff.)[b] | (0.3) | (0.7) | (12.6) | (8.1) |
| 2 | 64.0 | 36.0 | 14.8 | 21.1 |
| 2 | 75.7 | 24.3 | 12.5 | 11.8 |
| Average | 69.9 | 30.1 | 13.7 | 16.5 |
| (Percent Diff.) | (16.8) | (38.8) | (16.9) | (56.5) |
| 3 | 47.1 | 52.9 | 11.3 | 41.6 |
| 3 | 35.3 | 64.7 | 8.6 | 56.2 |
| Average | 41.2 | 58.8 | 9.9 | 48.9 |
| (Percent Diff.) | (28.6) | (20.1) | (27.1) | (29.9) |
| 4 | 53.7 | 46.3 | 12.3 | 34.1 |
| 4 | 51.9 | 48.1 | 11.0 | 37.2 |
| Average | 52.8 | 47.2 | 11.5 | 35.6 |
| (Percent Diff.) | (3.4) | (3.8) | (11.2) | (42.7) |
| 5 | 35.3 | 64.7 | 6.6 | 58.1 |
| 5 | 40.9 | 59.1 | 7.7 | 51.3 |
| Average | 38.1 | 61.9 | 7.2 | 54.7 |
| (Percent Diff.) | (14.7) | (9.1) | (15.4) | (12.4) |
| 6 | 37.7 | 62.2 | 6.0 | 56.2 |
| 6 | 66.3 | 33.7 | 13.4 | 20.3 |
| Average | 52.0 | 48.0 | 9.7 | 38.2 |
| (Percent Diff.) | (55.0) | (59.4) | (76.3) | (93.9) |
| 7 | 46.5 | 53.5 | 9.4 | 44.1 |
| 7 | 53.6 | 46.4 | 13.8 | 32.6 |
| Average | 50.0 | 50.0 | 11.6 | 38.4 |
| (Percent Diff.) | (14.2) | (14.2) | (37.9) | (30.0) |
| 8 | 55.7 | 44.3 | 14.6 | 29.6 |
| 8 | 47.3 | 52.7 | 10.8 | 41.9 |
| Average | 51.5 | 48.5 | 12.7 | 35.8 |
| (Percent Diff.) | (16.3) | (17.3) | (29.9) | (34.4) |

## Table 4-19

## INCINERATOR BOTTOM ASH LOSS-ON-IGNITION RESULTS (Continued)

| Run Number | Moisture, Percent | Total Residue, Percent | Volatile[a] Residue, Percent | Fixed[a] Residue, Percent |
|---|---|---|---|---|
| 9 | 70.2 | 29.8 | 15.5 | 14.2 |
| 9 | 68.2 | 31.8 | 15.5 | 16.2 |
| Average | 69.2 | 30.7 | 15.5 | 15.2 |
| (Percent Diff.) | (2.9) | (6.5) | (0) | (13.2) |
| 10 | 69.9 | 30.1 | 14.4 | 15.8 |
| 10 | 49.2 | 50.8 | 11.0 | 39.8 |
| Average | 60.0 | 40.4 | 12.7 | 27.8 |
| (Percent Diff.) | (34.8) | (51.2) | (26.8) | (86.3) |
| 11 | 73.6 | 26.4 | 14.1 | 12.2 |
| 11 | 60.1 | 39.9 | 14.0 | 25.8 |
| Average | 66.8 | 33.1 | 14.1 | 19.0 |
| (Percent Diff.) | (20.2) | (40.7) | (0.7) | (71.6) |
| 12 | 50.2 | 49.8 | 11.0 | 38.8 |
| 12 | 71.1 | 28.9 | 15.0 | 14.0 |
| Average | 60.6 | 39.3 | 13.0 | 26.4 |
| (Percent Diff.) | (34.5) | (53.1) | (30.8) | (93.9) |

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[a] Volatile and fixed residue are presented as a percentage of the total residue.

[b] Percent difference = $\{X_1-X_2\}/\{(X_1+X_2)/2\}$ X 100.

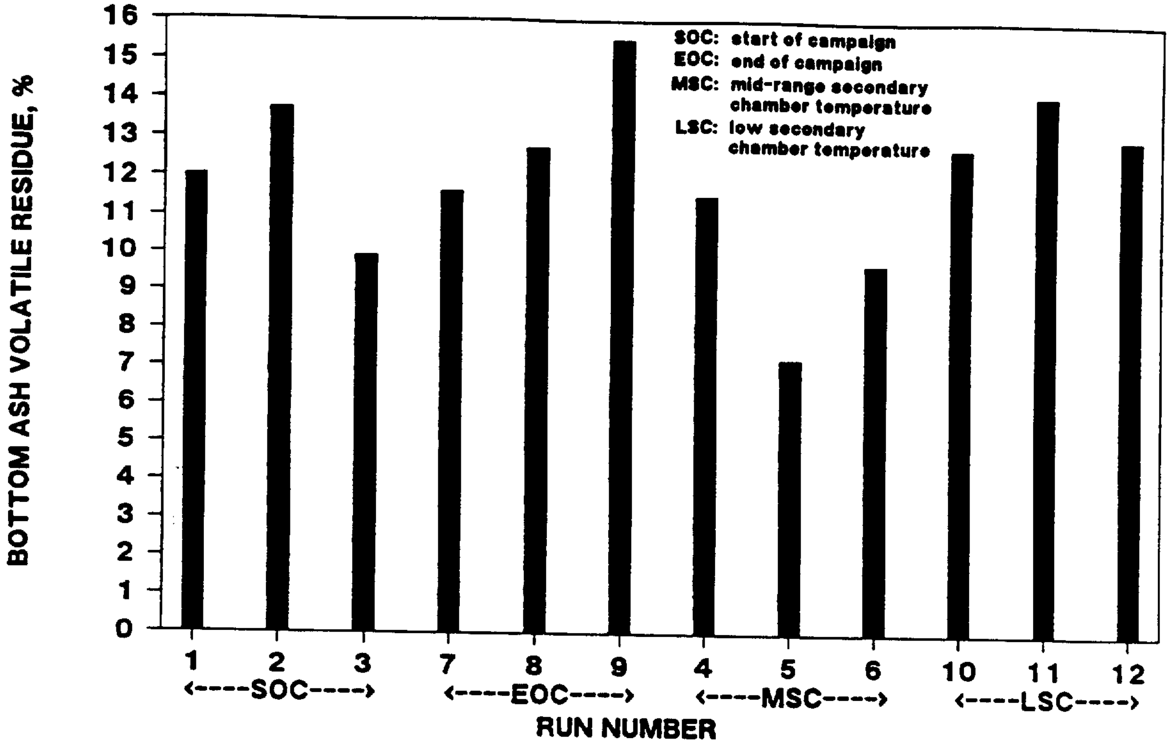


Figure 4-31. Bottom Ash Volatile Residue by Run Number

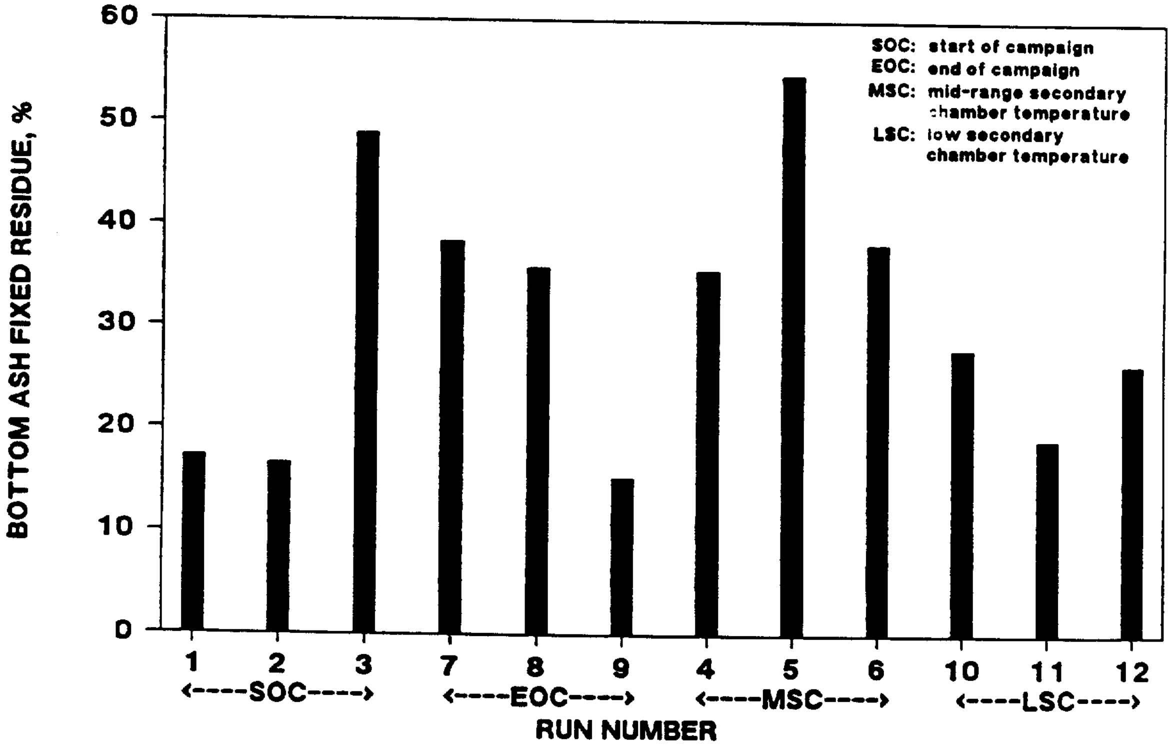


Figure 4-32. Bottom Ash Fixed Residue by Run Number

## REFUSE SAMPLING RESULTS

In an attempt to characterize the refuse at the Oswego County ERF, a random refuse load was sorted and each fraction weighed; a single daily sample was analyzed for CDD, CDF and potential precursors. Table 4-20 lists the refuse feed composition for each test run. As is shown in the table, the greatest fraction comes from paper products. This is important to note, since it is generally believed that paper products are a source of CDD(1,2). In addition, Run 7 has a much higher fraction of miscellaneous noncombustibles than the other test runs. Since the refuse sample for Run 7 contained a large fraction of noncombustibles (ground glass), it is not considered representative of a normal feed load and was not used for subsequent calculations.

The total sample weights for each test run, except Run 7, were averaged in order to estimate a normal load. A heavy load was assumed to be 25 percent larger and a light load 25 percent smaller than this normal load. Based on these assumptions and the run times given in Table 1-1, estimates of refuse feed rates were calculated. Table 4-21 presents the estimated feed rates. These feed rates were then compared to the plant's actual daily refuse receipts. In general, the estimated average plant refuse feed rates were within ± 30 percent of the actual plant refuse receipts.

Table 4-22 lists the refuse CDD and CDF results in pg per g of sample by homologue and test run. As is shown in the table, CDD was detected in the samples for only 5 of the 12 runs and CDF was detected in the samples for only 1 of the 12 test runs. In general, the only isomer detected in the samples was OCDD.

## Table 4-20

## REFUSE FEED COMPOSITION SUMMARY

| Run Number | Net Total Weight (lbs) | Feed Composition, Weight Percent | | | | | Miscellaneous | |
|---|---|---|---|---|---|---|---|---|
| | | Metal/ Glass | Wood | Paper | Plastic | Cloth | Combus-tible | Noncom-bustible |
| 1 | 636 | 7.3 | 9.5 | 57.0 | 6.4 | 2.9 | 10.6 | 6.1 |
| 2 | 581 | 4.6 | 7.1 | 73.4 | 5.7 | 3.6 | - | 5.5 |
| 3 | 562.5 | 7.4 | 4.4 | 65.7 | 7.5 | 4.4 | 0.8 | 9.9 |
| 4 | 422 | 3.9 | 9.1 | 66.4 | 6.0 | 4.3 | 1.5 | 8.8 |
| 5 | 648 | 5.2 | 2.6 | 28.8 | 6.1 | 2.9 | 37.6 | 16.9 |
| 6 | 897.5 | 4.4 | 8.7 | 24.6 | 3.8 | 2.8 | 48.1 | 7.6 |
| 7 | 1036 | 1.5 | 2.8 | 20.8 | 5.5 | 0.2 | 22.0 | 47.2 |
| 8 | 357 | 9.3 | 5.3 | 41.5 | 11.9 | 4.3 | 22.6 | 5.2 |
| 9 | 626 | 5.2 | 14.9 | 41.6 | 6.5 | 4.2 | 19.7 | 7.8 |
| 10 | 967 | 4.4 | 5.7 | 64.4 | 6.9 | 1.8 | 16.7 | - |
| 11 | 479.5 | 11.6 | 5.2 | 51.7 | 15.5 | 3.9 | 5.3 | 6.7 |
| 12 | 495 | 5.6 | 17.8 | 52.4 | 9.4 | 2.9 | 5.8 | 6.1 |

## Table 4-21

## REFUSE FEED RATE SUMMARY

| Run Number | Load | | | Run Time (hrs) | Estimated Refuse Feed Rate | | | Actual Plant Refuse Received (ton/day) |
|---|---|---|---|---|---|---|---|---|
| | | | | | Unit 1 | | Plant | |
| | Light | Normal | Heavy | | (lb/hr) | (ton/day)[a] | (ton/day)[b] | |
| 1 | 1 | 19 | 14 | 4.6 | 4960 | 59.5 | 238 | 332 |
| 2 | 12 | 23 | 1 | 4.4 | 4600 | 55.1 | 220 | 386 |
| 3 | 12 | 15 | 8 | 4.2 | 4980 | 59.8 | 239 | 269 |
| Average | | | | | 4850 | 58.1 | 232 | 329 |
| 4 | 10 | 10 | 24 | 5.3 | 5510 | 66.2 | 265 | 256 |
| 5 | 10 | 8 | 19 | 4.5 | 5280 | 63.4 | 254 | 225 |
| 6 | 7 | 14 | 3 | 2.9[c] | 4810 | 57.7 | 231 | 265 |
| Average | | | | | 5200 | 62.4 | 250 | 249 |
| 7 | 8 | 18 | 5 | 3.9 | 4710 | 56.5 | 226 | 251 |
| 8 | 5 | 20 | 10 | 4.0 | 5530 | 66.3 | 265 | 200 |
| 9 | 5 | 24 | 13 | 4.9 | 5460 | 65.5 | 262 | 202 |
| Average | | | | | 5230 | 62.8 | 251 | 218 |
| 10 | 12 | 12 | 14 | 5.3 | 4410 | 52.9 | 212 | 255 |
| 11 | 6 | 22 | 4 | 4.3 | 4440 | 53.3 | 213 | 203 |
| 12 | 9 | 17 | 2 | 4.0 | 4010 | 48.1 | 192 | 261 |
| Average | | | | | 4290 | 51.4 | 206 | 240 |

[a] The estimated Unit 1 daily feed rate assumes continuous operation throughout the day at the test run feed rate.

[b] The estimated plant feed rate is based on all four incinerators operating at the same average rate throughout the day as the Unit 1 test run feed rate.

[c] Run time does not include the port change time period because the refuse feed rates were not recorded during this period.

## Table 4-22

## REFUSE CDD AND CDF RESULTS, pg/g

| | Run Number | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
| **Dioxins** | | | | | | | | | | | | |
| Total MCDD | ND[a] | ND | ND | ND | ND | ND | ND | ND | ND | ND | ND | ND |
| Total DCDD | ND | ND | ND | ND | ND | ND | ND | ND | ND | ND | ND | ND |
| Total TrCDD | ND | ND | ND | ND | ND | ND | ND | ND | ND | ND | ND | ND |
| Total TCDD | ND | ND | ND | ND | ND | ND | ND | ND | ND | ND | ND | ND |
| Total PeCDD | ND | ND | ND | ND | ND | ND | ND | ND | ND | ND | ND | ND |
| Total HxCDD | ND | ND | ND | ND | ND | ND | ND | ND | ND | ND | ND | ND |
| Total HpCDD | ND | 1,588 | ND | ND | ND | ND | ND | ND | ND | ND | 7,310 | ND |
| 12346789-OCDD | 10,215 | 9,767 | ND | 3,304 | ND | 5,784 | ND | ND | ND | ND | | ND |
| Total CDD | 10,215 | 11,355 | ND | 3,304 | ND | 5,784 | ND | ND | ND | ND | 7,310 | ND |
| **Furans** | | | | | | | | | | | | |
| Total MCDF | ND | ND | ND | ND | ND | ND | ND | ND | ND | ND | ND | ND |
| Total DCDF | ND | ND | ND | ND | ND | 1,108 | ND | ND | ND | ND | ND | ND |
| Total TrCDF | ND | ND | ND | ND | ND | ND | ND | ND | ND | ND | ND | ND |
| Total TCDF | ND | ND | ND | ND | ND | ND | ND | ND | ND | ND | ND | ND |
| Total PeCDF | ND | ND | ND | ND | ND | ND | ND | ND | ND | ND | ND | ND |
| Total HxCDF | ND | ND | ND | ND | ND | ND | ND | ND | ND | ND | ND | ND |
| Total HpCDF | ND | ND | ND | ND | ND | ND | ND | ND | ND | ND | ND | ND |
| 12346789-OCDF | ND | ND | ND | ND | ND | ND | ND | ND | ND | ND | ND | ND |
| Total CDF | ND | ND | ND | ND | ND | 1,108 | ND | ND | ND | ND | ND | ND |

[a] Not detected.

# REFERENCES

1. Low Health Risk Seen for Dioxin in Paper Products, Chemical and Engineering News, January 11, 1988.

2. U.S. Environmental Protection Agency/Paper Industry Cooperative Dioxin Screening Study, March 1988.

# Section 5

# RELATIONSHIP BETWEEN OPERATING CONDITIONS AND COMBUSTION GAS VARIABLES

One of the primary objectives of this project was to determine, over a range of operating conditions, relationships between combustion gas variables (CEMs), plant operating conditions, and emission levels of CDD and CDF. The first step in addressing this objective is to determine how combustion gas variables vary with plant operating conditions. The questions specifically addressed in this section are:

- Which of the combustion gas and plant operating variables, if any, provide redundant information under all or some test conditions?
- Are there relationships between combustion gas variables and plant operating variables in both high and low temperature zones under all test conditions?

In summary, none of the combustion gas or plant operating variables was shown to provide redundant information. A correlation coefficient (r) of 0.9 was chosen as the level above which the parameters could be considered redundant. This implies that approximately 80 percent ($r^2 = 0.9^2 = 0.80$) of the variability in the dependent variable is explained by the independent variable(s). Several parameters were shown to correlate at an r between 0.8 and 0.9.

The lack of strong correlations between the combustion gas and operating variables may be the result of two causes. First, the magnitude of the change in the secondary chamber temperature (the primary independent variable) in this program was relatively small, ranging from 1650°F to 1850°F. The facility established these boundary limits in order to keep within emission permit limitations and to protect the process equipment. A larger experimental range may be necessary to produce stronger correlations. A second cause may be the result of the system control logic at the Oswego facility. Each incinerator system at the Oswego facility is equipped with automatic process controllers. The primary control variable is the secondary chamber temperature; this controls the combustion air split between the primary and secondary chambers. The secondary control variable is the primary chamber temperature. This temperature is regulated by feed sizes which are set by a controller for the incinerator operators to follow. Alarms are registered when a control parameter is outside the allowable bounds of the setpoint. These alarms signal the possible need for manual process adjustments to bring the control variables to within the specified limits.

The total air rate at the Oswego facility is fixed at a constant value and is normally not changed. However, for the two mid-campaign test conditions, the total air flowrate was adjusted to lower the temperature in the secondary chamber. In addition, for the low secondary chamber temperature test condition, the feed cycle, transfer ram and ash ram time intervals were manually adjusted by the operators to achieve the desired chamber temperatures and acceptable refuse volume reduction (burnout). Therefore, since several key operating parameters were varied for each test condition, this may have compounded any simple linear relationship(s) in the variables.

To investigate the relationships between operating conditions and combustion gas variables, Pearson product-moment coefficient correlations were computed for all sets of CEM and process variable data. Test run averages (unadjusted) were used in the correlations because the data were collected at various time intervals. It was not possible to estimate the response times for the different CEM analyzers or the lag time between the various monitoring locations so individual measurements could not be used. The resultant correlation coefficient matrices are presented in Appendix C.

## COMPARISON OF CEMS MEASURED AT THE SECONDARY CHAMBER EXIT AND ESP OUTLET

Pearson product-moment coefficient correlations were performed for the two sets of CEM data. However, none of the combustion gas variables at the secondary chamber exit showed a strong correlation ($|r| \geq 0.8$) with the combustion gas variables at the ESP outlet, indicating there were no strong linear relationships between the combustion gases at these two locations. This is expected since both monitoring locations are measuring the combustion gases outside the combustion zone and should, therefore, be measuring the same level. The lack of correlation could result from normal measurement uncertainty at one or both locations.

Therefore, t-tests were done to determine whether the CEMs measured at the secondary chamber exit were statistically different than those measured at the ESP outlet. The results are presented in Appendix D. The t-tests showed that Runs 6 and 8 CO concentrations and Run 4 $NO_x$ concentrations are statistically different between the two monitoring locations. However, none of the other variables was statistically different. This may explain why the combustion gas variables at the two locations did not correlate strongly.

The CEM parameters within each sampling location were then analyzed using Pearson product-moment correlations. The most strongly correlated variables are shown in Table 5-1.

Table 5-1.

COMBUSTION GAS CORRELATION MATRIX ($|r| \geq 0.8$)

| Variable/Location | Variable/Location | N | r | Significance Level |
|---|---|---|---|---|
| $O_2$ @ ESP outlet, % V | $CO_2$ @ ESP outlet, % V | 12 | -0.928 | 0.0001 |
| $O_2$ @ ESP outlet, % V | $NO_x$ @ ESP outlet, ppmv | 12 | -0.807 | 0.0015 |
| $O_2$ @ SC exit, % V | $CO_2$ @ SC exit, % V | 10 | -0.975 | 0.0001 |

As expected due to material balance considerations, $O_2$ shows a very strong negative correlation with $CO_2$ at both locations ($r > 0.9$). The high correlations validate the $O_2$ and $CO_2$ measurements. Figures 5-1 and 5-2 show scatter plots of the $O_2$ and $CO_2$ data at the secondary chamber exit and ESP outlet, respectively. As shown in the figures, the run groups tend to cluster together, with the low secondary chamber run group having the highest, and the end of campaign run group the lowest, oxygen levels.

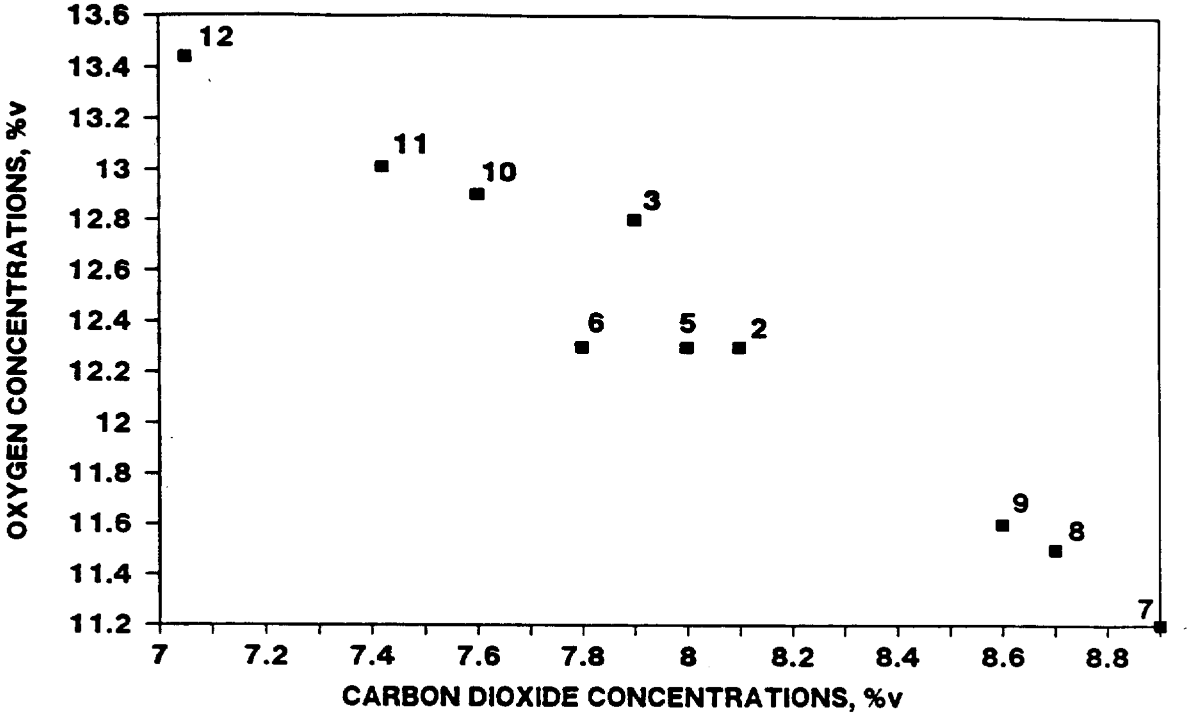


Figure 5-1. Oxygen vs. Carbon Dioxide Concentrations at the Secondary Chamber Exit Temperature (r = -0.975)

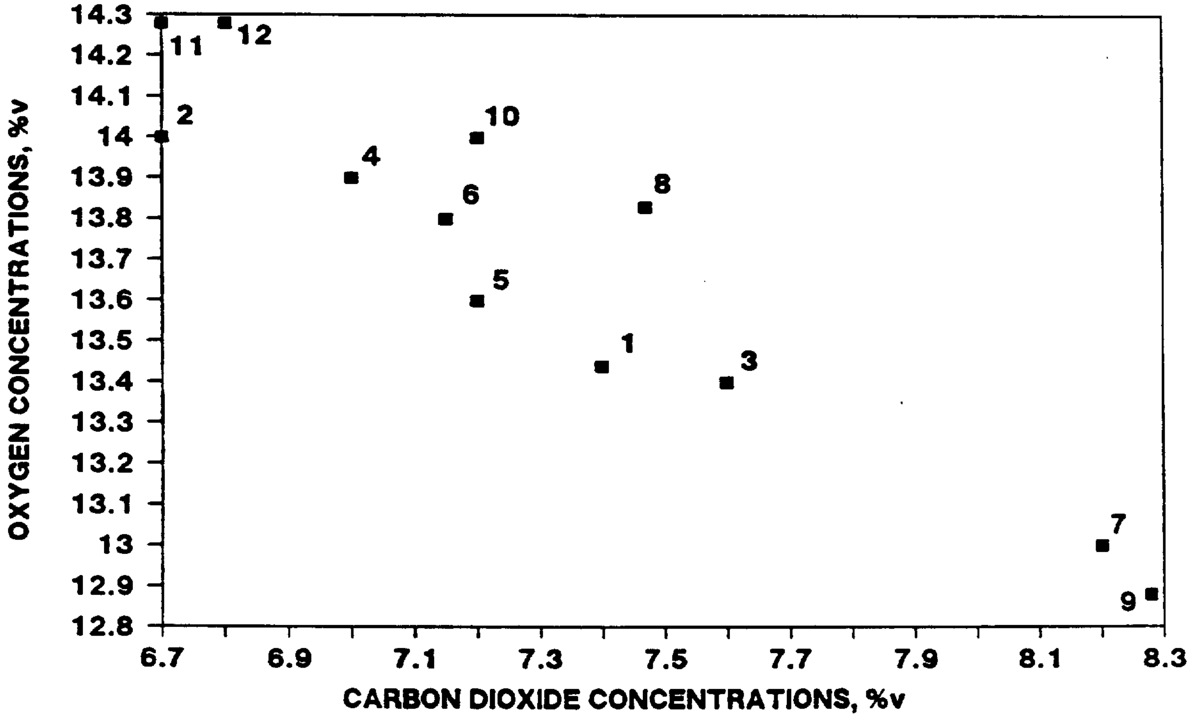


Figure 5-2. Oxygen vs. Carbon Dioxide Concentrations at the ESP Outlet (r = -0.928)

Oxygen measured at the ESP outlet also showed a negative correlation with $NO_x$ at the ESP outlet. This implies that as $O_2$ concentrations increase, $NO_x$ concentrations decrease. Assuming the majority of $NO_x$ formed from municipal solid waste incinerators is thermal $NO_x$, this relationship can be attributed to dilution; as more $O_2$ (combustion air) is introduced into the incinerator, the temperature would decrease and less thermal $NO_x$ would form. Figure 5-3 shows a scatter plot of these data. As shown in the figure, the data tend to group by test condition.

## COMPARISON OF CEM DATA MEASURED AT THE SECONDARY CHAMBER EXIT AND ESP OUTLET WITH PROCESS DATA

Pearson product-moment coefficient correlations were calculated for combustion gas data with process data. The most strongly correlated variables are listed in Table 5-2. As shown in the table, $O_2$ concentrations at both monitoring locations are negatively correlated with secondary chamber exit and boiler inlet temperature. These correlations are most likely due to dilution. Carbon dioxide measured at the secondary chamber exit showed positive correlations with secondary chamber temperature, secondary chamber exit temperature, and boiler inlet temperature. This is expected because $O_2$ and $CO_2$ are highly correlated due to combustion material balances. Figure 5-4 presents a scatter plot of $CO_2$ measured at the secondary chamber exit with secondary chamber exit temperature. As with the $O_2$ data, the $CO_2$ concentrations tend to cluster by test condition; the end of campaign test runs show the highest $CO_2$ concentrations.

On an average basis, CO did not correlate strongly with flue gas $O_2$, primary chamber temperature, secondary chamber temperature, or other process control measures. Figures 5-5 and 5-6 present scatter plots of CO measured at the secondary chamber exit versus primary and secondary chamber temperature, respectively. As shown in the figures, the data are scattered. However, the figures show that the end of campaign and low secondary chamber temperature conditions are different from the other two conditions.

The feed (loader) and ash ram cycle intervals were investigated to determine their effect, if any, on CO concentrations. Figures 5-7 and 5-8 show the ash ram cycles simultaneously with CO concentrations at the secondary chamber exit

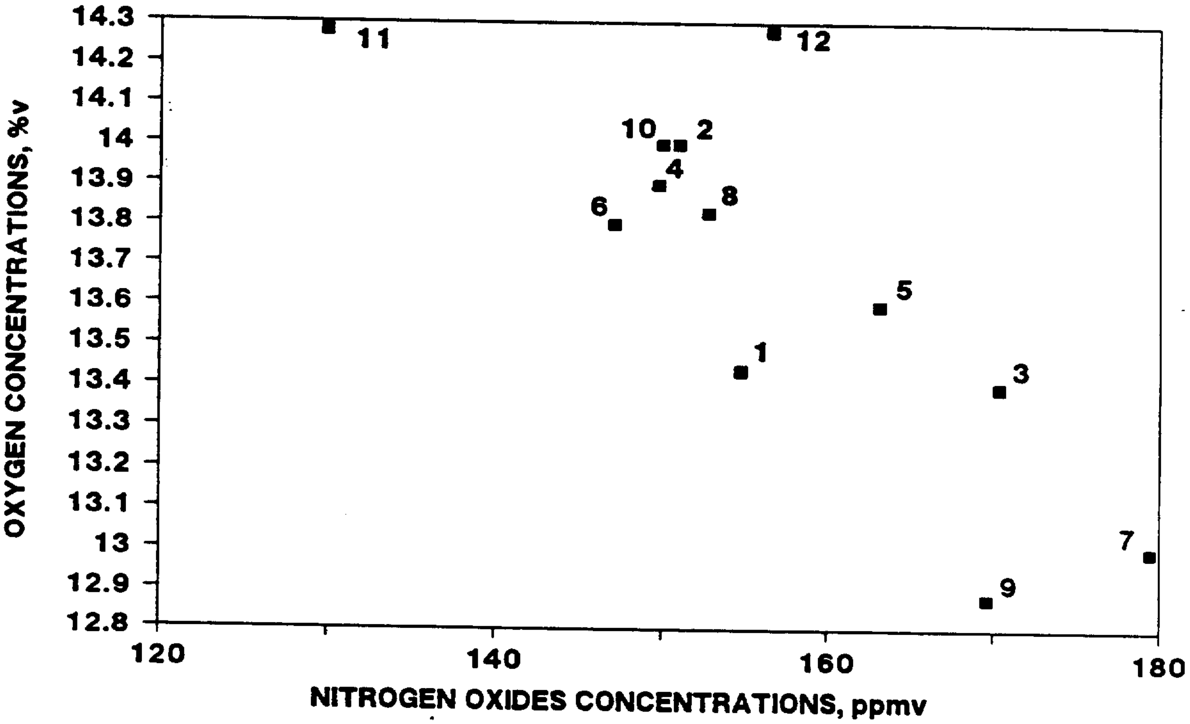


Figure 5-3. Oxygen vs. Nitrogen Oxides Concentrations at the ESP Outlet (r = -0.807)

## Table 5-2.

## PARAMETERS PROCESS CORRELATION MATRIX ($|r| \geq 0.8$)

| Variable/Location | Variable/Location | N | r | Significance Level |
|---|---|---|---|---|
| $O_2$ @ ESP outlet, % V | SC exit temp., $^oF$ | 11 | -0.834 | 0.0014 |
| $O_2$ @ ESP outlet, % V | Boiler inlet temp., $^oF$ | 12 | -0.847 | 0.0005 |
| $O_2$ @ SC exit, % V | SC exit temp., $^oF$ | 10 | -0.892 | 0.0005 |
| $O_2$ @ SC exit, % V | Boiler inlet temp., $^oF$ | 11 | -0.823 | 0.0019 |
| $O_2$ @ SC exit, % V | Lower chamber combustion air pressure, in. W.C. | 10 | -0.816 | 0.0040 |
| $CO_2$ @ SC exit, % V | SC exit temp., $^oF$ | 10 | -0.864 | 0.0013 |
| $CO_2$ @ SC exit, % V | SC temp., $^oF$ | 10 | -0.810 | 0.0045 |
| $CO_2$ @ SC exit, % V | Boiler inlet temp., $^oF$ | 10 | -0.878 | 0.0008 |
| THC @ SC exit, ppmv | Boiler outlet temp., $^oF$ | 10 | -0.815 | 0.0041 |

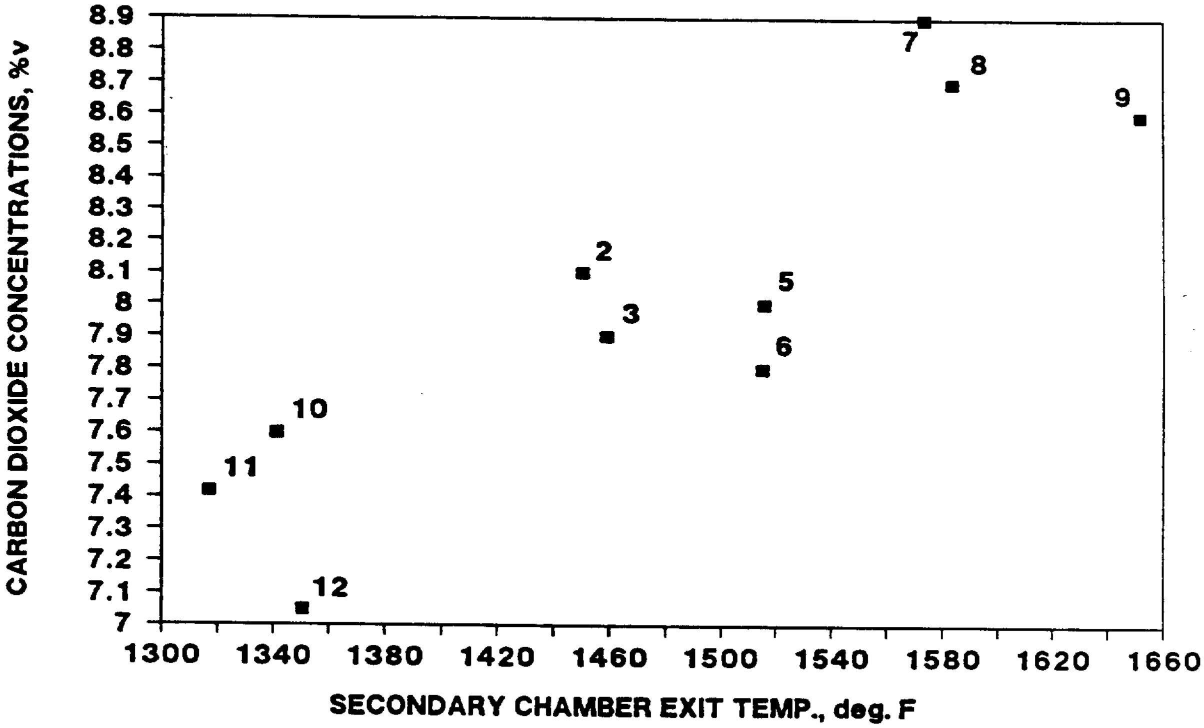


Figure 5-4. Carbon Dioxide at the Secondary Chamber Exit vs. Secondary Chamber Temperature (r = 0.864)

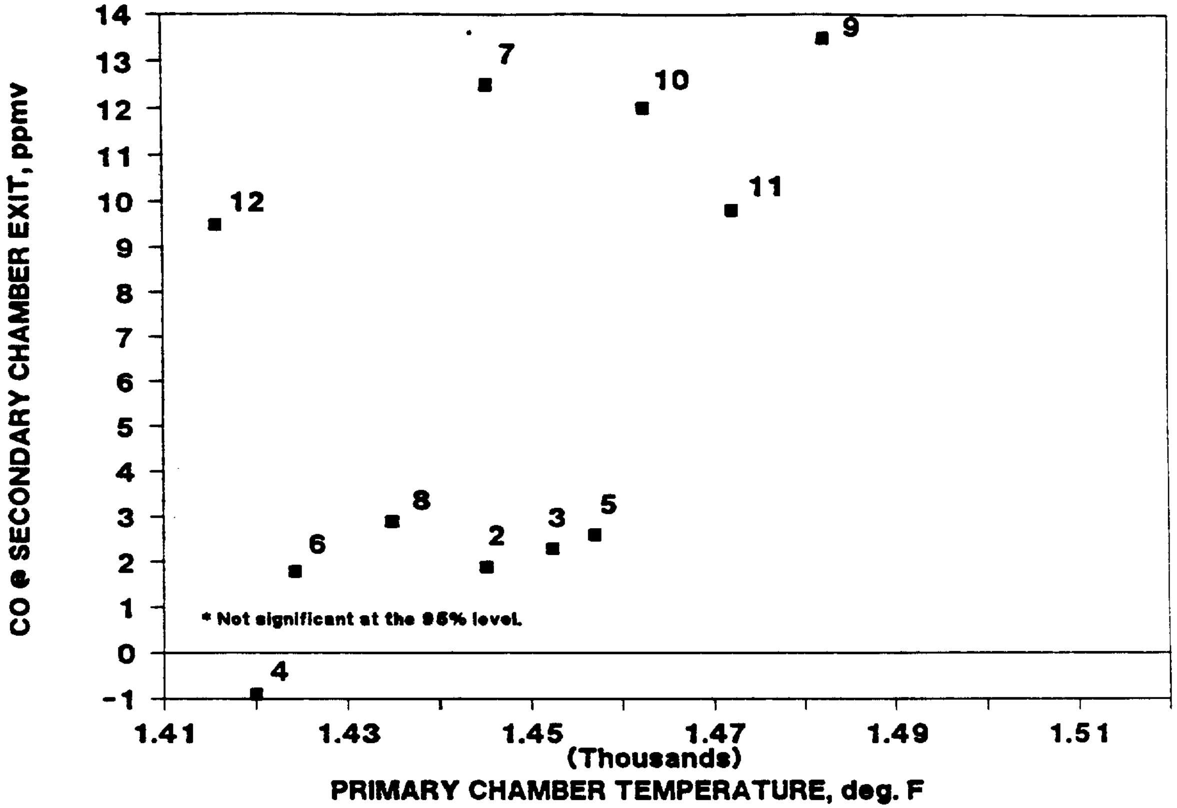


Figure 5-5. Carbon Monoxide at the Secondary Chamber Exit vs. Primary Chamber Temperature (r = 0.552*)

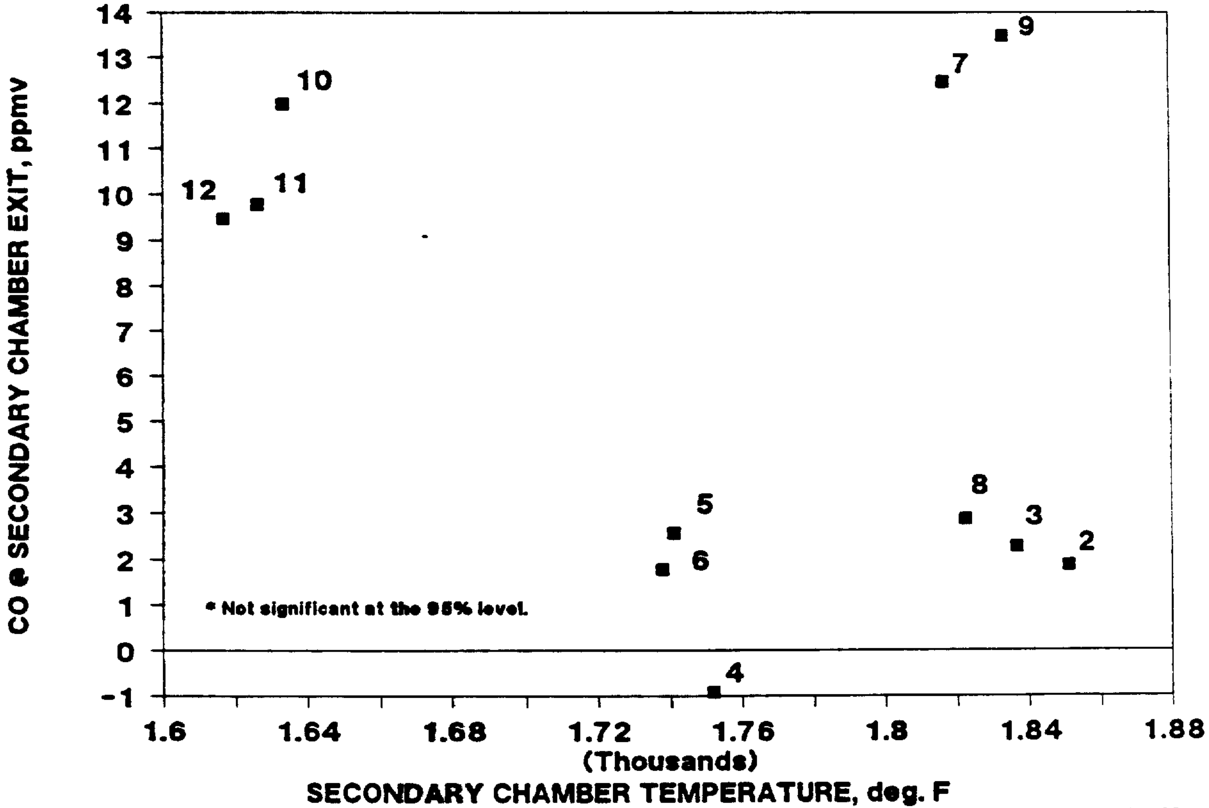


Figure 5-6. Carbon Monoxide at the Secondary Chamber Exit vs. Secondary Chamber Temperature (r = -0.311*)

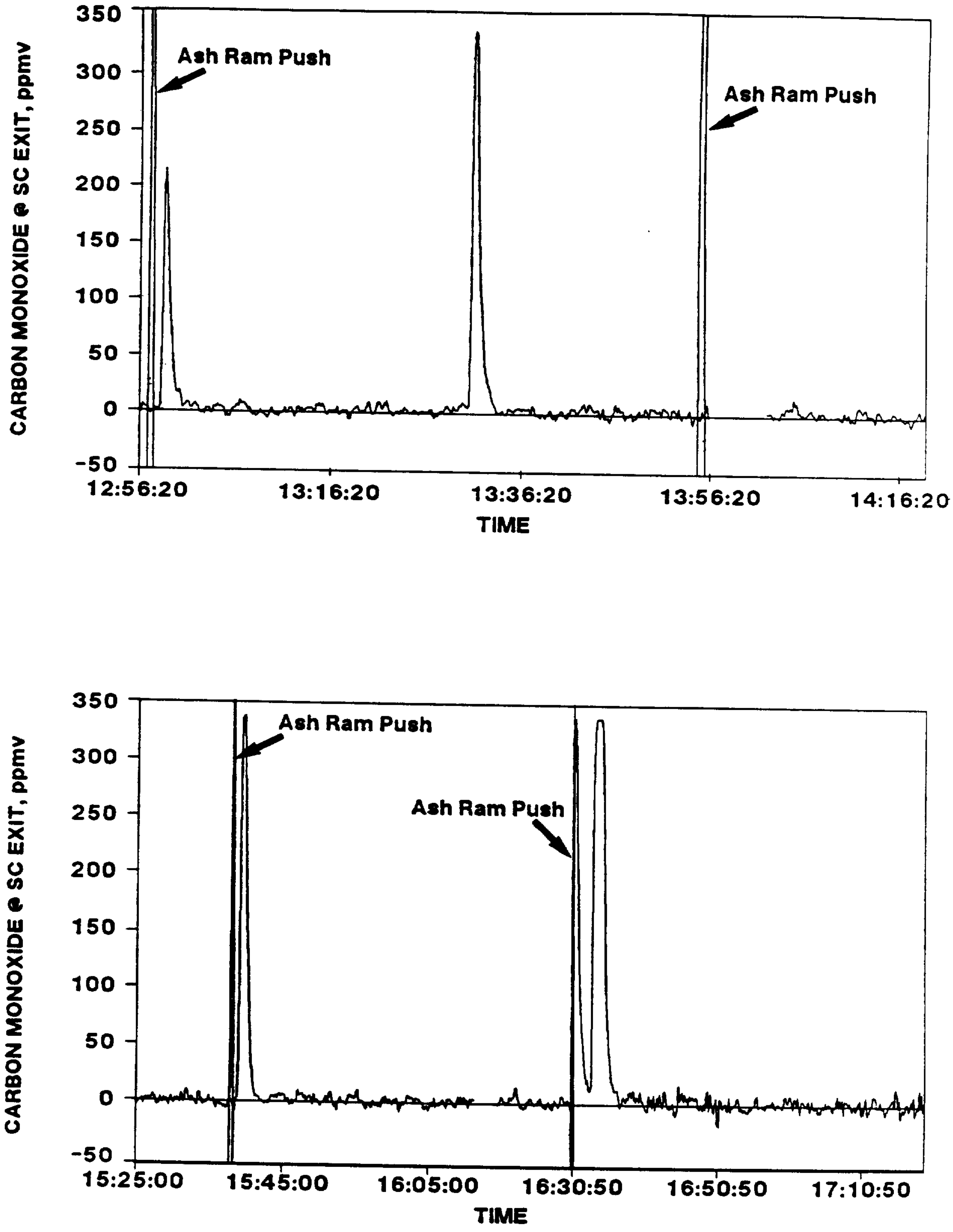
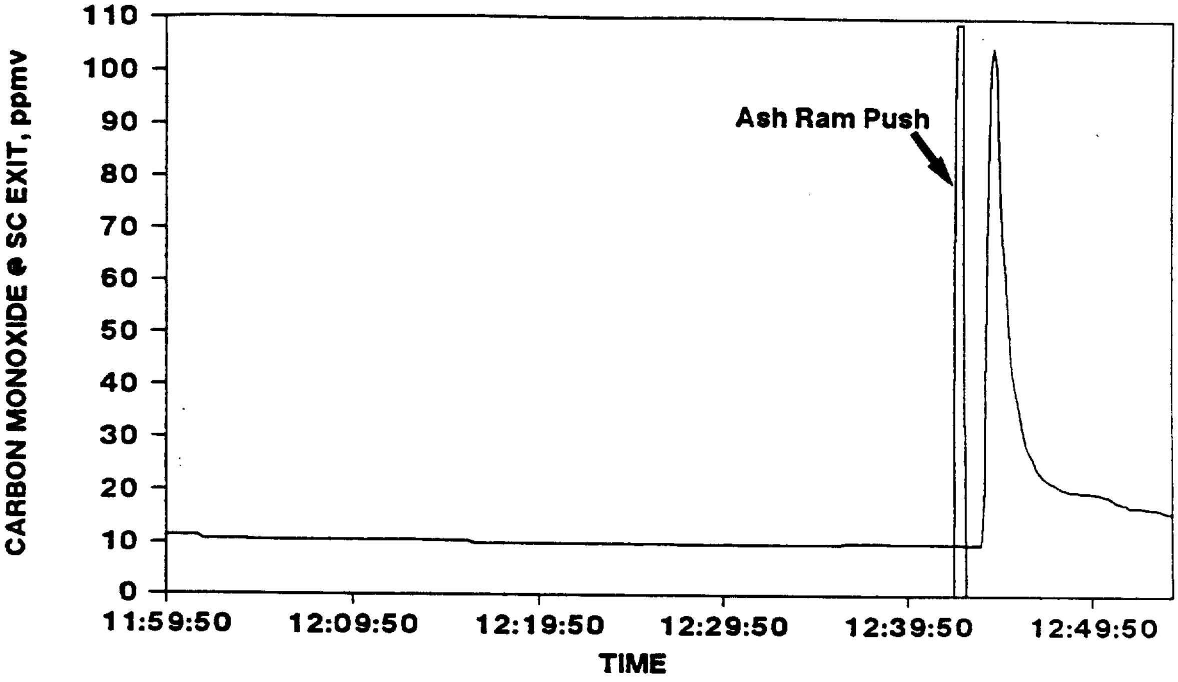


Figure 5-7. Ash Ram Time Interval and Carbon Monoxide Concentration at the Secondary Chamber Exit vs. Time - Run 7



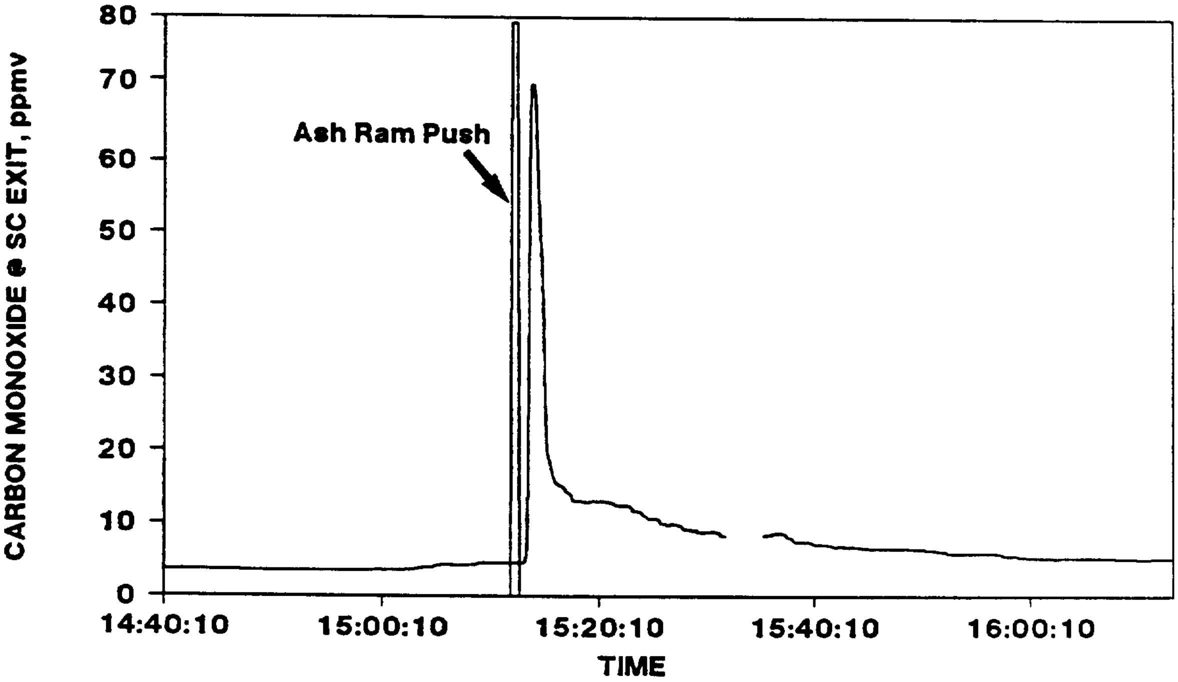


**Figure 5-8. Ash Ram Time Interval and Carbon Monoxide Concentration at the Secondary Chamber Exit vs. Time - Run 11**

for Runs 7 and 11. The data are divided by run time to show more detail. As shown in the figures, the CO spikes generally occur following ash ram operation. This may be caused by unburned refuse being exposed to combustion air when the ash ram pushes the refuse out of the furnace. This relationship may explain why no simple linear relationships of CO with key process control parameters were shown.

## Section 6

# STATISTICAL ASSESSMENT OF EXPERIMENTAL TEST CONDITIONS AND THEIR REPLICATION*

### INTRODUCTION

In the Oswego project, tests conducted at identical operating conditions were analyzed statistically to judge whether they were true replicates. This section presents the results of that data analysis and also identifies interrelationships between the CEM and incinerator operating variables. The following questions are discussed in detail:

- Are the individual runs in each operating condition replicates with respect to primary and secondary chamber temperatures?
- Are the secondary chamber temperatures for each operating condition different? Note that temperatures for the start and end of campaign test conditions should be the same, but the temperatures for the mid-range and low secondary chamber temperature test conditions should be different.
- Are the primary chamber temperatures the same for all runs under all operating conditions? The setpoint was 1450°F for all runs.
- Are the combustion gas variables (i.e., $O_2$, CO, $CO_2$, $NO_x$, $SO_2$, THC) the same or different for the replicate test runs in each operating condition and between operating conditions?
- Are the combustion gases monitored at the two locations the same for the replicates and between operating conditions?

A variety of statistical techniques, including cross-correlation, spectral, and cluster analyses, were used to address these questions. Ordinarily, the cross-relationships through time between responses (e.g., temperature and CO concentration, $O_2$ and CO concentrations) would be examined and characterized

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*Note: This section was prepared by Dr. Albert Paulson of Rensselaer Polytechnic Institute.

by cross-correlation analyses. However, virtually all of the character of the joint behavior of two time series x(t) and y(t) is captured by the spectral density and two-dimensional scatter plots of x(t) versus y(t), x(t-1) versus y(t), y(t-1), etc. Further, the two-dimensional scatter plots are particularly useful in interpreting the cross-correlation plots since the relative scale of the series x(t) and y(t) are needed for proper engineering and management interpretation.

## TIME SERIES WITH SPECTRAL AND CROSS-SPECTRAL ANALYSIS

Time series spectral analysis was used to investigate the question of reproducibility among triplicate runs. The following paragraphs discuss the time series analysis.

Time series data are typically analyzed in one or both of two domains: time or frequency. Time domain analysis describes the behavior of a series in terms of the way in which observations at different times are related statistically. Frequency domain methods seek to describe the fluctuations in one or more series in terms of sinusoidal behavior at various frequencies. The two approaches are mutually reinforcing. The time series data collected at Oswego are generally well behaved so that the time parameter may, in many cases of interest, be suppressed in a modeling analysis. The frequency domain analysis is typically referred to as spectral analysis and represents a decomposition of the time behavior into periodic components.

An invaluable aid in comparing the series is a careful visual inspection of the time series plots and the plots of the spectra. High resolution plots were generated on a CALCOMP precision plotter for all time series data (CEM and process operating data). These plots were then arranged to facilitate visual comparison of the replicate runs.

The reproducibility of the time series was first evaluated by examining the time series visually in both the time and frequency domains, and later by comparing a quantitative measure of the differences in the spectral density (frequency domain) for the replicate runs. For all the time series analyses, the replicate runs were compared by the following criteria:

- Differences in mean levels;
- Differences in standard deviations;
- Presence or absence of any trend in the time series and the degree to which such a trend dominates the series. This item includes all manner of nonstationarities, including breaking of trends; and
- Frequencies dominating the time series (i.e., those reflecting true periodicity).

The time series analyses focused on the stability and "repeatability" of the processes. The plots in the time domain were examined for apparent trends and instabilities in the variance structure or periodicities. Spectral analyses were conducted to detect sinusoidal components in the time series data or to define nonstationarities (trends, overrides, abrupt changes in control, etc.). A spectral analysis allocates the total variation of the series to different frequencies or periodic effects. These effects are then presented graphically as power density plots. A spectral power density plot is a nonnegative curve over the frequencies such that the integral of the curve is the total variance. A trend is viewed as a zero frequency nonstationarity (period longer than half the length of study). The integral over a restricted range is the variance component attributable to those frequencies. A trend shows up as a large peak at the origin. Other peaks indicate periodic events such as the feed or ash ram cycles.

On an overall basis, the results of the analyses of the combustion gas variable and operating parameter time series indicated that the replicate runs conducted under sets of nominal conditions can be considered as replicate runs for the purpose of analyzing CDD and CDF emissions. Although some differences in the time series were identified, they reflect micro-characteristics in the data that are of smaller order of magnitude than the differences in experimental groups. In particular, the analysis indicated that: 1) on a macro basis, the experimental conditions have been replicated, and 2) on a micro basis, some differences between replicate runs were identified. The major features of the time series can be interpreted without reference to these differences. However, these differences might provide explanations for any large differences in CDD and CDF levels between nominally replicate runs.

The 12 runs conducted at the Oswego, New York, facility resulted in, for each test run, time series in key process temperatures, pressures, and CO, $CO_2$, $O_2$ $NO_x$, $SO_2$, and THC concentrations. For this report, let x(t), where t=1, 2,. . ., N, represent a time series. The time behavior of two or more of these series could be of considerable importance in the interpretation and explanation of the test run results. On the other hand, if the time behavior of the series, both singly and jointly, is not important in the interpretation and explanation of the results, then such a finding as this greatly simplifies the analysis that must be conducted to deduce overall study results. It also greatly simplifies communicating the overall study results.

The time behavior of the 12 Oswego runs was investigated by time domain, spectral (frequency domain), and cross-correlational methods. Spectral methods summarize the information in the autocorrelation structure of a single time series x(t). The autocorrelation at lag L measures the extent to which the observation at time t is related to the observation at time t-L. The autocovariance of lag L for the time series x(t) is defined by:

$$c(L) = \frac{1}{N} \sum_{t=1}^{N-L} [x(t) - \bar{x}][x(t+L) - \bar{x}], \quad L = 0, 1, \ldots$$

where,

$$\bar{x} = \frac{1}{N} \sum_{t=1}^{N} x(t).$$

The autocorrelation at time lag L is simply the normalized autocovariance, i.e.,

$$\text{corr}(L) = c(L)/c(0).$$

The spectrum is the Fourier cosine transform of the autocovariance function. The spectrum can be used to determine periodicity in the time behavior of an individual series. Nonstationarities in time series will be reflected by a large value of the spectrum in the neighborhood of zero frequency; that means that the periodicity of a component such as trend over time is infinite.

When observing two series, the relevant aspects are the internal structure of each and the joint structure, or the dependence of either series on the other. Similarities between the spectra of two series, such as peaks at similar frequencies, may raise the possibility that the series are related. The joint behavior of two time series x(t) and y(t) is captured by the cross-correlation coefficients of the series. The cross-covariance at lag L between two time series x(t) and y(t), where t = 1, 2, . . ., N, L = . . ., -2, -1, 0, +1, +2, . . ., is defined by:

$$\mathrm{cov}(x,y:L) = \begin{cases} \dfrac{1}{N}\displaystyle\sum_{t=1}^{N-L} [x(t) - \bar{x}][y(t+L) - \bar{y}], & L = 0, 1, 2, \ldots \\[2ex] \dfrac{1}{N}\displaystyle\sum_{t=1}^{N+L} [y(t) - \bar{y}][x(t-L) - \bar{x}), & L = 0, -1, -2, \ldots, \end{cases}$$

where,

$$\bar{x} = \frac{1}{N}\sum_{t=1}^{N} x(t), \quad \bar{y} = \frac{1}{N}\sum_{t=1}^{N} y(t).$$

Note that cov(x,y:L) is not necessarily equal to cov(y,x:L). The cross-correlation between x(t) and y(t) at lag L is defined by:

$$\mathrm{corr}(x,y:L) = \mathrm{cov}(x,y:L)/[\mathrm{cov}(x,x:0)\ \mathrm{cov}(y,y:0)]^{1/2}.$$

For the 12 Oswego runs, the CEM time series data at the ESP outlet were collected at 20-second intervals; the CEM time series data at the secondary chamber exit (SCE) and the process time series data were collected at 10-second intervals. All of the time series data were processed by averaging appropriately to produce time series values at one-minute intervals. The magnitude of the lag L is thus a multiple of the time series intervals, (e.g., L = 0, ±1, ±2, ... signifies 0, ±10, ±20,... seconds or 0, ±20, ±40, ... seconds, or 0, ±1, ±2,... minutes). All the original time series data represent time-integrated averages over their respective collection intervals. The appropriate time unit of L is explicit in the following discussion.

Figure 6-1 provides examples of cross-correlation plots for Run 11 at several sampling locations. These plots are based on the one-minute time series constructed from the original data. The character of the plots based on the one-minute plots is virtually identical over comparable units of time (e.g., 10 minutes) to those based on the 10- and 20-second time series data. That is, the combustion processes are sufficiently smooth, dominated by inertia, and in (effectively) steady-state control to preclude loss of cross-correlational information in moving from shorter to longer time intervals between time series observations. The cross-correlation plot of CO versus temperature for the secondary chamber exit of Run 11 indicates that relatively high levels of CO are leading relatively high temperatures by a little less than 10 minutes, but that this relationship vanishes between 10- and 20-minute lags. However, even though this correlation is weak, it probably reflects a particular aspect of the control process. Unless the dioxin and furan measurements for Run 11 indicate that something unusual has occurred, this aspect of the analysis need not be pursued further. These cross-correlation plots are typical across all the Oswego runs.

# Section 7

# ANALYSIS OF CDD AND CDF TEST RESULTS

## INTRODUCTION

This section presents the results of the statistical and engineering analyses designed to investigate the relationships between CDD and CDF concentrations, and plant operating conditions, combustion gases, and potential CDD and CDF precursors. The findings with respect to the following questions are addressed in this section.

- Which single value representations of the combustion gas and plant operating values correlate at a significant level with the following CDD and CDF variables: 2,3,7,8-TCDD and -TCDF isomers, sum of all homologues, and total 2,3,7,8 substituted homologues?
- Do the multinomial homologue distributions of CDD and CDF vary as a function of plant operating conditions? Do they vary over the same test conditions? Over different test conditions? As a function of single value representations of the combustion gas variables?
- Does the percentage of CDD and CDF in the front half of the Modified Method 5 train vary as a function of plant operating conditions? Does it vary over the same test conditions? Over different test conditions? What about the back half of the Modified Method 5 train relative to these same questions?

Thirty-six CDD and CDF measurements were made, composed of twelve test runs at three sampling locations. The CDD and CDF test results are summarized in Section 4 and complete results are included in Appendix D.

### Units

As in previous studies, flue gas CDD and CDF data are expressed in several different sets of units including: ng/dscm, ng/dscm normalized to 7 percent $O_2$, ng/dscm normalized to 12 percent $CO_2$, and ug/hr. Emission factor estimates were calculated in terms of ng/g of refuse using the calculated refuse feed rates presented in Section 4. The CDD and CDF concentrations expressed in ng/dscm are most representative of the raw data, reflecting the amount measured in the sample divided by the flue gas sample volume. To account for possible excess air dilution effects when comparing measurements at different locations or for different tests, a common convention is to normalize the concentrations to a constant (usually 7 percent) oxygen level. Normalized values are thus calculated:

$$\text{Concentration}_{7\%\ O_2} = \text{Concentration}_{\text{Actual}} \times \frac{(21-7)}{(21 - \%\ O_2)}$$

where,

$\text{Concentration}_{7\%\ O_2}$ = compound concentration at 7 percent reference $O_2$

$\text{Concentration}_{\text{Actual}}$ = compound concentration at actual conditions, and

$O_2$ = actual $O_2$ concentration measured, percent by volume, dry

The majority of the analyses were performed using two sets of CDD and CDF data, measured concentrations and concentrations normalized to 7 percent $O_2$. Another commonly used convention is normalization to 12 percent $CO_2$; this was used only to compare the Oswego results to previous studies. To capture the effects of actual flue gas conditions, the data were not normalized for those comparisons using data measured at the same location or when comparing a parameter with $O_2$ concentrations. Comparing normalized data to $O_2$ concentrations could mask any potential relationships that may exist.

## Data Analysis Methods

The CDD and CDF data analysis was performed using several techniques, beginning with visual observations of trends in the data. More rigorous statistical methods were then used to search for statistically valid relationships in the data.

Linear, pairwise relationships were explored using Pearson product-moment correlation coefficients. Next, analysis of variance (ANOVA) was used to test for similarity in the sets of data. If the ANOVA results showed differences between the run group means, multiple range tests were used to determine which of the means differed. Cluster analysis was performed to determine which test runs were most similar. These statistical methods are defined and discussed in the following paragraphs.

The Pearson correlation coefficient, r, can be interpreted as the fraction of the total variation which is explained by the least-squares regression line (i.e., the ratio of explained variation to total variation). In other words, r is a measure of how well the linear least-squares regression line fits the data. An $|r| = 1$ implies a perfect correlation, while an $r = 0$ implies there is no correlation or the explained variation is zero. If r is positive, the two correlated variables tend to increase or decrease together and the slope of the least-squares regression line is positive; a negative r implies one variable tends to increase as the other decreases and the slope of the regression line is negative. It should be noted that the Pearson product-moment correlation coefficient measures only linear correlations. If r is close to zero, this implies there is little linear correlation. However, there may be, in fact, a strong nonlinear correlation.

An analysis of variance F-test (ANOVA) is a statistical method which simultaneously tests for the equality of means of several groups. This method is an extension of the Student's t test, which tests for the equality of two means. The groups of averages analyzed by ANOVA can be classified by more than one characteristic. The simplest analysis of variance technique is a one-way ANOVA. This method is used to test for the equality of several means classified by only one characteristic. For example, the equality of average CDD concentrations at the three sampling locations can be tested with a one-way ANOVA. Simply stated, this method computes a ratio based on two sources of variability in the CDD concentrations: the between-group and within-group variability. The between-group variability is comprised of the variability of the CDD means between the three locations. The within-group variability is comprised of the variability of the 12 CDD concentrations around the mean at each location, pooled over all three locations. It is important to note that for ANOVA, if the means are equal, the within-group variability will be large compared to the between-group variability and the ratio of these two variances will follow an F distribution. This ratio is therefore compared to a critical (tabulated) F value for a desired confidence level. If the F-test for the equality of these two variances is rejected, it can be concluded that the means are not equal. Thus, the means can be compared using population variance information.

These same concepts can be extended using ANOVA for a variable classified by more than one characteristic. For example, each CDD measurement can be classified by two characteristics: sampling location and test condition. A two-way ANOVA compares the means for each location and test condition. Here the null hypothesis being tested consists of three parts:

- $H_0(1)$: The means at each location are equal;
- $H_0(2)$: The means at each test condition are equal; and
- $H_0(3)$: There is no interaction between location and test condition.

The variation due to location and test condition is then used to determine if any of the means are significantly different, resulting in the acceptance or rejection of each of these hypotheses.

Associated with each ANOVA model is a significance level which determines whether or not one should accept the given hypothesis. The level of significance of a test is the maximum probability with which one would be willing to risk a Type I error. A Type I error means rejecting the null hypothesis when the null hypothesis is true. In one-way ANOVAs, the null hypothesis is that all treatment means are equal, or for example, that all of the operating condition means are equal within each location. If the null hypothesis is true, the treatment populations (the different operating conditions), which by assumption are normal, have a common mean as well as a common variance. Thus, there exists just one treatment population and all operating conditions would be statistically identical. On the other hand, if the null hypothesis is rejected, a difference exists between treatment means (i.e., the operating condition means).

A significance level of 0.05 means that the probability of incorrectly rejecting the null hypothesis that all the means are equal is 0.05 or 5 percent. In other words, the probability of making an error is small (5 percent) and there is a 95 percent chance that the means truly differ.

Usually a significance level of 0.05 or smaller indicates the differences between the means are significant. A significance level between 0.05 and 0.10 falls into somewhat of a grey area and, for the purposes of this report, will be called marginally significant. When the level is greater than 0.10, the chances of rejecting the null hypothesis when the null is true becomes large, and the test is therefore not significant.

As described previously, an ANOVA is a statistical method which tests for differences among groups, such as operating condition. If a difference is detected, the ANOVA does not specify which operating conditions have significantly different averages. ANOVA simply determines if at least one group average is statistically different from the others. A statistical test which aids in determining the distinct groups is a multiple range test.

A number of multiple range tests have been developed. A problem with these tests is that they do not control experiment-wise error. That is, most of these tests do not have a controlled alpha error (or significance level) for the experiment. The uncontrolled alpha error is due to the fact that multiple comparisons are being made (e.g., between operating conditions), and the probability of detecting a difference between any set of groups when no difference actually exists becomes relatively large. Thus, ANOVA is used to determine statistically significant differences among groups and multiple range tests are used in this study to qualitatively determine which groups have different averages.

Cluster analysis was used to further explore relationships in the data. In a cluster analysis, statistical techniques are used to identify within a given data set, inherently similar groups of data which are different from the other groups. For this study, cluster analysis was used to classify or group similar test runs based on CDD and CDF concentrations.

A large number of clustering methods have been developed for a variety of applications, and any general discussion of cluster analysis will necessarily be difficult to present. Since all methods are mathematically valid, the clustering method that best derives the true clusters in the data should be used. However, since some clustering methods perform better than others for a particular data set and since measures of the performance of clustering methods for a given data set are frequently contradictory and inconclusive, the choice of the best clustering technique is often left to judgment. In this study, an appropriate clustering method was selected by using several methods and comparing the resulting clusters. If little difference was detected between methods, it was concluded that the clusters were insensitive to the clustering method and actual relationships could then be explored. The clustering algorithm used in this study is Ward's minimum variance method. Ward's method calculates the similarity between clusters using the ANOVA sum of squares. The sum of squares is the sum of the squared difference between the CDD and CDF concentrations for each test run in the cluster, and the cluster average values. At each stage of clustering, the pairs of clusters merged are those which minimize the within-cluster sum of squares. Thus, the relative increase in the sum of squares at each clustering stage reflects the similarity of the clusters.

Dendrograms are a graphical display of the relationship between the clusters at the various clustering stages. They illustrate the similarity (or dissimilarity) of the variables in the clusters, as represented by distance. For the example described above, a dendrogram would have each test run represented along the x axis, and the similarity, or distance measure, represented along the y axis. An increase in distance on the y axis indicates the allowable within-cluster sum of squares must be greater for the test runs to be similar. Thus, test runs joined nearer to the origin are more similar; whereas, those joined at a greater distance are less similar.

In a dendrogram, a vertical line is projected above each test run, similar to the sides of a bar in a bar chart. The vertical lines extend to the value of the distance measure (point on the y axis) where they are joined in a cluster. At this point, the vertical lines are connected with a horizontal line, similar to a bar chart. Thus, the two test runs joined in the first cluster would have the shortest bar connecting them. A new vertical line extends from the middle of this bar to connect this cluster to another cluster (test run), the length of which will again indicate the similarity of this cluster to the next. Thus, the relationship of the test runs is illustrated for every stage of clustering in a single dendrogram. (The time series data can also be used for clustering purposes rather than the means alone.)

A very important component of the analyses involved interpretation of the statistically significant results from engineering and combustion chemistry points of view. All statistically significant relationships between variables were reviewed. The apparently casual relationships are not discussed in detail in the text. A complete listing of all the results is included in Appendix C to allow the reader to investigate relationships in the data not presented in this section. Those correlations that in the authors' opinions could meaningfully be interpreted are discussed in the text.

## ORGANIZATION OF THIS SECTION

Table 7-1 presents a summary of unadjusted total CDD and CDF concentrations and mass rates measured at the three sampling locations by test run and averaged over the test run groups; Table 7-2 lists the normalized total CDD and CDF concentrations. Table 7-3 shows normalized and unadjusted total 2,3,7,8-TCDD and 2,3,7,8-TCDF concentrations measured at the three sampling locations. It is important to note that for the majority of the test runs, no detectable levels of 2,3,7,8-TCDD were measured at the secondary chamber exit or ESP inlet. Therefore, it is more likely that statistical analysis with this small data set may result in correlations due to scatter in the data and not actual linear relationships in the data. Several interesting observations can be made from the data shown in the summary tables. These include comparisons of average CDD and CDF concentrations:

1. To CDD and CDF flue gas concentrations from other similar incinerators;
2. Under different secondary chamber temperature conditions, and
3. At start and end of campaign (Runs 1-3 versus Runs 7-9) test conditions, reflecting different heat transfer efficiencies.

Other comparisons include the relative amounts of CDD versus CDF from an overall perspective, by sampling location and differences between the

## Table 7-1
## TOTAL CDD AND CDF CONCENTRATIONS AND MASS EMISSION RATES

| | | SECONDARY CHAMBER EXIT | | | | ESP INLET | | | | ESP OUTLET | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| TEST CONDITION[a] | RUN NUMBER | TOTAL CDD, ng/dscm | TOTAL CDD, ug/hr | TOTAL CDF, ng/dscm | TOTAL CDF, ug/hr | TOTAL CDD, ng/dscm | TOTAL CDD, ug/hr | TOTAL CDF, ng/dscm | TOTAL CDF, ug/hr | TOTAL CDD, ng/dscm | TOTAL CDD, ug/hr | TOTAL CDF, ng/dscm | TOTAL CDF, ug/hr |
| Start of Campaign, SCE = 1800 deg. F | 1 | 18.4 | 307.6 | 175.7 | 2937.4 | 31.1 | 516.8 | 83.6 | 1389.1 | 80.0 | 1508.7 | 129.7 | 2446.0 |
| | 2 | 2.9 | 50.3 | 545.5 | 9453.5 | 31.2 | 512.6 | 83.9 | 1378.4 | 70.5 | 1317.6 | 123.2 | 2302.5 |
| | 3 | 9.5 | 156.2 | 250.5 | 4119.9 | 16.8 | 272.6 | 47.4 | 769.1 | 72.4 | 1402.3 | 120.9 | 2341.7 |
| | AVG. | 10.3 | 171.4 | 323.9 | 5503.6 | 26.4 | 434.0 | 71.6 | 1178.9 | 74.3 | 1409.5 | 124.6 | 2363.4 |
| Mid-range Secondary Chamber Temperature, SCE = 1750 deg. F | 4 | 3.2 | 49.6 | 59.0 | 914.2 | 33.3 | 522.2 | 101.4 | 1590.2 | 72.6 | 1319.8 | 125.3 | 2277.9 |
| | 5 | 17.7 | 275.8 | 127.0 | 1978.7 | 28.0 | 432.0 | 86.4 | 1332.9 | 54.4 | 942.8 | 102.7 | 1779.8 |
| | 6 | 4.3 | 63.7 | 519.0 | 7689.2 | 20.8 | 315.6 | 83.8 | 1271.4 | 47.2 | 790.7 | 134.8 | 2258.2 |
| | AVG. | 8.4 | 129.7 | 235.0 | 3527.4 | 27.4 | 423.3 | 90.5 | 1398.2 | 58.1 | 1017.8 | 120.9 | 2105.3 |
| End of Campaign, SCE = 1800 deg. F | 7 | 54.7 | 803.9 | 400.5 | 5886.0 | 39.1 | 556.7 | 134.5 | 1915.0 | 80.8 | 1258.9 | 156.2 | 2433.6 |
| | 8 | 27.2 | 423.8 | 154.5 | 2407.1 | 58.9 | 926.7 | 241.2 | 3794.8 | 41.8[b] | 687.5[b] | 119.3[b] | 1962.1[b] |
| | 9 | 27.2 | 451.5 | 280.5 | 4656.1 | 42.2[b] | 666.1[b] | 140.1[b] | 2211.3[b] | 124.3 | 2101.3 | 259.3 | 4383.5 |
| | AVG. | 36.4 | 559.7 | 278.5 | 4316.4 | 46.7 | 716.5 | 171.9 | 2640.4 | 82.3 | 1349.2 | 178.3 | 2926.4 |
| Low Secondary Chamber Temperature, SCE = 1650 deg. F | 10 | 63.4 | 975.9 | 171.1 | 2633.8 | 173.6 | 2925.9 | 295.9 | 4987.2 | 218.9 | 3756.3 | 279.6 | 4798.0 |
| | 11 | 38.5 | 584.8 | 224.1 | 3403.9 | 121.1 | 1880.6 | 203.5 | 3160.2 | 170.6 | 2840.6 | 233.5 | 3887.9 |
| | 12 | 40.9 | 539.2 | 125.0 | 1648.0 | 125.7 | 1873.0 | 193.5 | 2883.2 | 147.6 | 2149.1 | 181.2 | 2638.4 |
| | AVG. | 47.6 | 700.0 | 173.4 | 2561.9 | 140.1 | 2226.5 | 231.0 | 3676.9 | 179.0 | 2915.3 | 231.4 | 3774.7 |
| 12 Run Average | | 25.7 | 390.2 | 252.7 | 3977.3 | 60.2 | 950.1 | 141.3 | 2223.6 | 98.4 | 1673.0 | 163.8 | 2792.5 |

[a] SCE = Secondary Chamber Exit; temperatures represent setpoints for condition indicated.

[b] Front half train results not reported; total train results assume no CDD or CDF detected in front half of sampling train.

Table 7-2.

TOTAL CDD AND CDF CONCENTRATIONS CORRECTED TO 7% OXYGEN

| TEST CONDITION[a] | RUN NUMBER | SECONDARY CHAMBER EXIT TOTAL CDD, ng/dscm @7% $O_2$ | SECONDARY CHAMBER EXIT TOTAL CDF, ng/dscm @7% $O_2$ | ESP INLET TOTAL CDD, ng/dscm @7% $O_2$ | ESP INLET TOTAL CDF, ng/dscm @7% $O_2$ | ESP OUTLET TOTAL CDD, ng/dscm @7% $O_2$ | ESP OUTLET TOTAL CDF, ng/dscm @7% $O_2$ |
|---|---|---|---|---|---|---|---|
| Start of Campaign, SCE = 1800 deg. F | 1 | 28.7 | 274.5 | 57.7 | 155.0 | 148.3 | 240.4 |
| | 2 | 4.7 | 881.6 | 62.8 | 169.0 | 142.1 | 248.2 |
| | 3 | 16.2 | 429.9 | 31.1 | 87.9 | 134.2 | 224.1 |
| | AVG. | 16.5 | 528.7 | 50.5 | 137.3 | 141.5 | 237.6 |
| Mid-range Secondary Chamber Temperature, SCE = 1750 deg. F | 4 | 5.3 | 98.7 | 66.1 | 201.4 | 144.1 | 248.8 |
| | 5 | 28.7 | 205.2 | 53.3 | 164.6 | 103.6 | 195.5 |
| | 6 | 6.9 | 838.8 | 40.7 | 164.0 | 92.3 | 263.9 |
| | AVG. | 13.6 | 380.9 | 53.4 | 176.7 | 113.3 | 236.1 |
| End of Campaign, SCE = 1800 deg. F | 7 | 78.3 | 574.0 | 68.8 | 236.7 | 142.1 | 274.8 |
| | 8 | 40.2 | 228.5 | 115.3 | 472.2 | 81.9[b] | 233.5[b] |
| | 9 | 40.6 | 419.3 | 73.3[b] | 243.4[b] | 216.0 | 450.6 |
| | AVG. | 53.0 | 407.3 | 85.8 | 317.4 | 146.7 | 319.6 |
| Low Secondary Chamber Temperature, SCE = 1650 deg. F | 10 | 110.1 | 297.2 | 349.8 | 596.2 | 441.1 | 563.3 |
| | 11 | 67.7 | 394.4 | 255.1 | 428.5 | 359.3 | 491.8 |
| | 12 | 75.8 | 231.6 | 264.8 | 407.6 | 310.9 | 381.7 |
| | AVG. | 84.5 | 307.7 | 289.9 | 477.4 | 370.4 | 478.9 |
| 12 Run Average | | 41.9 | 406.1 | 119.9 | 277.2 | 193.0 | 318.1 |

[a] SCE = Secondary Chamber Exit; temperatures represent setpoints for condition indicated.

[b] Front half train results not reported; total train results assume no CDD or CDF detected in front half of sampling train.

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## Table 7-3.

## 2,3,7,8-TCDD AND 2,3,7,8-TCDF CONCENTRATIONS UNADJUSTED AND ADJUSTED TO 7% OXYGEN

| TEST CONDITION[a] | RUN NUMBER | SECONDARY CHAMBER EXIT |  |  |  | ESP INLET |  |  |  | ESP OUTLET |  |  |  |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
|  |  | 2,3,7,8-TCDD, ng/dscm | 2,3,7,8-TCDD, ng/dscm @7% $O_2$ | 2,3,7,8-TCDF, ng/dscm | 2,3,7,8-TCDF, ng/dscm @7% $O_2$ | 2,3,7,8-TCDD, ng/dscm | 2,3,7,8-TCDD, ng/dscm @7% $O_2$ | 2,3,7,8-TCDF, ng/dscm | 2,3,7,8-TCDF, ng/dscm @7% $O_2$ | 2,3,7,8-TCDD, ng/dscm | 2,3,7,8-TCDD, ng/dscm @7% $O_2$ | 2,3,7,8-TCDF, ng/dscm | 2,3,7,8-TCDF, ng/dscm @7% $O_2$ |
| Start of Campaign, SCE = 1800 deg. F | 1 | ND | ND | 4.2 | 6.5 | ND | ND | 3.6 | 6.6 | ND | ND | 5.5 | 10.2 |
|  | 2 | ND | ND | 9.3 | 15.0 | ND | ND | 3.6 | 7.2 | 0.1 | 0.3 | 4.9 | 9.9 |
|  | 3 | ND | ND | 5.7 | 9.7 | ND | ND | 2.6 | 4.8 | ND | ND | 4.9 | 9.1 |
|  | AVG. | ND | ND | 6.4 | 10.4 | ND | ND | 3.3 | 6.2 | 0.1 | 0.3 | 5.1 | 9.7 |
| Mid-range Secondary Chamber Temperature, SCE = 1750 deg. F | 4 | ND | ND | 2.6 | 4.4 | 0.3 | 0.5 | 3.4 | 6.7 | 0.2 | 0.4 | 4.2 | 8.3 |
|  | 5 | 0.3 | 0.5 | 5.7 | 9.1 | ND | ND | 3.5 | 6.6 | 0.1 | 0.3 | 4.0 | 7.7 |
|  | 6 | ND | ND | ND | ND | ND | ND | 3.9 | 7.6 | 0.2 | 0.5 | 4.7 | 9.1 |
|  | AVG. | 0.3 | 0.5 | 4.2 | 6.8 | 0.3 | 0.5 | 3.6 | 7.0 | 0.2 | 0.4 | 4.3 | 8.4 |
| End of Campaign, SCE = 1800 deg. F | 7 | 0.7 | 0.9 | 7.5 | 10.8 | ND | ND | 7.2 | 12.8 | 0.3 | 0.5 | 6.6 | 11.6 |
|  | 8 | ND | ND | 6.8 | 10.0 | 0.9 | 1.7 | 11.7 | 22.8 | 0.3 | 0.6 | 5.2 | 10.2 |
|  | 9 | 0.5 | 0.7 | 6.9 | 10.3 | 0.4 | 0.7 | 6.0 | 10.4 | 4.6 | 8.0 | 10.6 | 18.4 |
|  | AVG. | 0.6 | 0.8 | 7.1 | 10.4 | 0.7 | 1.2 | 8.3 | 15.3 | 1.7 | 3.0 | 7.5 | 13.4 |
| Low Secondary Chamber Temperature, SCE = 1650 deg. F | 10 | 1.3 | 2.2 | 9.3 | 16.2 | 1.3 | 2.6 | 7.1 | 14.3 | 1.0 | 2.1 | 11.9 | 23.9 |
|  | 11 | 0.6 | 1.1 | 11.4 | 20.1 | 0.4 | 0.9 | 5.9 | 12.4 | 0.4 | 0.8 | 9.7 | 20.5 |
|  | 12 | 0.5 | 0.9 | 5.5 | 9.9 | ND | ND | 8.2 | 17.2 | 0.4 | 0.7 | 7.4 | 15.6 |
|  | AVG. | 0.8 | 1.4 | 8.7 | 15.4 | 0.9 | 1.8 | 7.1 | 14.6 | 0.6 | 1.2 | 9.7 | 20.0 |
| 12 Run Average |  | 0.6 | 0.9 | 6.6 | 10.7 | 0.6 | 1.2 | 5.6 | 10.8 | 0.7 | 1.2 | 6.6 | 12.9 |

[a] SCE = Secondary Chamber Exit; temperatures represent setpoints for condition indicated.

secondary chamber exit and ESP inlet and between the ESP inlet and outlet. These and other topics are discussed in the following order:

- COMPARISON OF OSWEGO CDD AND CDF EMISSIONS TO OTHER INCINERATORS
- LOCATION, SECONDARY CHAMBER TEMPERATURE, AND HEAT TRANSFER SURFACE AREA EFFECTS ON CDD AND CDF CONCENTRATIONS
- RELATIONSHIP OF CDD AND CDF CONCENTRATIONS WITH OPERATING AND COMBUSTION GAS VARIABLES
- PLANT OPERATING CONDITION EFFECTS ON CDD AND CDF HOMOLOGUE DISTRIBUTIONS
- LOCATION EFFECTS ON CDD AND CDF HOMOLOGUE DISTRIBUTIONS
- CDD AND CDF MEASURED IN THE FRONT AND BACK HALF FRACTIONS OF THE MODIFIED METHOD 5 TRAIN
- COMPARISON OF PRECURSOR DATA TO CDD AND CDF CONCENTRATIONS
- ESP COLLECTION EFFICIENCY

## COMPARISON OF OSWEGO CDD AND CDF EMISSIONS TO OTHER INCINERATORS

Tables 7-4 and 7-5 present uncontrolled and controlled CDD and CDF data, respectively, from EPA's Municipal Waste Combustion Data Base(1) and the Oswego tests (12-run averages). The comparisons shown are based on tetra- through octa-homologues adjusted to 12 percent $CO_2$, since these were the normalized units used in the MWC study. When the Oswego controlled CDD and CDF concentrations are compared to those at a similar starved air modular facility with an ESP for particulate control (Red Wing), the CDD and CDF emissions are an order of magnitude less. It should be noted that the ESP operating temperature at Red Wing is approximately $600^{o}F$. Since this temperature is within the CDD and CDF temperature formation window, this may explain why the CDD and CDF concentrations are so high at this facility. The uncontrolled Oswego CDD concentrations are approximately the same as, and the CDF concentrations are higher than, those measured at a starved air modular facility that does not have a control device (Prince Edward Island).

## Table 7-4.

## SUMMARY OF TETRA- THROUGH OCTA-CHLORODIBENZO-p-DIOXIN CONCENTRATIONS MEASURED AT MWC FACILITIES

| Facility Type and Name[a] | Test Condition | ng/Nm$^3$ @ 12% CO$_2$ Upstream of Control Device | ng/Nm$^3$ @ 12% CO$_2$ Downstream of Control Device |
|---|---|---|---|
| Mass Burn | | | |
| Waterwall | | | |
| ESP | | | |
| Hampton (1981) | Normal | | 5,850 |
| Hampton (1983) | Normal | | 1,990 |
| Hampton (1984) | Normal | | 10,700 |
| North Andover | Normal | 155 | 92.8 |
| Saugus | Normal | | 169 |
| Tulsa (Units 1 & 2) | Normal | | 18.9 |
| Umea, fall | Normal | | 190 |
| Umea, fall | Low temp | | 341 |
| Umea, spring | Normal | | 268 |
| Peekskill | 12-run average | 131.6 | 56.5 |
| WSH/DI/FF | | | |
| Quebec | 110°C | 636 | 0.165 |
| Quebec | 125°C | 1,540 | |
| Quebec | 140°C | 1,340 | |
| Quebec | 200°C | 1,070 | 6.35 |
| Wurzburg | Normal | | 22.1 |
| SD/FF | | | |
| Marion County | Normal | | 1.13 |
| Quebec | 140°C | 1,140 | |
| Quebec | 140°C & Recycle | 1,370 | 0.381 |
| Refractory | | | |
| ESP | | | |
| Philadelphia (NW1) | Normal | | 5,370 |
| Philadelphia (NW2) | Normal | | 2,890 |
| Starved Air | | | |
| No control device | | | |
| Prince Edward Island | Normal | 109 | |
| Prince Edward Island | Long | 109 | |
| Prince Edward Island | High | 63.1 | |
| Prince Edward Island | Low | 125 | |
| ESP | | | |
| Red Wing | Normal | | 1,540 |
| Oswego | 12-run average | 99.9 | 148.4 |

[a] WSH = water spray humidifier
DI = dry injection
FF = fabric filter
SD = spray dryer

## Table 7-5.

## SUMMARY OF TETRA- THROUGH OCTA-CHLORODIBENZOFURAN CONCENTRATIONS MEASURED AT MWC FACILITIES

| Facility Type and Name[a] | Test Condition | $ng/Nm^3$ @ 12% $CO_2$ Upstream of Control Device | Downstream of Control Device |
|---|---|---|---|
| Mass Burn | | | |
| Waterwall | | | |
| ESP | | | |
| Hampton (1981) | Normal | | 10,900 |
| Hampton (1983) | Normal | | 7,640 |
| Hampton (1984) | Normal | | 14,800 |
| North Andover | Normal | 85 | 242 |
| Saugus | Normal | | 411 |
| Tulsa (Units 1 & 2) | Normal | | 15.5 |
| Umea, fall | Normal | | 312 |
| Umea, fall | Low temp | | 404 |
| Umea, spring | Normal | | 224 |
| Peekskill | 12-run average | 299.8 | 101.1 |
| WSH/DI/FF | | | |
| Quebec | 110°C | 334 | 2.49 |
| Quebec | 125°C | 1,030 | |
| Quebec | 140°C | 1,070 | 1.03 |
| Quebec | 200°C | 588 | 1.26 |
| Wurzburg | Normal | | 27.9 |
| SD/FF | | | |
| Marion County | Normal | | 0.423 |
| Quebec | 140°C | 689 | |
| Quebec | 140°C & Recycle | 903 | 0.947 |
| Refractory | | | |
| ESP | | | |
| Philadelphia (NW1) | Normal | | 5,890 |
| Philadelphia (NW2) | Normal | | 2,870 |
| Starved Air | | | |
| No control device | | | |
| Prince Edward Island | Normal | 144 | |
| Prince Edward Island | Long | 159 | |
| Prince Edward Island | High | 96.6 | |
| Prince Edward Island | Low | 98.7 | |
| ESP | | | |
| Red Wing | Normal | | 1,770 |
| Oswego | 12-run average | 206.9 | 234.9 |

[a] WSH = water spray humidifier
DI = dry injection
FF = fabric filter
SD = spray dryer

## LOCATION, SECONDARY CHAMBER TEMPERATURE AND HEAT TRANSFER SURFACE AREA EFFECTS ON CDD AND CDF CONCENTRATIONS

In this discussion, possible relationships between CDD and CDF concentrations measured and plant operating conditions are explored. In the first part, observations are made by visually inspecting tabular and graphical presentations of the data. This is followed by a statistical analysis of possible relationships.

### Observations from the Data

CDD and CDF concentrations at 7 percent $O_2$ by test run and location are shown in Figures 7-1 and 7-2. As shown in Figure 7-1, there is a distinct sampling location effect. For all but one test run, the total CDD measured at the ESP inlet is greater than the amount measured at the secondary chamber exit; the same is true for the ESP outlet and inlet. However, this trend is not present for total CDF. For the majority of the test runs, the ESP inlet and outlet CDF concentrations are similar. However, the CDF concentrations measured at the secondary chamber exit vary considerably between test runs.

One hypothetical cause for these apparent differences could be due to analytical uncertainty as high as 50 percent in the CDD and CDF results. However, a recent study of a compilation of CDD and CDF sampling and analytical results concluded that the mean coefficient of variance for the ASME method due to all error factors including process changes and sampling and analytical errors, is 0.38 and the mean coefficient of variance for sampling and analysis combined is probably closer to 0.20.(2)

Another possible explanation for the higher concentrations of CDD at the ESP inlet and outlet is formation of CDD downstream of the incinerator. Several mechanisms have been hypothesized by researchers to account for the presence of CDD and CDF downstream of the combustion zone in municipal waste combustors. These hypotheses include: a) the presence of CDD and CDF in the refuse which are not destroyed in the combustion process; b) reaction of products of incomplete combustion in the gas phase or on the flyash (e.g., chlorophenols, chlorobenzenes, and other potential precursors); c) de novo synthesis of CDD and CDF on flyash involving metal chloride catalysis;

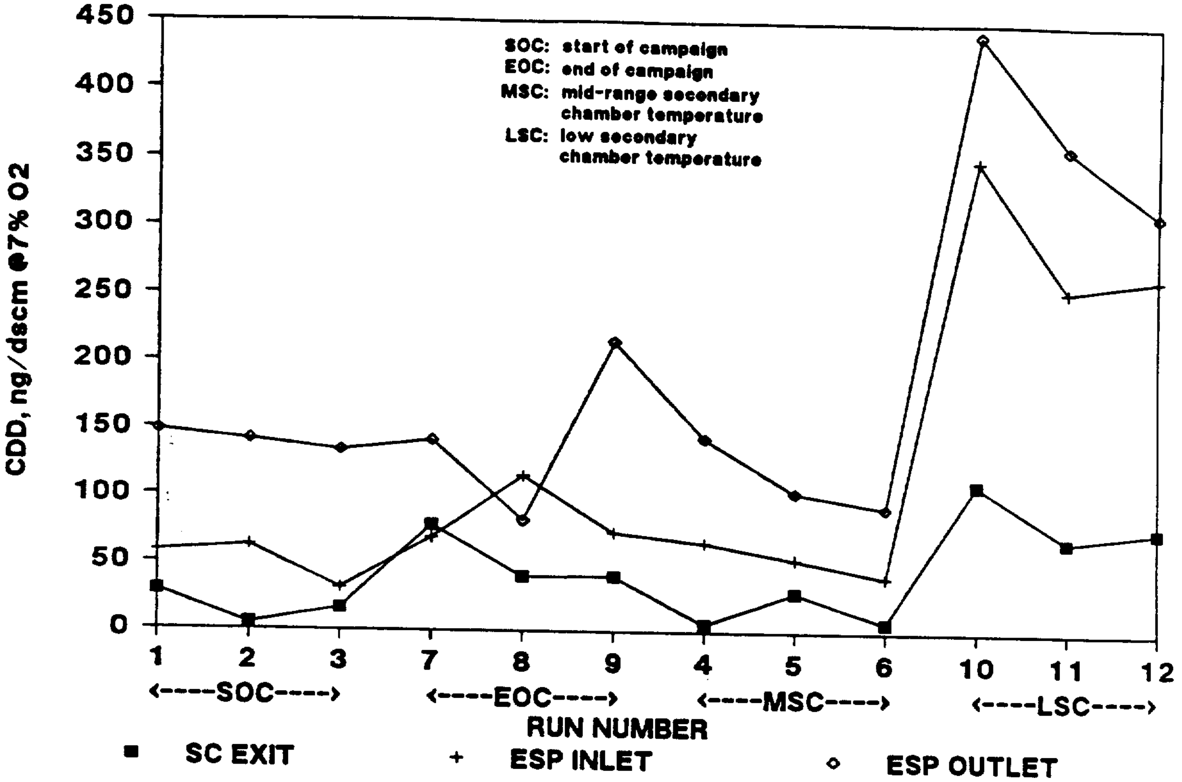

Figure 7-1. Total CDD by Test Run Number and Location

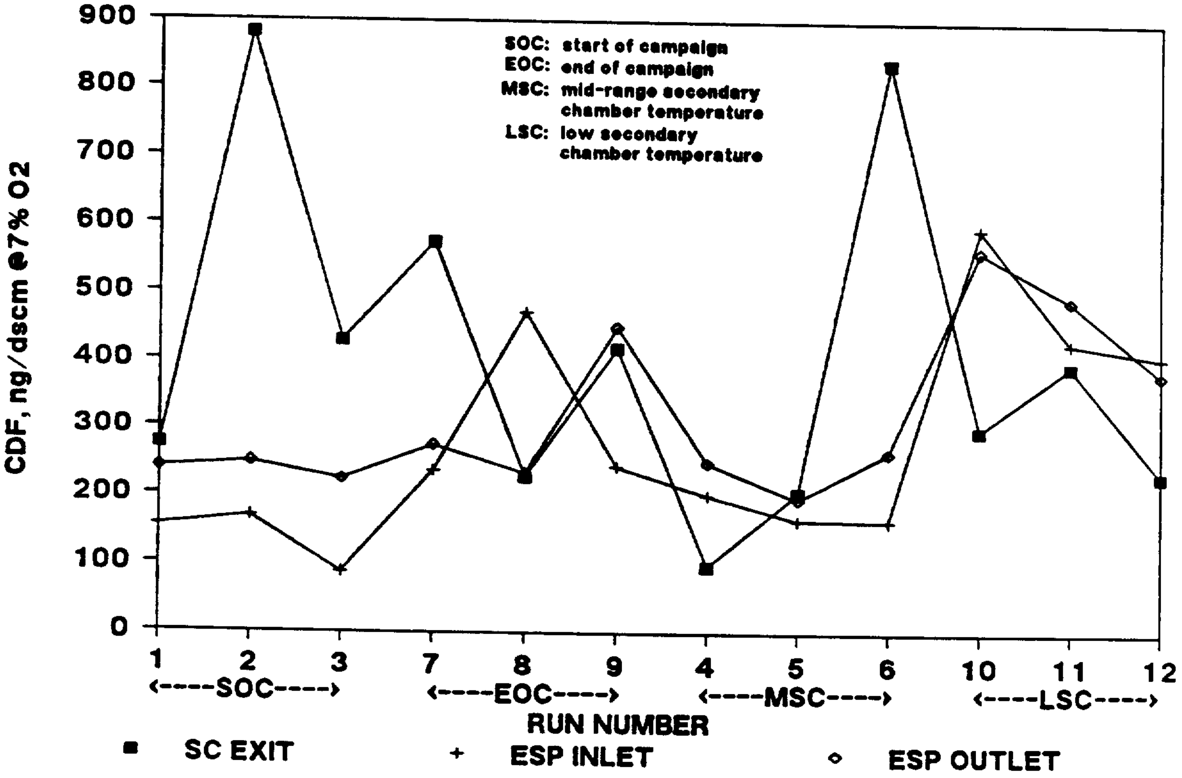

Figure 7-2. Total CDF by Test Run Number and Location

and d) de novo synthesis from particulate carbon. These hypotheses are discussed below.

Refuse sampling was conducted at the Oswego facility and the samples were analyzed for mono- through octa-chlorinated CDD and CDF. However, CDD was detected in only 5 of the 12 samples and CDF in only 1 of the 12 samples. It should be noted that only one random refuse load per CDD and CDF test run could be sorted due to the time involved in sorting the sample, and only those fractions that could be readily processed into a laboratory sample were analyzed. The fractions not prepared for analysis may have contained CDD and CDF contaminated components. In addition, the random refuse load may have had unusually low levels of CDD or CDF.

At Oswego, the CDD level in the refuse ranged from 0.2 to 0.8 ng/g; the CDF level detected in the one refuse sample was 0.08 ng/g. The limited amount of refuse data available from the Pittsfield and PEI studies show CDD levels of 3 to 5 ng/g,(3) with low or nondetectable levels of CDF. Using 12-run averages of the estimated refuse feed rates and the CDD and CDF concentrations given in Section 4, it is estimated that about 0.18 ng CDD/g refuse and 1.77 ng CDF/g refuse would be emitted in the flue gas, as measured at the secondary chamber exit. Comparing these values to the levels of CDD and CDF contained in the refuse would indicate that between 10 and 80 percent of the CDD contained in the refuse is destroyed in the combustion zone, while CDF forms in the combustion zone.

Figures 7-3 and 7-4 present the estimates of the amount of CDD and CDF, respectively, emitted from the secondary chamber per g of refuse burned by run number. As shown in the figures, there is more CDD emitted at the low secondary chamber temperature and end of campaign test conditions. This may be due to the low secondary chamber temperature allowing formation of CDD in the combustion zone, and ash buildup in the secondary chamber and fouled heat transfer surfaces (end of campaign test runs) possibly allowing the formation of CDD via metal catalysis or from particulate carbon.

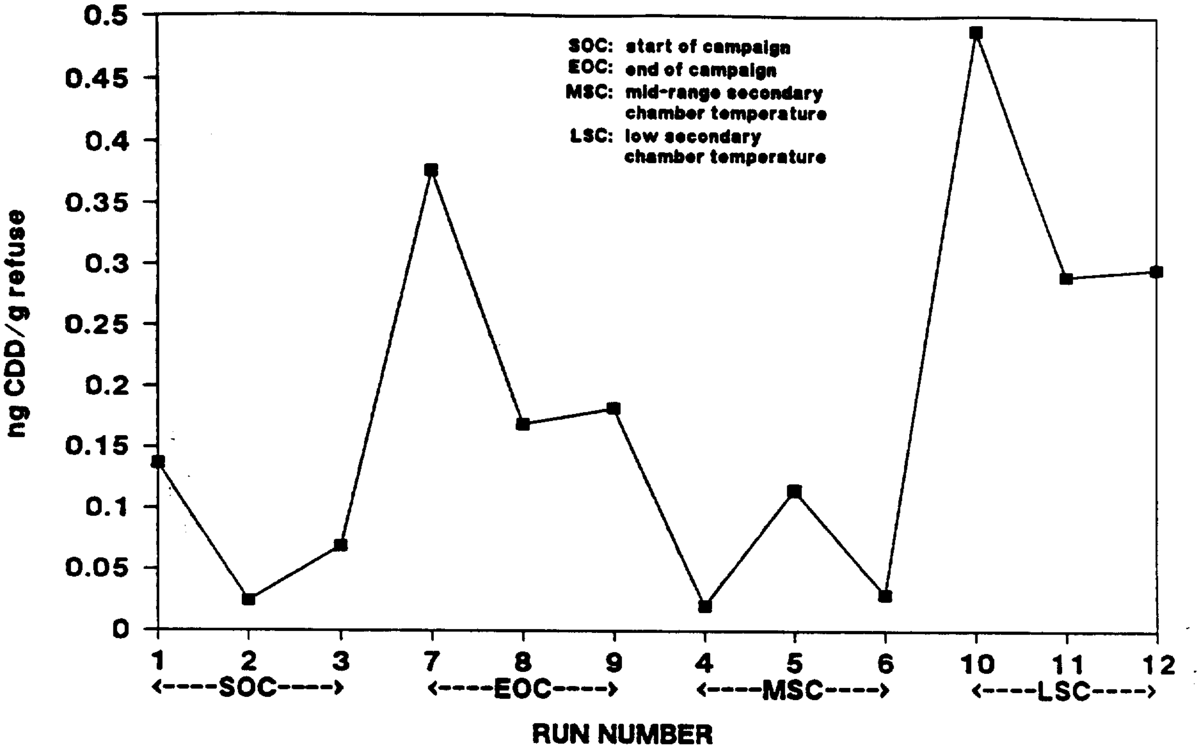

Figure 7-3. ng CDD Measured at the Secondary Chamber Exit per g Refuse by Run Number

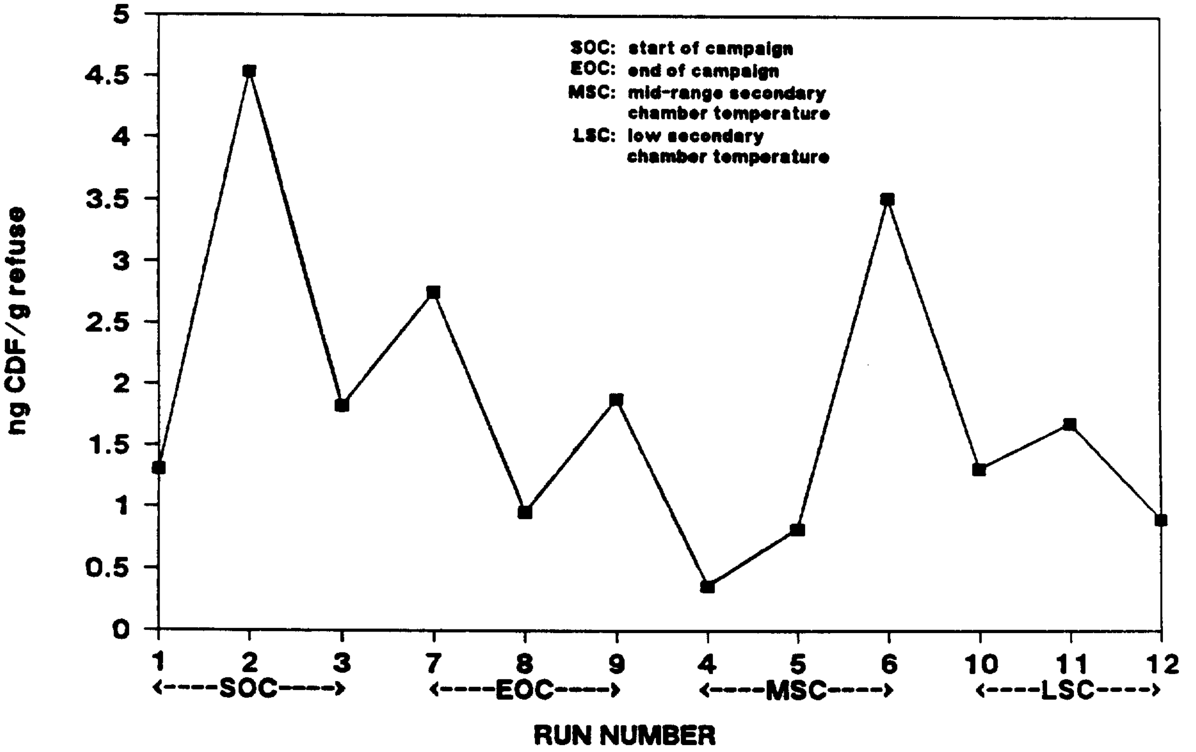

Figure 7-4. ng CDF Measured at the Secondary Chamber Exit per g Refuse by Run Number

Experimental studies suggest that temperatures of 930 to 1440°F promote CDD formation, while temperatures >1440°F destroy CDDs.(4,5,6) Bussa *et al*. show that PCB pyrolysis at 1020°F to 1200°F forms CDF.(7) However, pyrolysis at temperatures greater than 1290°F causes 99 percent destruction of PCBs and no CDF formation. No bed temperatures are available at Oswego; however, flue gas temperatures measured in the primary and secondary chambers show that gases in the combustion zone reached or exceeded the 1200 to 1440°F needed to destroy CDD and CDF.

Total CDD and CDF concentrations were compared to the target precursor concentrations to determine if there were any relationships in the data; however, scatter plots of the data showed no discernible trends. It is important to note that, in the case of CDD, these precursors would be expected to first form predioxins before forming the CDD molecule. In addition, even if the predioxin formed, this formation would not ensure CDD forms, as several known precursors reach an equilibrium with the predioxin.

Recent studies of CDD formation and destruction by Vogg and Steiglitz indicate that formation of CDD in flyash can occur at temperatures between approximately 430°F and 750°F (220°C and 400°C), peaking at 570°F (300°C).(8) In these studies, the flyash was heated for two hours without a change in CDD and CDF concentrations when the temperature was below 390°F (200°C), a 10-fold increase at 570°F (300°C) and complete destruction at 1110°F (600°C).(9,10)

Figures 7-5 and 7-6 present temperature profile plots for the Oswego facility. As shown in Figure 7-5, formation of CDD and CDF on flyash between the combustion zone and the secondary chamber exit is unlikely to be occurring at this facility due to the high flue gas temperatures (1650°F to 1800°F) in the secondary chamber, which are above the temperatures suggested by Vogg and Steiglitz as optimum for such formation. However, as shown in the figures, the flue gases pass through the suggested optimal temperature window at some point between the secondary chamber exit and the ESP inlet. In addition, the ESP operating temperature for this program was between 428°F and 500°F, indicating CDD and CDF could potentially form via catalytic interaction with the flyash between these locations.

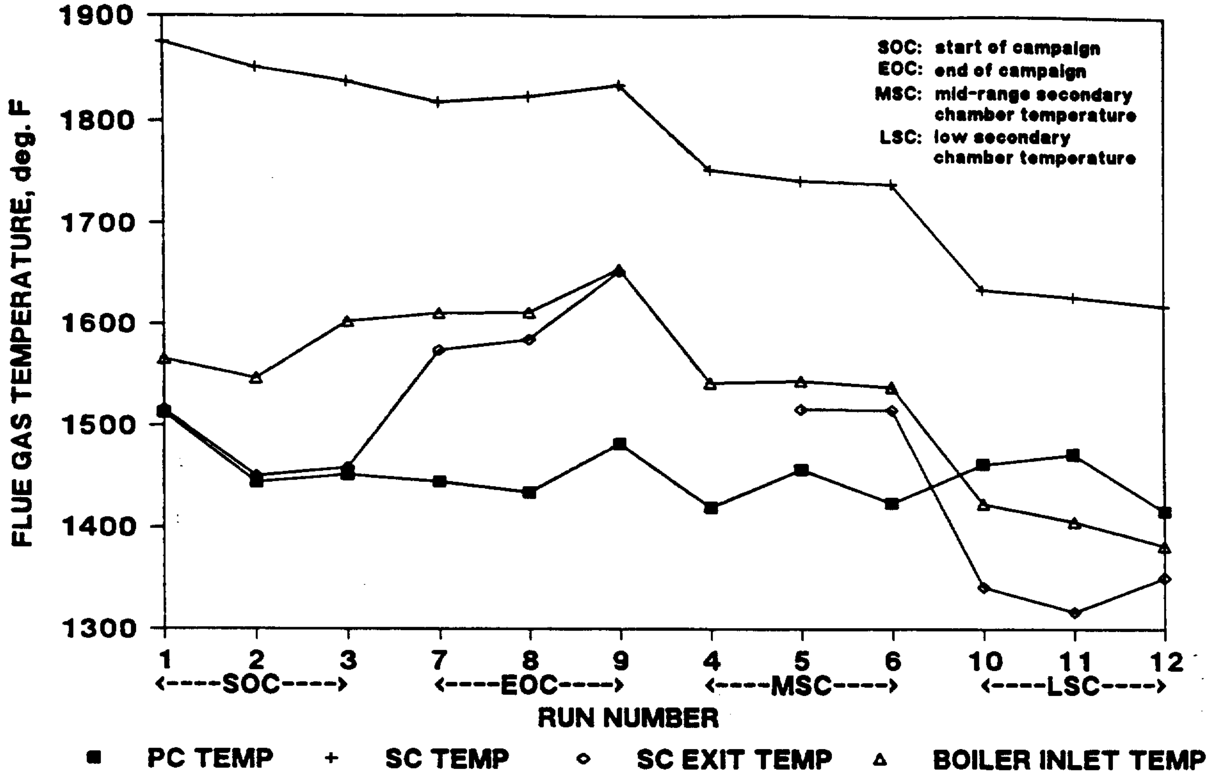

**Figure 7-5. Continuously Monitored Flue Gas Temperature by Run Number**

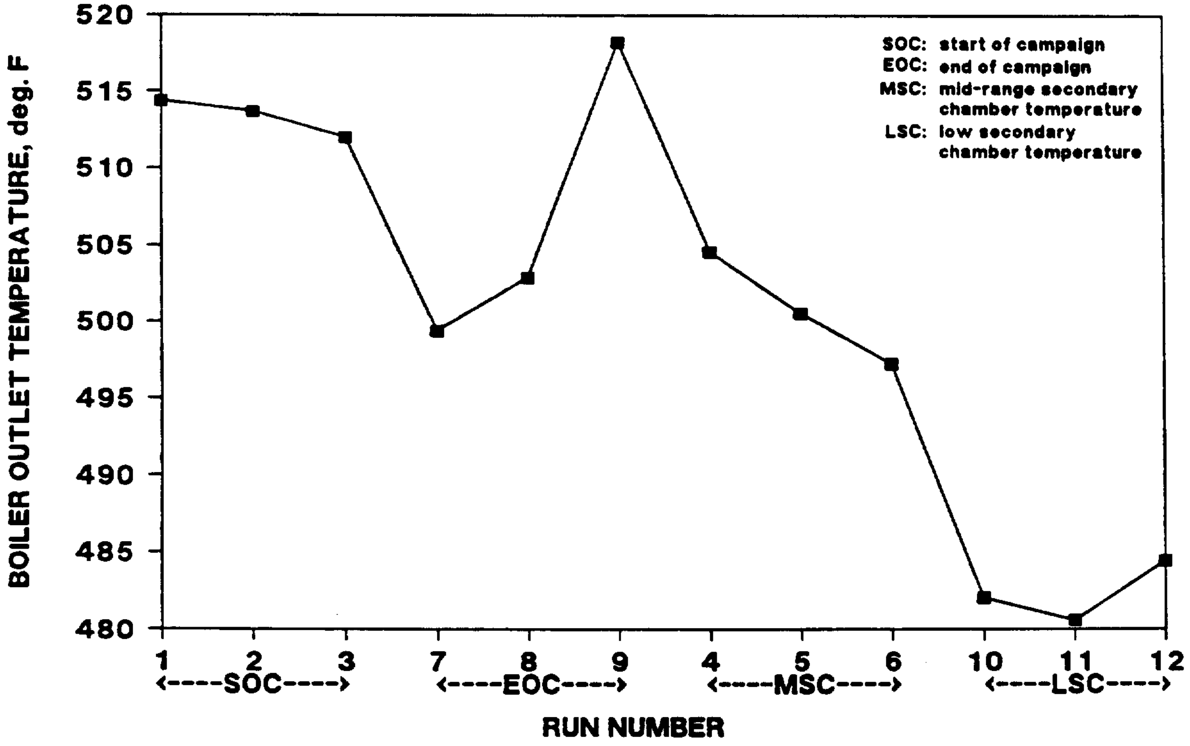

**Figure 7-6. Continuously Monitored Boiler Outlet Temperature by Run Number**

Other researchers have proposed that CDD and CDF can be formed at temperatures of about 570°F (300°C) from particulate carbon entrained in MWC flue gases.(11) As stated above, the flue gas would reach this temperature at some point between the secondary chamber exit and the ESP inlet, as heat is removed from the boiler train, and CDD and CDF could possibly form from particulate carbon.

The Oswego data were examined using Pearson product-moment correlation coefficients to see if any of the hypothesized mechanisms and their temperature or potential precursor dependencies could be observed. The differential and fractional change in CDD and CDF concentrations between the secondary chamber exit and ESP inlet and between the ESP inlet and outlet, as well as total CDD and CDF concentrations at the three sampling locations were correlated with the following parameters: secondary chamber exit temperature, boiler inlet temperature, ESP inlet manual temperature, change in secondary chamber exit and ESP inlet temperature, change in ESP inlet and outlet temperature, total chlorobenzene, chlorophenol, and PAH concentrations at the secondary chamber exit and ESP outlet, flowrate measured at the ESP inlet and secondary chamber exit, inverse flowrate measured at the ESP inlet and secondary chamber exit, and secondary chamber exit and ESP inlet flue gas moisture.

Due to the differences in combustion gas temperatures and flue gas flowrates between the test runs, the rate of gas cooling and the time at which the gases are held at the hypothesized optimal formation temperatures vary from run to run. However, no direct measurements of the rate of cooling or actual gas residence times are available. Therefore, surrogates for these variables were chosen. The fractional and differential changes in CDD or CDF concentrations were calculated to reflect the amount of CDD or CDF formed between the two locations. The temperature changes were calculated to define the temperature window the flue gas encounters as it passes through the heat recovery equipment or ESP. The inverse of the flue gas flowrate was chosen as a surrogate indicator of residence time.

The fractional change in CDD or CDF between the ESP inlet and secondary chamber exit was calculated by the following equation:

$$\text{Fractional Change} = \frac{(\text{Concentration}_{\text{Inlet}} - \text{Concentration}_{\text{SC Exit}})}{\text{Concentration}_{\text{Inlet}}}$$

The differential change in CDD or CDF concentrations between the ESP inlet and secondary chamber exit was calculated by subtracting the CDD or CDF concentrations measured at the secondary chamber exit from the CDD or CDF measured at the ESP inlet. The fractional and differential changes in the CDD and CDF concentrations measured between the ESP inlet and outlet were calculated in a similar fashion.

Pearson product-moment correlation coefficients were generated for the above data set. The most significant results ($|r| >= 0.8$) of the correlation coefficient determinations are shown in Table 7-6.

The differential change between the CDD concentrations at the secondary chamber exit and ESP inlet inversely correlated with the secondary chamber exit temperature, boiler inlet temperature, and ESP inlet manual temperature. This implies that as the temperature increases, the CDD concentrations decrease. This would lend support to the theory that temperatures greater than 1440$^{o}$F destroy CDD.

Figures 7-7 through 7-11 present scatter plots of selected correlations. As shown in the figures, the run groups tend to cluster around one another with the low secondary chamber temperature run group standing apart from the other run groups. In addition, all of the figures show a negative correlation indicating that the higher the temperature, the lower the CDD concentration.

Figures 7-12 through 7-17 show CDD and CDF concentrations measured at the secondary chamber exit versus primary chamber temperature, secondary chamber temperature and refuse moisture. As shown in the figures, the data are scattered and do not group by test condition.

## Table 7-6.

## PEARSON CORRELATION MATRIX FOR CDD AND CDF CONCENTRATIONS WITH TEMPERATURE

| Dioxin/Furan | Process Variable | r | N |
|---|---|---|---|
| ▲CDD (ESP inlet - SC Exit), ng/dscm @ 7% $O_2$ | SC Exit temp., $^oF$ | -0.812 | 11 |
| ▲CDD (ESP inlet - SC Exit), ng/dscm | SC Exit temp., $^oF$ | -0.813 | 11 |
| ▲CDD (ESP inlet - SC Exit), ng/dscm @ 7% $O_2$ | ESP inlet manual temp, $^oF$ | -0.816 | 12 |
| ▲CDD (ESP inlet - SC Exit), ng/dscm @ 7% $O_2$ | Boiler inlet temp, $^oF$ | -0.876 | 12 |
| ▲CDD (ESP inlet - SC Exit), ng/dscm | Boiler inlet temp, $^oF$ | -0.871 | 12 |
| Total CDD @ ESP inlet, ng/dscm | ESP inlet manual temp, $^oF$ | -0.800 | 12 |
| Total CDD @ ESP inlet, ng/dscm @ 7% $O_2$ | ESP inlet manual temp, $^oF$ | -0.813 | 12 |
| Total CDD @ ESP inlet, ng/dscm | Boiler inlet temp, $^oF$ | -0.800 | 12 |
| Total CDD @ ESP inlet, ng/dscm @ 7% $O_2$ | Boiler inlet temp, $^oF$ | -0.827 | 12 |

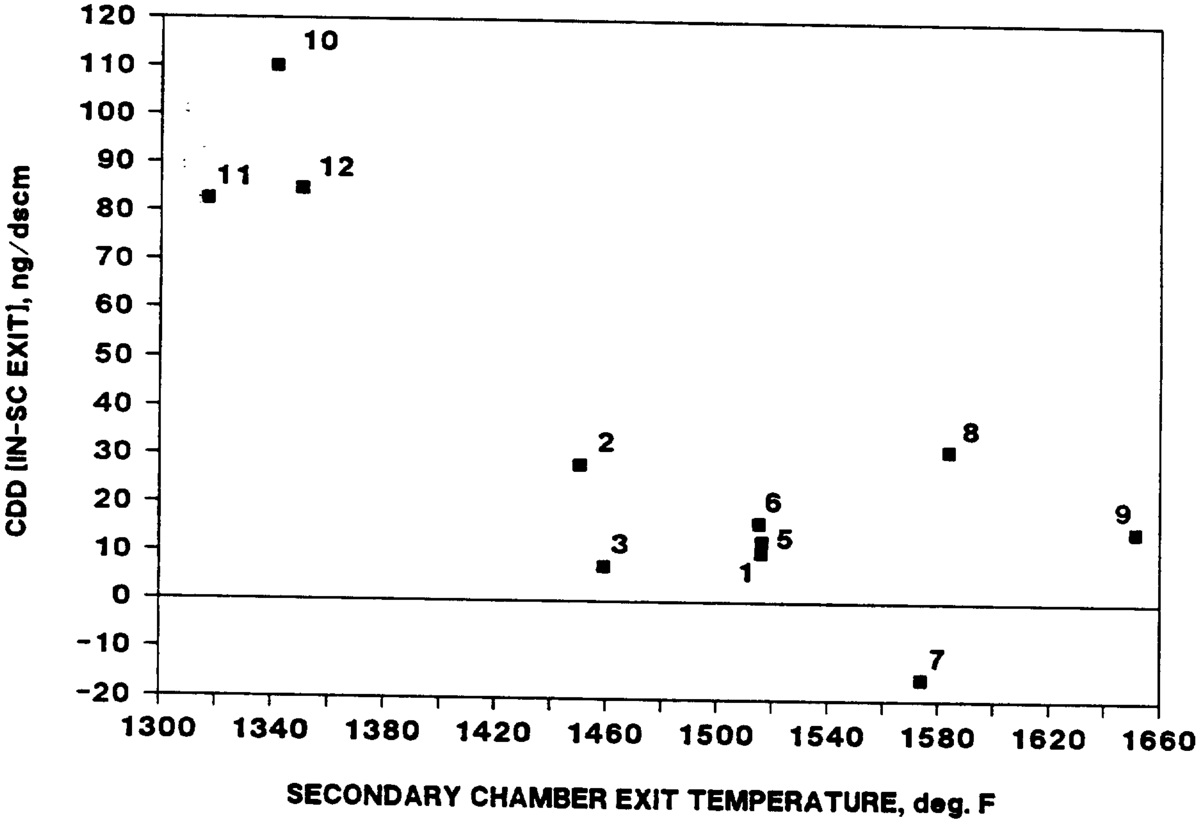

Figure 7-7. Differential Change in CDD vs.
Secondary Chamber Exit Temperature (r = -0.813)

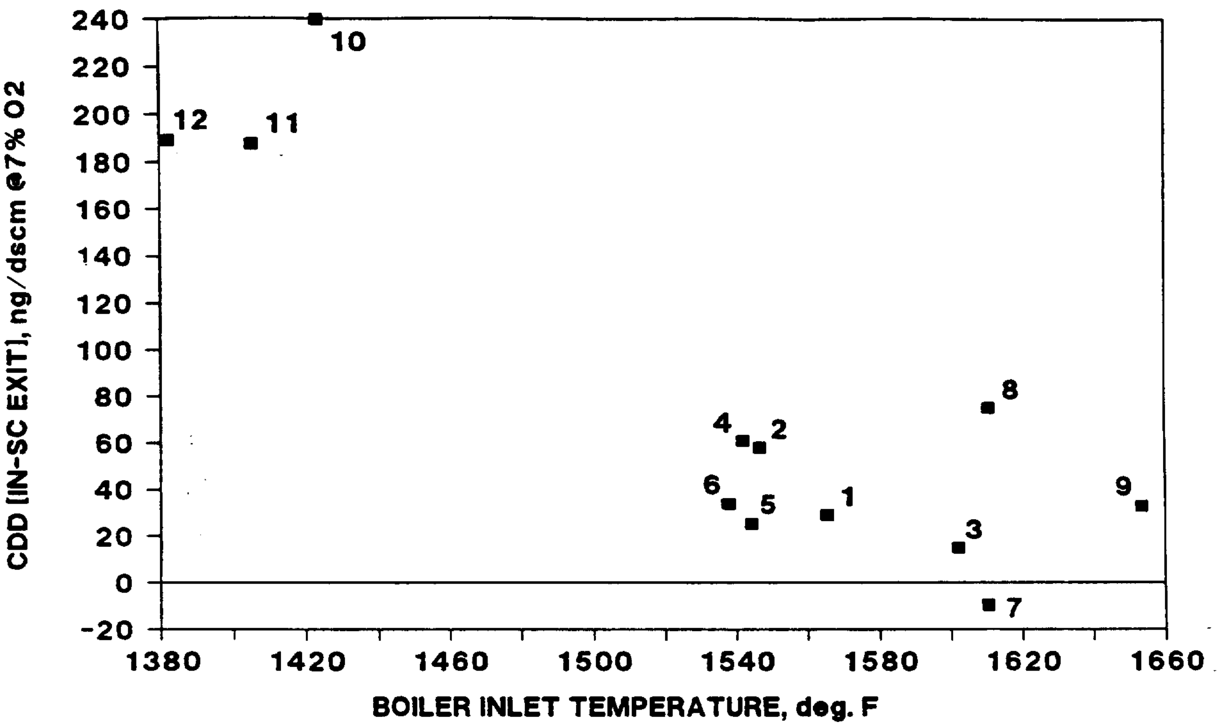

Figure 7-8. Differential Change in CDD vs. Boiler Inlet Temperature (r = -0.876)

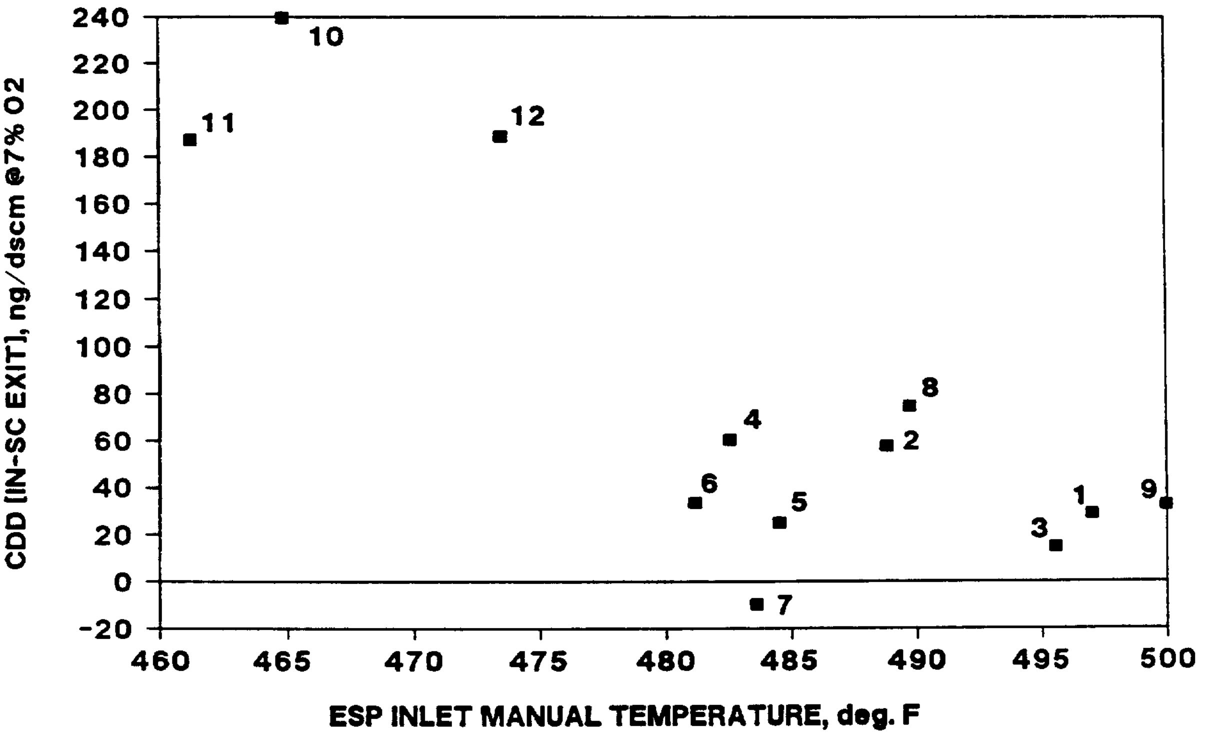

Figure 7-9. Differential Change in CDD vs. ESP Inlet Manual Temperature (r = -0.816)

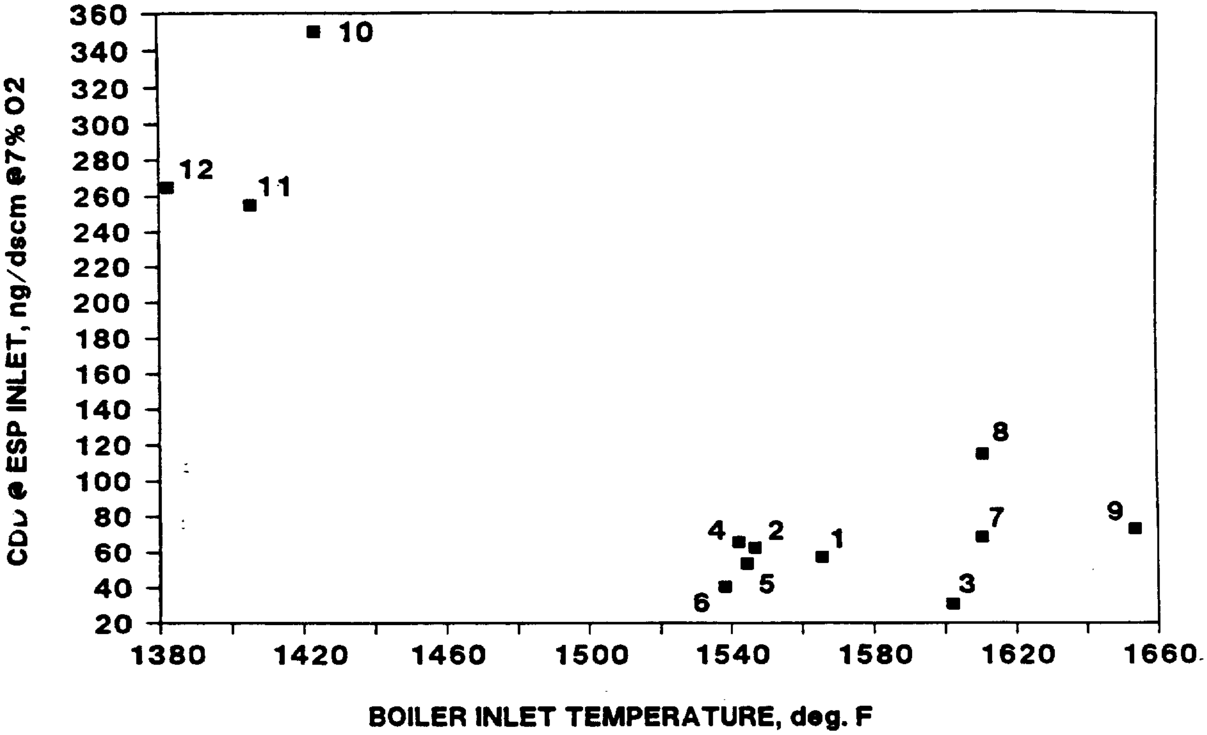

Figure 7-10. Total CDD at the ESP Inlet vs. Boiler Inlet Temperature (r = -0.827)

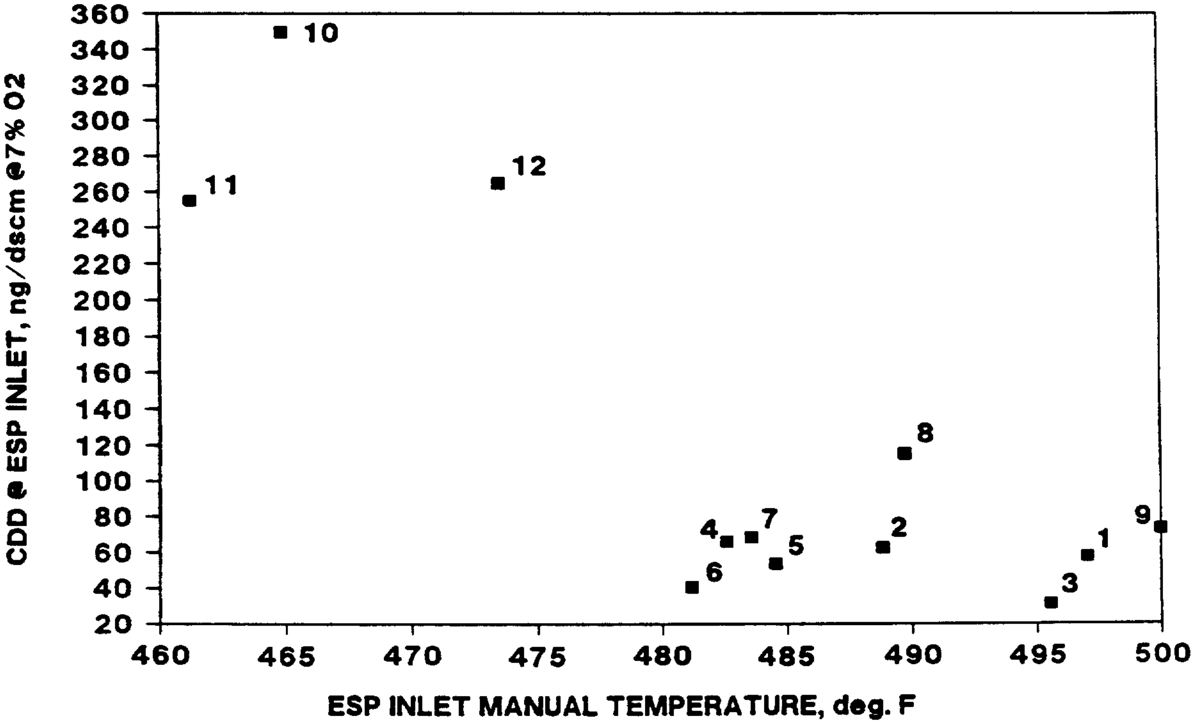

Figure 7-11. Total CDD at the ESP Inlet vs. ESP Inlet Manual Temperature (r = -0.813)

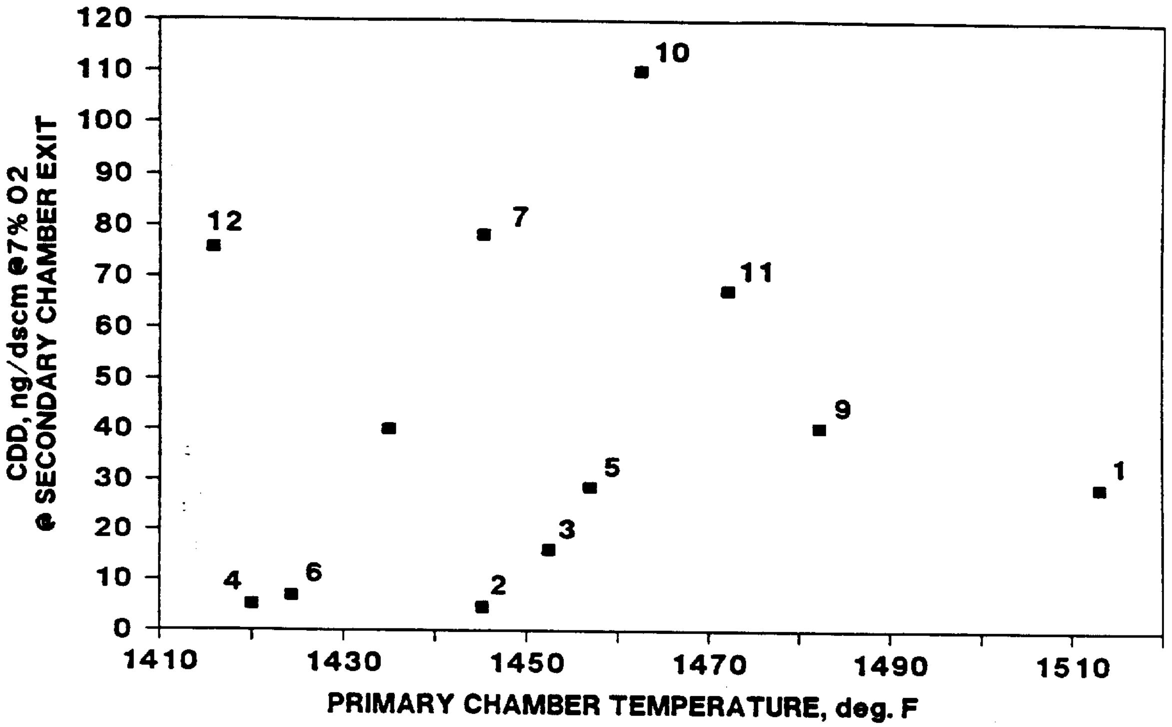

Figure 7-12. CDD at the Secondary Chamber Exit vs. Primary Chamber Temperature

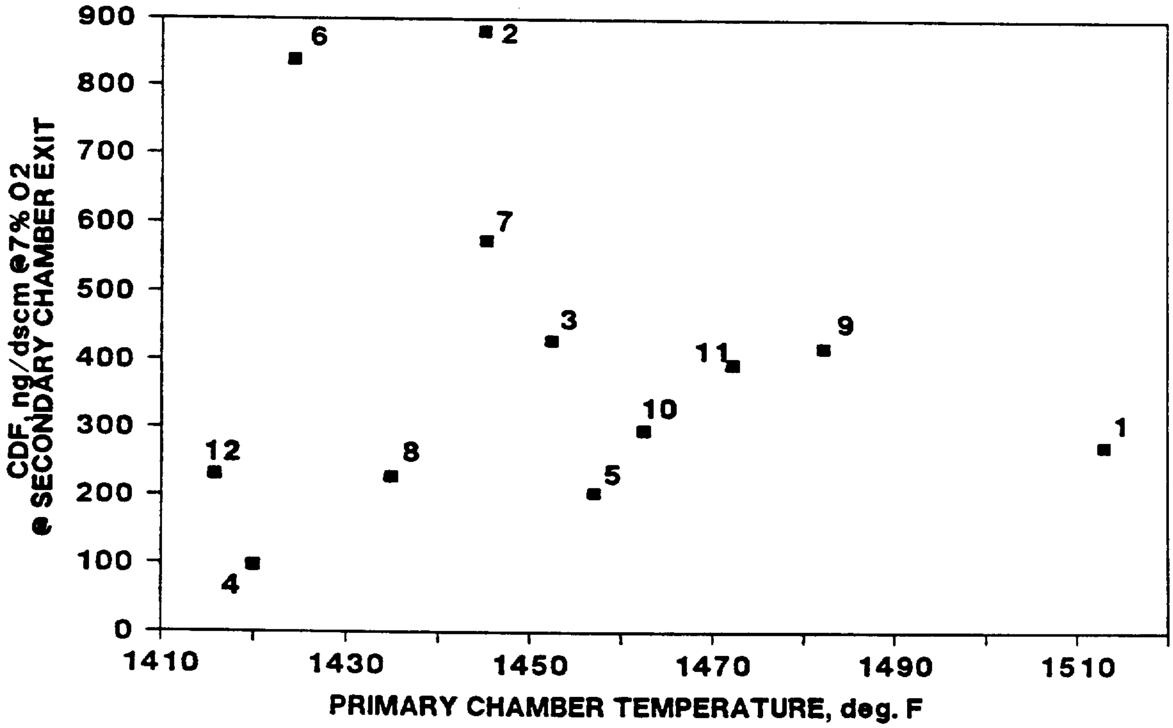

Figure 7-13. CDF at the Secondary Chamber Exit vs. Primary Chamber Temperature

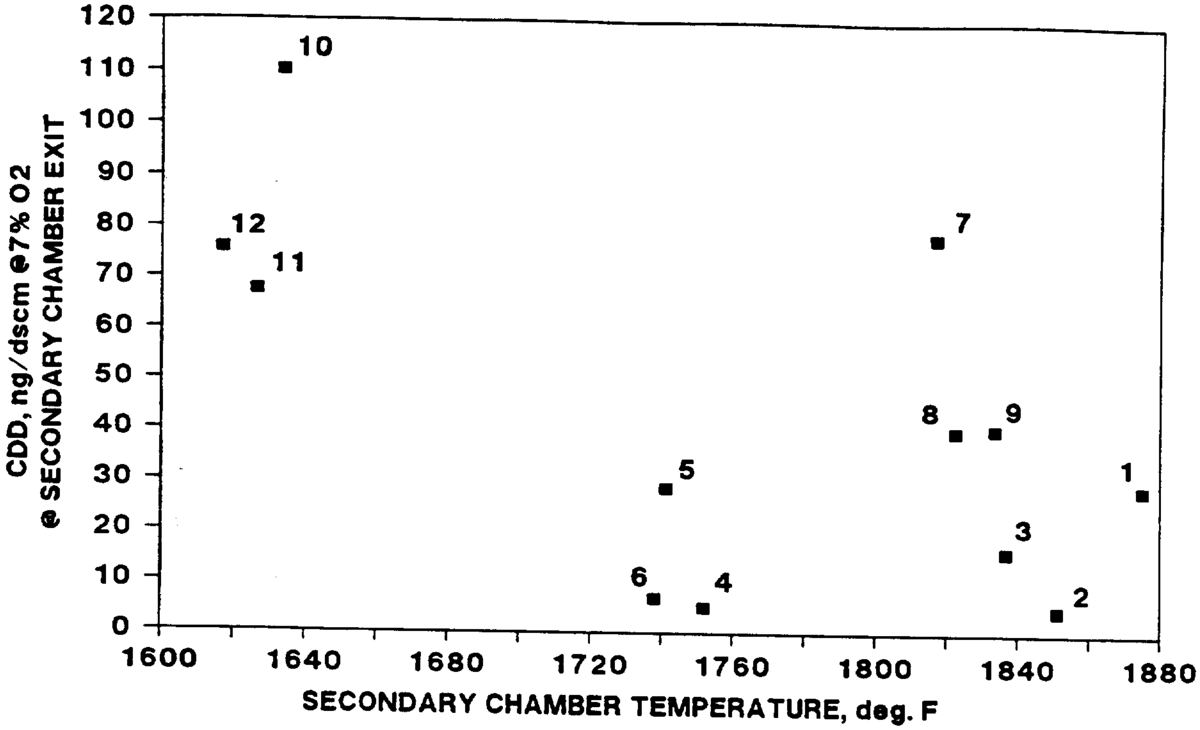

Figure 7-14. CDD at the Secondary Chamber Exit vs. Secondary Chamber Temperature

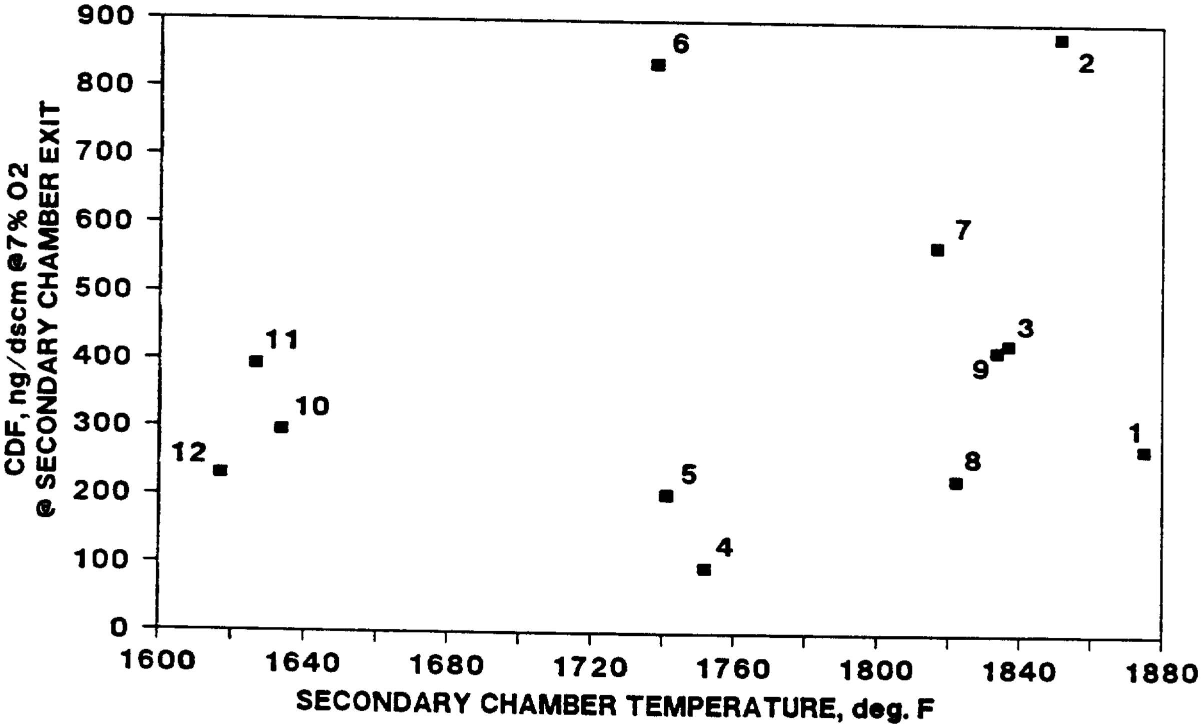

Figure 7-15. CDF at the Secondary Chamber Exit vs. Secondary Chamber Temperature

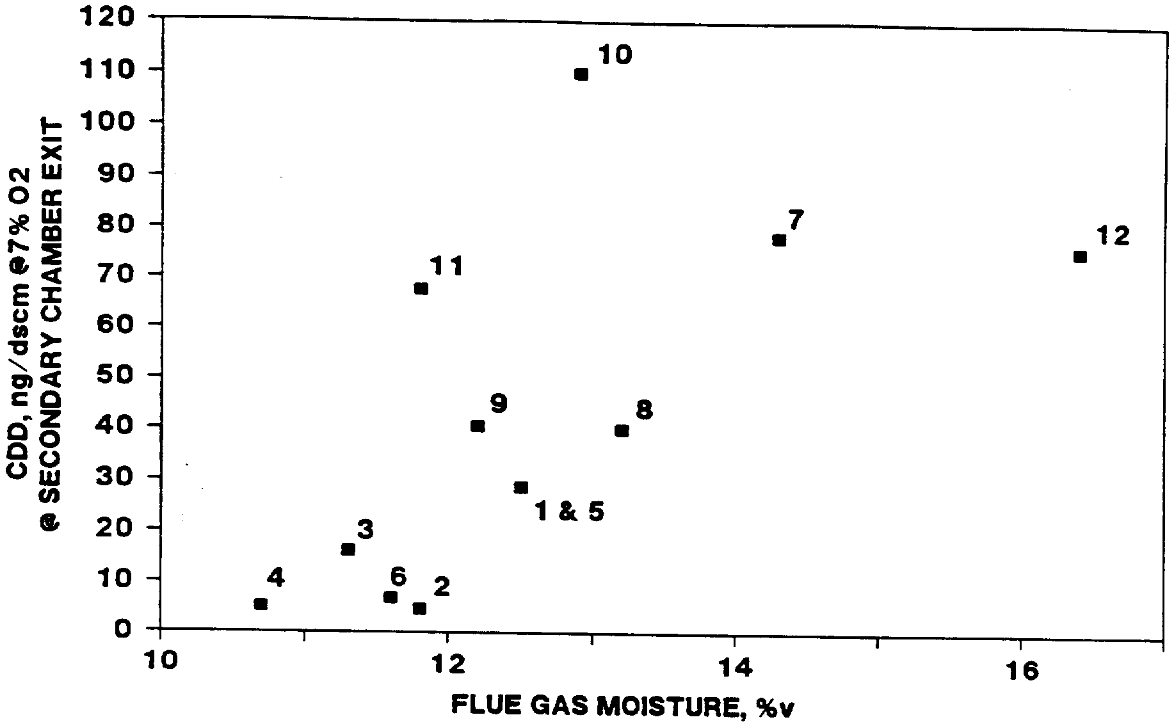

Figure 7-16. CDD at the Secondary Chamber Exit vs. Flue Gas Moisture

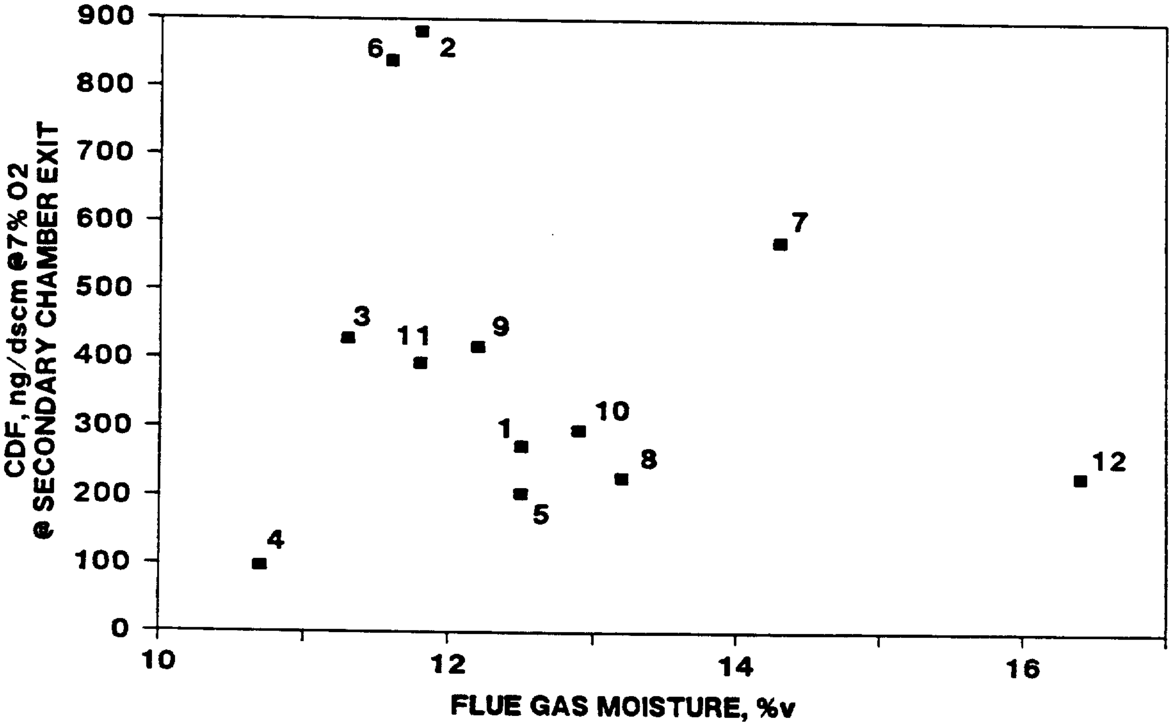

Figure 7-17. CDF at the Secondary Chamber Exit vs. Flue Gas Moisture

From an overall perspective, an important question to ask is: Based on these data taken under different test conditions, how should the unit be run to minimize the formation or reformation of CDD and CDF? Figures 7-18 and 7-19 show CDD and CDF mass rates for the three sampling locations. Figure 7-18 clearly shows that more CDD is generated per hour for the low secondary chamber temperature test condition; the CDD mass emission rates for the other test conditions do not vary significantly. As shown in Figure 7-19, Runs 2 and 6 appear to be significantly different from the other test runs in their respective run groups. No obvious reason could be found to explain why these runs appear to be different from the other runs within the respective run groups. Excluding these two runs, the CDF mass rates are also higher for the low secondary chamber test series.

## Secondary Chamber Temperature Effects

The Oswego data were compared to the results from a test program conducted at Prince Edward Island (PEI) to determine secondary chamber temperature effects on CDD and CDF concentrations. The three 33 ton-per-day (TPD) two-stage Consumat incinerators at PEI are similar to those at Oswego. In addition, the test program at PEI included tests at both high and low secondary chamber temperature test conditions similar to the program conducted at Oswego. The setpoints and CDD and CDF concentrations for the tests conducted at PEI and Oswego are shown in Table 7-7.

As is shown in the table, CDD and CDF concentrations are higher for the mid-range secondary chamber temperature condition at Oswego than for the high secondary chamber temperature condition at PEI. This may be due to the higher temperatures in the secondary chamber at PEI causing partial destruction of CDD and CDF. The CDD and CDF concentrations at both facilities were highest for the low secondary chamber temperature conditions; the secondary chamber temperature setpoint was the same at the two facilities. It is interesting to note that the CDD and CDF concentrations measured at the PEI and Oswego facilities at the boiler inlet and secondary chamber exit, respectively, were low or nondetectable for the low and high secondary chamber test conditions. Therefore, formation or reformation of CDD and CDF may have occurred at the

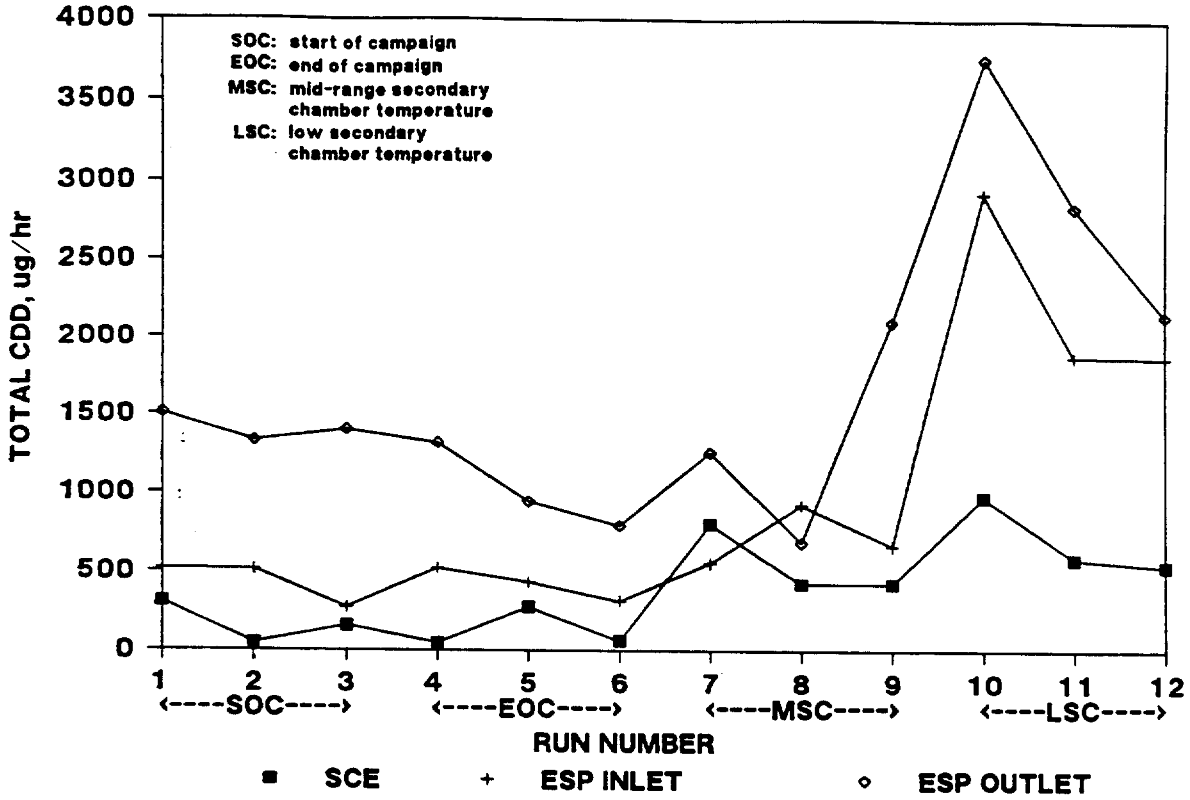

Figure 7-18. CDD Mass Rate by Run Number

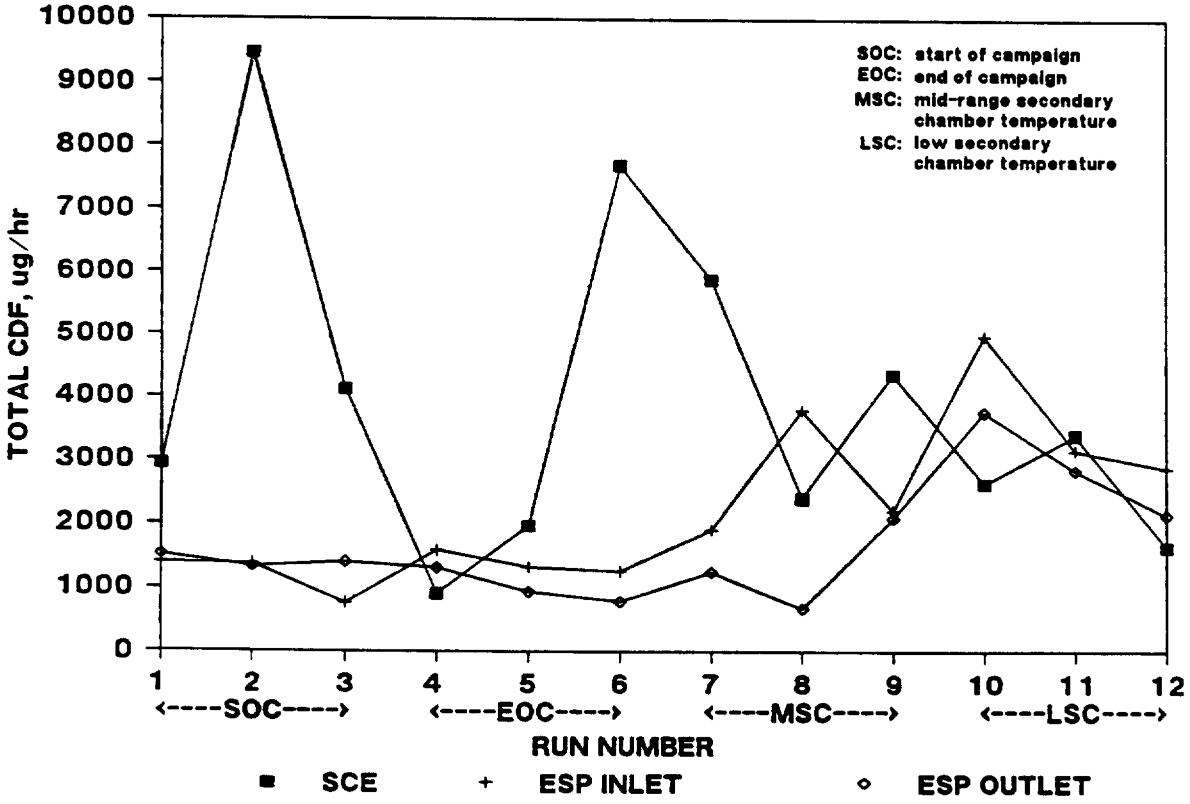

Figure 7-19. CDF Mass Rate by Run Number

## Table 7-7.

## OSWEGO AND PEI DATA

| | PEI | | OSWEGO | |
|---|---|---|---|---|
| | Primary Chamber Setpoint, °F | Secondary Chamber Setpoint, °F | Primary Chamber Setpoint, °F | Secondary Chamber Setpoint, °F |
| Normal Operation | 1290 | 1830 | 1450 | 1850 |
| Low Secondary Chamber Temperature | 1290 | 1650 | 1450 | 1650 |
| Mid-range Secondary Chamber Temperature | - | - | 1450 | 1750 |
| High Secondary Chamber Temperature | 1290 | 2075 | - | - |

| | CDD, ng/NM$^3$ @ 7% $O_2$ | | CDF, ng/NM$^3$ @ 7% $O_2$ | | CDD, ng/dscm @ 7% $O_2$ | | | CDF, ng/dscm @ 7% $O_2$ | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Boiler Inlet | Stack | Boiler Inlet | Stack | SCE | ESP Inlet | Stack | SCE | ESP Inlet | Stack |
| Low Secondary Chamber Temperature | 25 | 126 | 18 | 101 | 85 | 290 | 370 | 308 | 477 | 479 |
| Mid-range Secondary Chamber Temperature | - | - | - | - | 14 | 53 | 113 | 381 | 177 | 236 |
| High Secondary Chamber Temperature | 1.2 | 66 | 0 | 101 | - | - | - | - | - | - |

PEI facility as well as at the Oswego facility. The primary temperature setpoints were lower at PEI; it is not known what effect this may have had on the CDD and CDF concentrations measured.

Figures 7-20 and 7-21 show Oswego and PEI CDD and CDF concentrations, respectively, at the ESP inlet (stack) and secondary chamber exit (boiler inlet) by secondary chamber temperature setpoint. As shown in the figures, CDD concentrations decrease with increasing temperature. CDF concentrations do not show this pattern but are relatively constant with respect to secondary chamber temperature.

### Heat Transfer Surface Area Effects

As part of the Oswego test program, an attempt was made to determine the effect of incinerator maintenance on CDD and CDF formation. The start of campaign runs (Runs 1-3) were designed to evaluate operation of the boiler with clean heat transfer surfaces and clean air distribution equipment. These test runs would be expected to have lower CDD and CDF levels than the end of campaign runs (Runs 7-9), since the air distribution system would be operating as designed, and combustion should be more uniform. The end of campaign runs were performed when the furnace was near the end of the normal cycle between shutdowns for inspection and cleaning and maintenance. Testing at this condition demonstrates operation with ash buildup in the secondary chamber as well as dirty heat transfer surfaces and ESP plates. This would tend to cause higher temperatures and lower retention times in the incinerator and boiler. The primary and secondary chamber temperature setpoints chosen for these sets of tests were 1450°F and 1800°F, respectively.

The data in Table 7-2 shows that, as expected, the average CDD and CDF concentrations at each sampling location are generally lower for the start of campaign runs than for the end of campaign runs. However, the differences seen are not very large, in some instances less than 10 percent.

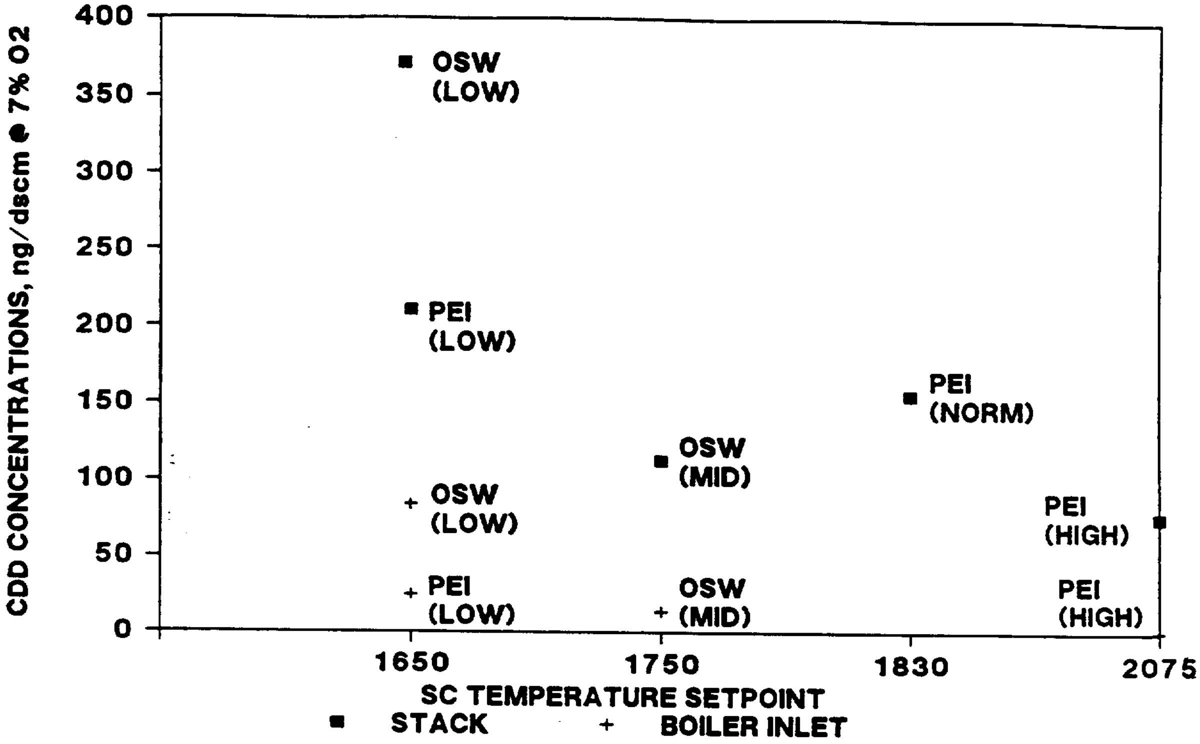

Figure 7-20. CDD Concentrations at the Boiler Inlet and Stack vs. Secondary Chamber Temperature

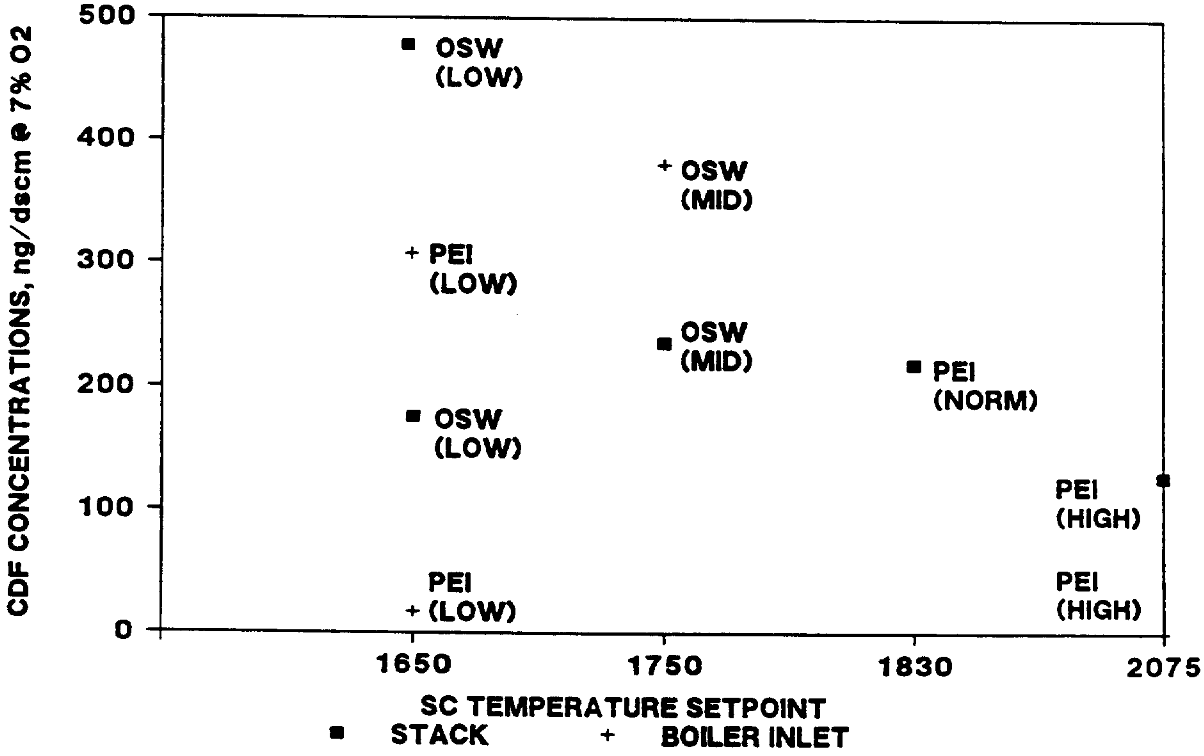

Figure 7-21. CDF Concentrations at the Boiler Inlet and Stack vs. Secondary Chamber Temperature

## COMPARISON OF CDD AND CDF CONCENTRATIONS MEASURED

Pearson product-moment correlations were performed between the CDD and CDF concentrations measured at each sampling location. Figures 7-22, 7-23 and 7-24 present scatter plots of the results. As is shown in the first figure, the CDD concentrations at the secondary chamber exit are not linearly correlated with the CDF concentrations at this location. However, the CDD and CDF concentrations are highly correlated at the ESP inlet and outlet, as shown in the latter two figures. In addition, the low secondary chamber temperature test runs stand apart from the remaining run groups; the primary chamber temperature was unstable during Run 10, which is probably why this test run stands apart from the others.

As shown in the summary tables (Tables 7-1 and 7-2), for all test runs and at all sampling locations, the CDF concentrations measured are higher than the CDD concentrations. At the secondary chamber exit, the ratio of the 12-run average CDF concentration to the 12-run average CDD concentration is approximately 10. This ratio drops to 2.3 and 1.7 at the ESP inlet and outlet, respectively. This is due, in part, to a disproportionate increase in the CDD concentration compared to the CDF concentration. The 12-run average CDD concentration increases by a factor of 3 between the secondary chamber exit and ESP inlet sampling locations; whereas, the 12-run average CDF concentration decreases by a factor of 1.5. The 12-run average CDD concentration further increases by a factor of 1.6 between the ESP inlet and outlet; the CDF concentration increases by a factor of 1.1.

The CDD concentrations measured at the ESP inlet were higher than those measured at the secondary chamber exit for all but one test run. Excluding the low secondary chamber test runs, the CDF concentrations generally decreased between these two locations. For all but one test run, the CDD concentrations measured at the ESP outlet were higher than those measured at the ESP inlet; the CDF concentrations increased between the two locations for all but three of the test runs.

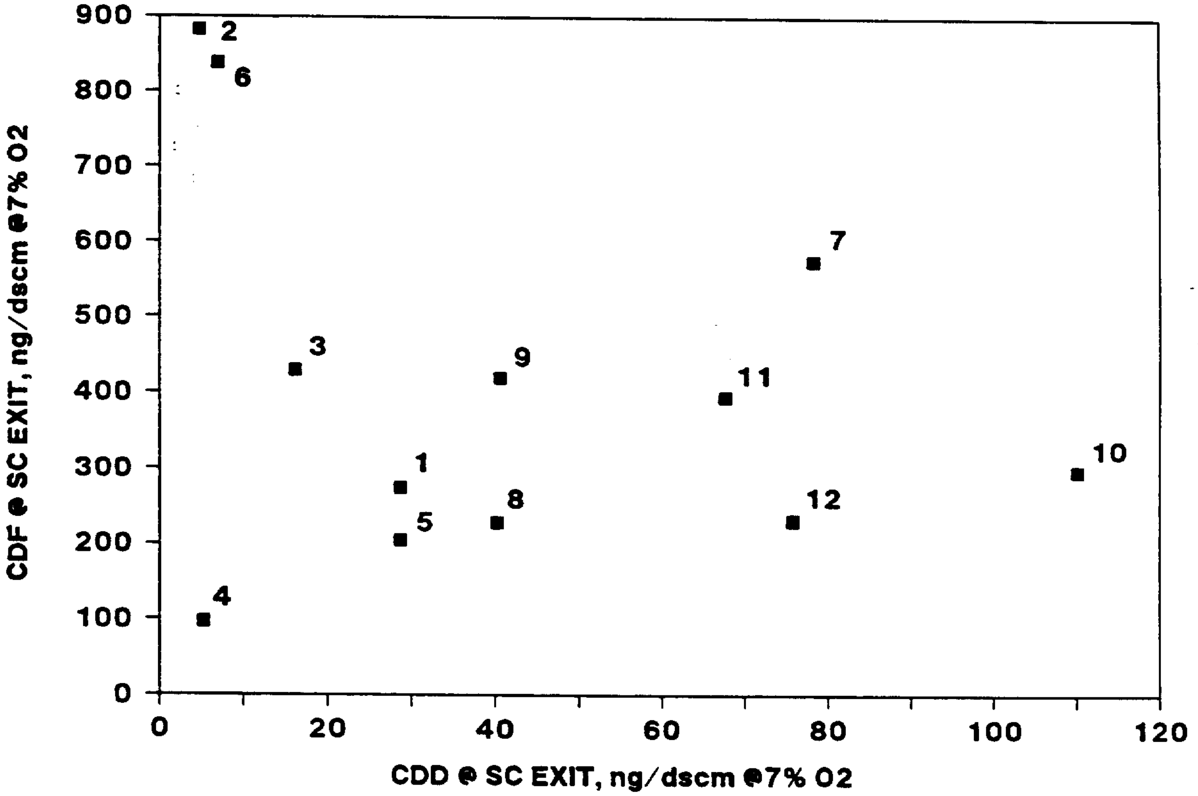

Figure 7-22. CDD vs. CDF Concentrations at the Secondary Chamber Exit (r = -0.260)

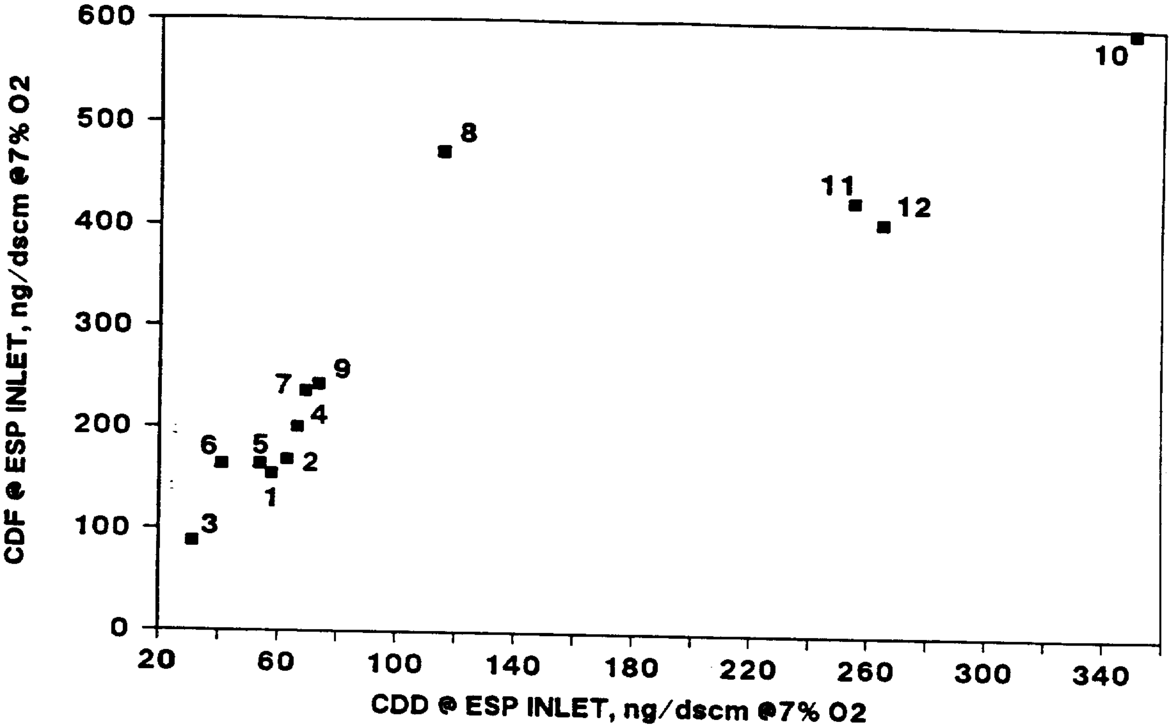

Figure 7-23. CDD vs. CDF Concentrations at the ESP Inlet (r = 0.894)

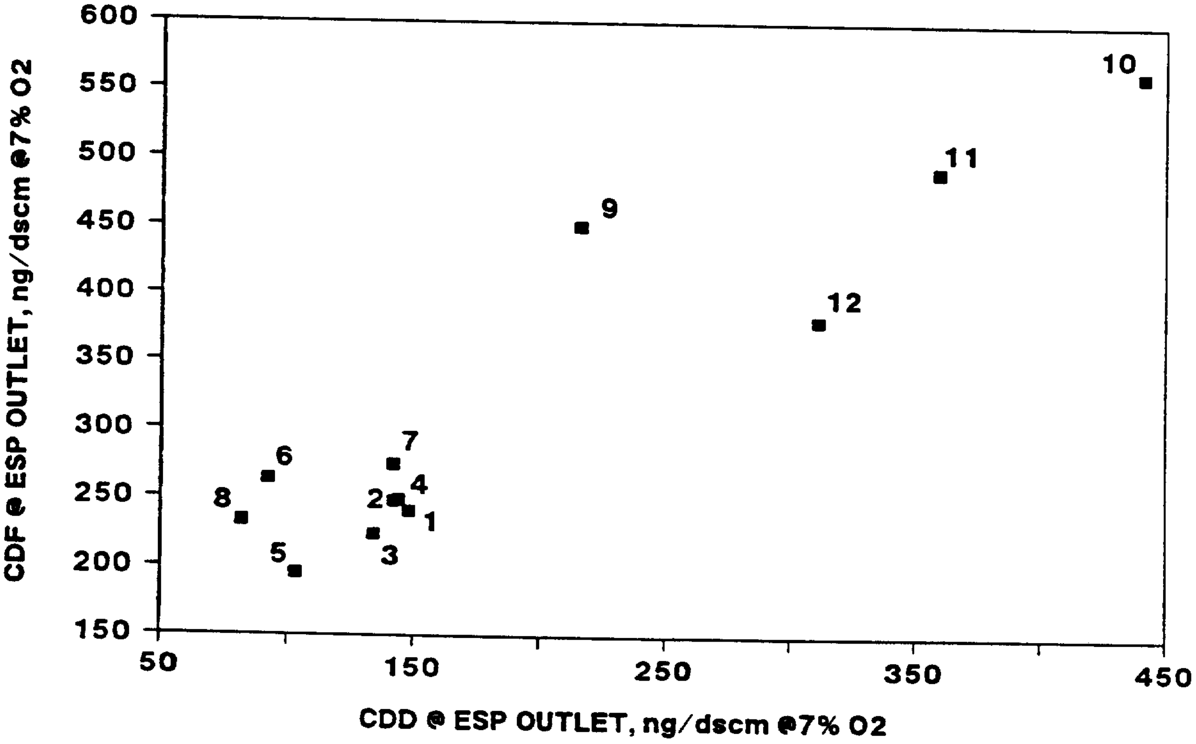

Figure 7-24. CDD vs. CDF Concentrations at the ESP Outlet (r = 0.930)

The CDD and CDF concentrations measured at the secondary chamber exit may be considered to represent the CDD and CDF resulting from the combustion process. These compounds may have been formed or reformed in the combustion zone or may have simply volatilized from the refuse. By comparing the relative amounts of CDD and CDF at the secondary chamber exit and ESP inlet (ignoring the potential sampling and analytical inconsistencies), one can get an idea of the relative contributions from the combustion process compared to the amount formed after combustion as the flue gases cool down. Ignoring sampling and analytical bias, it would appear that approximately 35 percent of total CDD at the ESP inlet is formed or reformed in the combustion zone (i.e., prior to the secondary chamber exit) and the remaining 65 percent is formed in the boiler train (i.e., between the secondary chamber exit and ESP inlet). Comparing the CDD concentrations across the entire system shows that only about 22 percent of the total CDD at the ESP outlet is formed or reformed in the combustion zone and 78 percent is formed downstream in the boiler and ESP. Comparing the CDF concentrations across the entire system shows a 28 percent decrease in total CDF between the secondary chamber exit and ESP outlet.

## STATISTICAL ANALYSIS

Two statistical methods were used to explore the effects of location and operating conditions on CDD and CDF concentrations. Analysis of variance (ANOVA) was used to test the effects of operating condition and location, both together and separately, on CDD and CDF. Cluster analysis was then used to explore the effect of operating conditions on CDD and CDF simultaneously.

It should be noted that cluster analysis does not provide probability estimates when exploring relationships among variables. In other words, relationships are not determined by cluster analysis to be statistically significant at a pre-specified level. Thus, cluster analysis provides less formal answers but is capable of addressing more complex questions with graphical representations.

### Analysis of Variance Models

Two sets of ANOVA models were used to test for operating condition and location effects on total CDD and CDF concentrations. The interaction effect of operating condition and location effects on CDD and CDF concentrations was also included in the initial set of ANOVA models.

ANOVA models were designed to answer the following questions:

- Are the CDD and CDF concentrations different for the different sample measurement locations and for the different operating conditions?
- Are the CDD and CDF concentrations different for low secondary chamber temperature vs. mid-range secondary chamber temperature operating conditions?
- Are the CDD and CDF concentrations different for start of campaign vs. end of campaign operating conditions? A cluster analysis was also performed to further explore the effects of operating conditions on CDD and CDF, simultaneously, by location.

### ANOVA Model I

The first set of ANOVA models was designed to test for differences in CDD and CDF concentrations between locations and operating conditions. These two main effects (location and operating condition) and the interaction of the two were included. The results are contained in Appendix B.

Table 7-8 presents the CDD and CDF concentrations, by operating condition, averaged over the three locations and Table 7-9 shows the CDD and CDF concentrations, by location, averaged over the four operating conditions. Whereas these tables show the differences in CDD and CDF concentrations over operating conditions and locations, the ANOVAs determine which of these differences are statistically significant.

As can be seen in the summary statistics in Table 7-8, the CDD and CDF average concentrations are higher for the low secondary chamber temperature condition than for the other operating conditions. The mid-range secondary chamber temperature condition had the lowest average CDD and CDF concentrations. Although the CDD and CDF averages appear to follow the same trends over operating conditions, only CDD differences between operating conditions are statistically different.

## Table 7-8.

## CDD AND CDF CONCENTRATIONS BY OPERATING CONDITION AVERAGED OVER LOCATION

| Operating Condition | CDD, ng/dscm @ 7% $O_2$ | N | CDF, ng/dscm @ 7% $O_2$ | N |
|---|---|---|---|---|
| Start of Campaign | 69.57 | 9 | 301.16 | 9 |
| Low Secondary Chamber Temperature | 248.28 | 9 | 421.34 | 9 |
| Mid-Range Secondary Chamber Temperature | 60.13 | 9 | 264.52 | 9 |
| End of Campaign | 94.52 | 9 | 348.13 | 9 |

Table 7-9 shows the CDD and CDF concentrations by location averaged over all operating conditions. The highest CDD average concentrations were at the ESP outlet, whereas the highest CDF average concentrations were at the hotzone. Overall, CDD and CDF concentrations increased between the ESP inlet and the ESP outlet. The CDD average concentration also increased substantially between the hotzone and the ESP inlet; whereas, the CDF average concentration decreased between the hotzone and ESP inlet. Further analysis showed that the CDD and CDF concentrations were statistically different between sampling locations.

Figures 7-25 and 7-26 chart the CDD and CDF concentrations, respectively, by operating condition and location, providing a graphical, more detailed view of the data in Tables 7-8 and 7-9. Since, statistically, the CDD and CDF concentrations were shown to behave differently over operating conditions and locations, the results will be presented separately for both sets of ANOVAs.

Results of the CDD Analyses. The CDD ANOVA model shows that both location and operating condition have a significant effect on the CDD concentrations. Also, the interaction effect of location and operating condition was significant. A significant interaction can inflate or deflate the significance of the main effects and is thus explored further.

The effect of the interaction between operating condition and location for CDD concentrations can be seen in Figure 7-25. Because the operating condition with the highest average CDD concentration was observed at the low secondary chamber temperature test conditions, and the location with the highest average CDD was at the ESP outlet, the single highest average CDD concentration would be expected to be at the ESP outlet for the low secondary chamber temperature operating condition. This is shown in the figure. The operating condition with the lowest average CDD concentration was the mid-range secondary chamber temperature test condition, and the location with the lowest CDD average was the secondary chamber exit. As shown in Figure 7-25, the lowest CDD average did occur at the secondary chamber exit for mid-range secondary chamber temperature conditions.

## Table 7-9.

## CDD AND CDF CONCENTRATIONS BY LOCATION AVERAGED OVER ALL RUN CONDITIONS

| Location | CDD, ng/dscm @ 7% $O_2$ | N | CDF, ng/dscm @ 7% $O_2$ | N |
|---|---|---|---|---|
| Secondary Chamber Exit | 41.49 | 12 | 406.16 | 12 |
| ESP Inlet | 119.90 | 12 | 277.17 | 12 |
| ESP Outlet | 192.98 | 12 | 318.04 | 12 |

Thus, the effects of operating condition and location on CDD concentrations interact, producing CDD average concentrations which are not simply the sum of the operating condition and location effects. Because of this interaction, the main effects of operating condition and location may be inflated or deflated in the ANOVA results. For example, there may be a significant difference in CDD averages between operating conditions, but the effect may differ among the three locations. Or, conversely, there may be a significant difference in CDD averages between location, but the location effect may differ among the operating conditions.

The hypothesis that the two main effects of operating condition and location are not significant after considering the interaction effect can be tested. This test uses the strength of interaction effect as a point of reference, or the error term. The main effect is significant if it is large relative to this term.

The results show both location and operating condition had significant effects (at the 0.02 and 0.01 levels, respectively) on CDD after accounting for the interaction effect. Thus, location and operating condition are independently significant as well as interacting to produce significant differences in CDD concentrations.

<u>Results of the CDF Analyses</u>. The same ANOVA model was performed for the CDF concentrations. Since mean CDF concentrations were not significantly different due to either main effect when the interaction was included, another ANOVA using a main-effects-only model was performed. Independently, the main effects of location and operating condition did not have a significant effect on the CDF concentrations. Two additional ANOVA models were done to further investigate any trends. One tested for the main effect of location only and the other ANOVA tested for the main effect of operating condition only. Again, differences in CDF concentrations were not significant for either. Further analyses were performed in ANOVA Model II to investigate whether there were significant trends within each location and operating condition.

Conclusions of ANOVA Model I. This first set of ANOVA models was performed to determine if the main effects of location and operating condition or the interaction of the two caused significant differences in CDD and CDF concentrations. Main effects and interaction effects were found to be significant for the CDD concentrations but not for the CDF concentrations.

Thus, mean CDD concentrations were significantly different between locations and between operating conditions. There also exists an interaction effect between location and operating condition for CDD concentrations. The significant interaction effect for the CDD concentrations, however, did not diminish the main effects of location and operating condition. This was tested by considering the interaction effect as an error term and then testing whether or not both the main effects were still significant for the CDD concentrations.

Since the main effects of location and operating condition and the interaction of the two were not significant for the CDF model, a second set of ANOVA models was constructed to explore the main effects separately for the CDF concentrations. Again, the main effects were not significant. That is to say, there is no difference between locations or between operating conditions for CDF concentrations. ANOVA Model II will test for differences within each location and operating condition. These analyses which look at differences within operating conditions and locations are called one-way ANOVAs and are described below (ANOVA Model II.)

ANOVA Model II. (One-way ANOVAs)

The previous analysis showed location and operating condition affects CDD concentrations; neither significantly affected CDF concentrations. A second set of ANOVA models was constructed to explore the effects of operating condition on CDF concentrations separately for each location and also the effects of location on CDF concentrations separately for each operating condition. Since it was determined that location, operating condition, and the interaction of the two are significant for CDD concentrations, these additional ANOVAs were not necessary for the CDD concentrations. However, they help to provide further insight into which particular operating condition or location is the driving force in these differences.

As explained above, the model used for this purpose is a one-way ANOVA. An assumption of these models is that test run results within each condition or location are replicate values. The question of whether or not the test runs within each condition and location are truly replicates is explored later in this section and in Section 6.

The first set of one-way ANOVAs (ANOVA Model IIA) was performed to model CDD and CDF concentrations for each location as a function of operating condition only. A second set of one-way ANOVAs (ANOVA Model IIB) was done to model CDD and CDF concentrations for each operating condition as a function of location only.

One-way ANOVA Model IIA. Table 7-10 shows average CDD and CDF concentrations for each operating condition by location which were tested for equality by the first one-way ANOVA. In addition, Table 7-10 shows the significance levels for each of the six one-way ANOVAs. Figures 7-27 through 7-32 depict the CDD and CDF concentrations used for each of these six one-way ANOVA models. The validity of the ANOVA assumption of test run replicates within each operating condition can be evaluated with these graphs.

Duncan's multiple range test was used to help determine which CDD or CDF averages were different among operating conditions. Again, the CDD and CDF averages were compared separately. Duncan's results are also shown in Table 7-10. An "H" beside the mean designates an operating condition with an average statistically higher than the other averages within the location, and an "L" designates an operating condition with an average statistically lower than the other averages within the location. A CDD mean that is not marked with either letter is not significantly different from the other operating condition CDD means within the location. The same rule is true for CDF means.

## Table 7-10.

## CDD AND CDF CONCENTRATIONS AVERAGED BY OPERATING CONDITION FOR EACH LOCATION[a]

| Location and Operating Condition | CDD, ng/dscm @ 7% $O_2$ | N | CDF, ng/dscm @ 7% $O_2$ | N |
|---|---|---|---|---|
| <u>Secondary Chamber (S.C.) Exit</u>: | | | | |
| Significance Level | 0.0049 | | 0.7957 | |
| Start of Campaign | 16.60 | 3 | 528.7 | 3 |
| End of Campaign | 51.20 | 3 | 407.3 | 3 |
| Low S.C. Temperature | 84.53 (H) | 3 | 307.7 | 3 |
| Mid-range S.C. Temperature | 13.63 (L) | 3 | 381.0 | 3 |
| <u>ESP Inlet</u>: | | | | |
| Significance Level | 0.0001 | | 0.0057 | |
| Start of Campaign | 50.57 (L) | 3 | 137.23 (L) | 3 |
| End of Campaign | 85.73 (L) | 3 | 317.47 | 3 |
| Low S.C. Temperature | 289.90 (H) | 3 | 477.20 (H) | 3 |
| Mid-range S.C. Temperature | 53.40 (L) | 3 | 176.57 | 3 |
| <u>ESP Outlet</u>: | | | | |
| Significance Level | 0.0007 | | 0.0138 | |
| Start of Campaign | 141.53 (L) | 3 | 237.57 (L) | 3 |
| End of Campaign | 146.63 (L) | 3 | 319.63 (L) | 3 |
| Low S.C. Temperature | 370.40 (H) | 3 | 478.93 (H) | 3 |
| Mid-range S.C. Temperature | 113.37 (L) | 3 | 236.03 (L) | 3 |

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[a] The letters in parentheses represent the results of Duncan's multiple range tests (H=high and L=low).

Results of the CDD analysis. These ANOVA models test whether the CDD averages were equal among operating conditions for each location. All three CDD one-way ANOVAS were significant at the 0.005 level or better (Appendix A). This was to be expected since the first set of ANOVAs showed that the main effect of operating condition was significant. As can be seen in Table 7-10, CDD averages at the low secondary chamber temperature operating condition were consistently higher than the other averages. In fact, at the ESP inlet and outlet, the average concentration of CDDs at the low secondary chamber temperature condition was more than twice as large as the CDD concentrations at any other operating condition. The mid-range secondary chamber temperature operating condition provided the lowest CDD averages for two of the three locations (hotzone and ESP outlet). The differences between these operating conditions seem to be the strongest. In conclusion, since strong differences exist between operating conditions at each location, ANOVA Model I found operating condition to be an important main effect for the CDD concentrations.

Figures 7-27, 7-28, and 7-29 show the data used in the first set of one-way ANOVAs for the CDD concentrations. Although the end of campaign operating condition concentrations seem to vary somewhat, the replicates appear to be fairly constant within operating conditions. The variability between replicates also seems to be greatest at the secondary chamber exit, which may partly explain why the ANOVA results were not quite as significant at this location as for the other locations. This variability was not so extreme, however, as to disrupt the consistency of the trends between locations.

Duncan's multiple range test showed that the CDD averages at the low secondary chamber temperature condition were higher than at the other operating conditions for each of the locations. With respect to this multiple range test, the ESP inlet and the ESP outlet concentrations appear to be more similar to each other.

Results of the CDF analysis. The first set of ANOVA models determined that there was not a significant difference between operating conditions for the CDF concentrations when averaged over all of the locations. However, when the one-way ANOVA models were performed for each location, they showed that operating condition has a significant effect at the ESP inlet and the ESP outlet, with significance levels of about 0.01. Operating condition was not significant at the hotzone for the CDF concentrations. These results are consistent with the trends observed in Table 7-10.

Figures 7-30, 7-31, and 7-32 show the data used in the CDF model. The CDF concentrations within operating conditions at the ESP inlet and the ESP outlet (Figures 7-31 and 7-32) are relatively constant, except that they appear to be varying slightly more for the end of campaign operating condition (as did the CDD concentrations). However, this variation does not seem to affect the results of the one-way ANOVAs nor the results of Duncan's test, which showed consistent trends at both the ESP inlet and outlet.

Figure 7-30 shows quite a bit of variability within replicates at the secondary chamber exit. For example, CDF concentrations range from 98.9 to 838.7 ng/dscm at 7 percent $O_2$ for the mid-range secondary chamber temperature operating condition. The end of campaign operating condition CDF concentrations also fluctuate more than at the other conditions. This variability brings into question the assumption that the test run results are true replicates within operating conditions. Significant results may not have been found for CDF concentrations at the secondary chamber exit because the assumption of replicates within operating conditions may not be a valid assumption for this location. That is, either there was no difference between operating conditions at this location, or the test runs were not replicates at this location, indicating the variation was too large to detect differences in the CDF means.

Duncan's test shows the CDF averages for the low secondary chamber temperature operating condition at the ESP inlet and outlet are higher than the CDF averages for the start of campaign operating condition. Figures 7-31 and 7-32 show that the CDF concentrations are relatively consistent at both the low secondary chamber temperature and start of campaign operating conditions. Duncan's test also shows that the end of campaign and mid-range secondary chamber temperature condition CDF concentrations were lower than average; the low secondary chamber temperature condition CDF concentrations were higher than average. This also reflects the behavior of the CDD concentrations at the ESP outlet. No differences were detected by Duncan's test for CDF concentrations at the secondary chamber exit. Again, this was consistent with the ANOVA results, which showed there was not a significant difference between the operating condition means at the secondary chamber exit.

In conclusion, for CDF concentrations, differences in operating condition were significant only at the ESP inlet and outlet; this explains why the ANOVA Model I showed the main effect of operating condition was not significant for CDF concentrations.

In summary, Table 7-10 shows that CDD and CDF results are fairly consistent at the ESP inlet and ESP outlet locations. For example, Duncan's multiple range test showed that the low secondary chamber temperature operating condition was always the operating condition with the above average concentrations, and that the start of campaign test condition always had a lower than average concentration for these two locations.

<u>One-way ANOVA Model IIB</u>. Table 7-11 shows the CDD and CDF average concentrations for each location by operating condition which were tested for equality with the second set of one-way ANOVAs. Figures 7-33 through 7-40 depict the CDD and CDF concentrations used for each of these six additional one-way ANOVA models. These figures can also be used to examine the validity of the ANOVA assumptions; in particular, the assumption of replicates within locations.

<u>Results of the CDD analysis</u>. These ANOVA models tested whether the CDD averages were equal among location for each operating condition. The models show that all of the CDD ANOVAs were significant at a level below 0.002 except the end of campaign operating condition, which was marginally significant at the 0.09 level.

The CDD concentrations used in the second set of one-way ANOVAs are shown in Figures 7-33 through 7-36. The replicates appear to be fairly constant within

## Table 7-11.

## CDD AND CDF CONCENTRATIONS AVERAGED BY LOCATION FOR EACH OPERATING CONDITION[a]

| Location and Operating Condition | CDD, ng/dscm @ 7% $O_2$ | N | CDF, ng/dscm @ 7% $O_2$ | N |
|---|---|---|---|---|
| Start of Campaign: | | | | |
| Significance Level | 0.0001 | | 0.0912 | |
| Secondary Chamber Exit | 16.60 (L) | 4 | 528.7 (H) | 4 |
| ESP Inlet | 50.57 (M) | 4 | 137.2 (L) | 4 |
| ESP Outlet | 141.53 (H) | 4 | 237.6 | 4 |
| End of Campaign: | | | | |
| Significance Level | 0.0913 | | 0.6953 | |
| Secondary Chamber Exit | 51.20 (L) | 4 | 407.3 | 4 |
| ESP Inlet | 85.73 | 4 | 317.5 | 4 |
| ESP Outlet | 146.63 (H) | 4 | 319.6 | 4 |
| Low Secondary Chamber Temperature: | | | | |
| Significance Level | 0.0011 | | 0.1037 | |
| Secondary Chamber Exit | 84.53 (L) | 4 | 307.3 | 4 |
| ESP Inlet | 289.90 (H) | 4 | 477.4 | 4 |
| ESP Outlet | 370.40 (H) | 4 | 478.93 | 4 |
| Mid-Range Secondary Chamber Temperature: | | | | |
| Significance Level | 0.0019 | | 0.5715 | |
| Secondary Chamber Exit | 13.63 (L) | 4 | 381.0 | 4 |
| ESP Inlet | 53.40 (M) | 4 | 176.6 | 4 |
| ESP Outlet | 113.37 (H) | 4 | 236.0 | 4 |

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[a] The letters in parentheses represent the results of Duncan's multiple range tests (H=high and L=low).

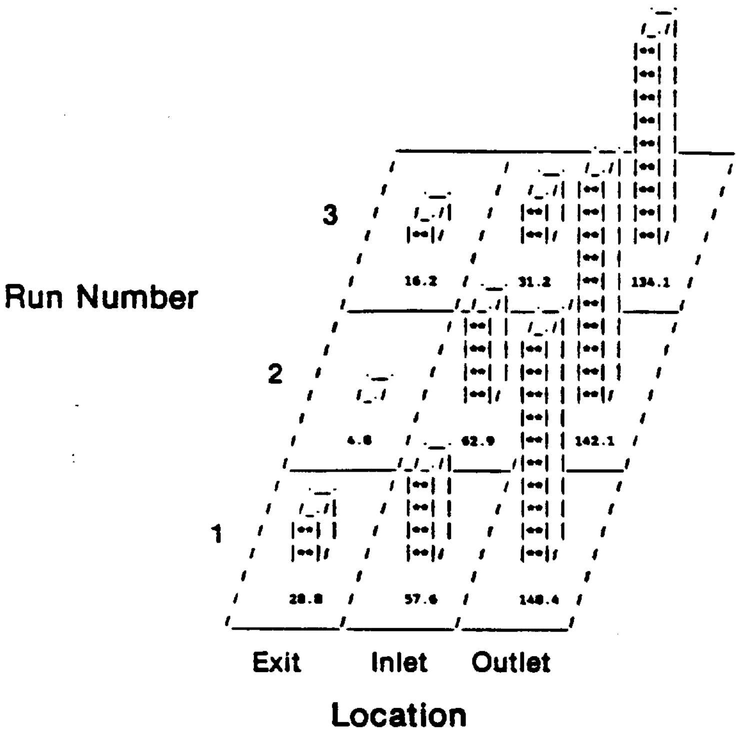

Figure 7-33. Comparison of CDD Concentrations by Location, Start of Campaign

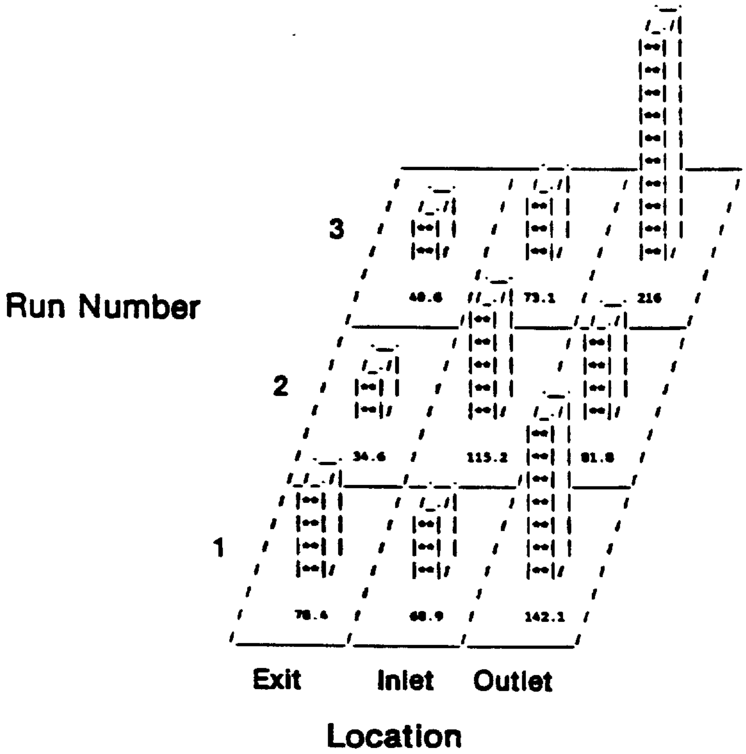

Figure 7-34. Comparison of CDD Concentrations by Location, End of Campaign

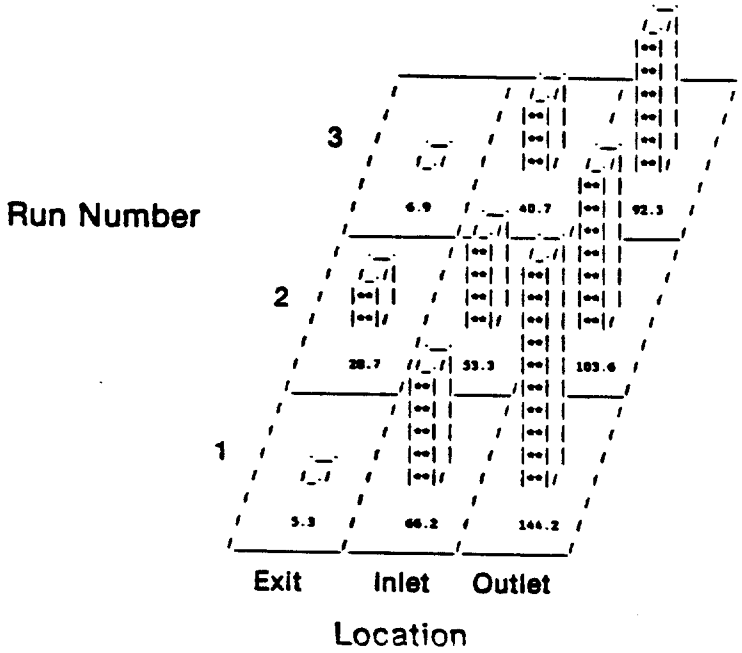

Figure 7-35. Comparison of CDD Concentrations by Location, Mid-Range Secondary Chamber Temperature

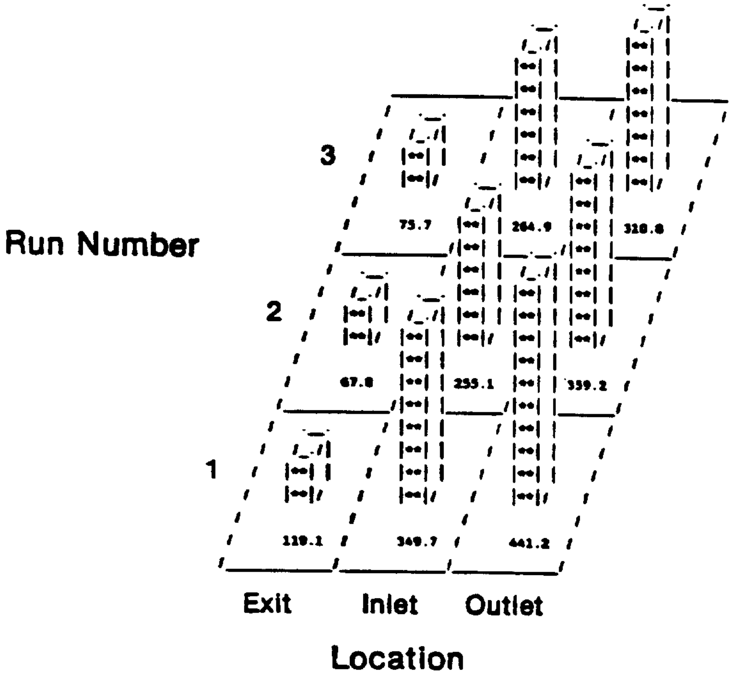

Figure 7-36. Comparison of CDD Concentrations by Location, Low Secondary Chamber Temperature

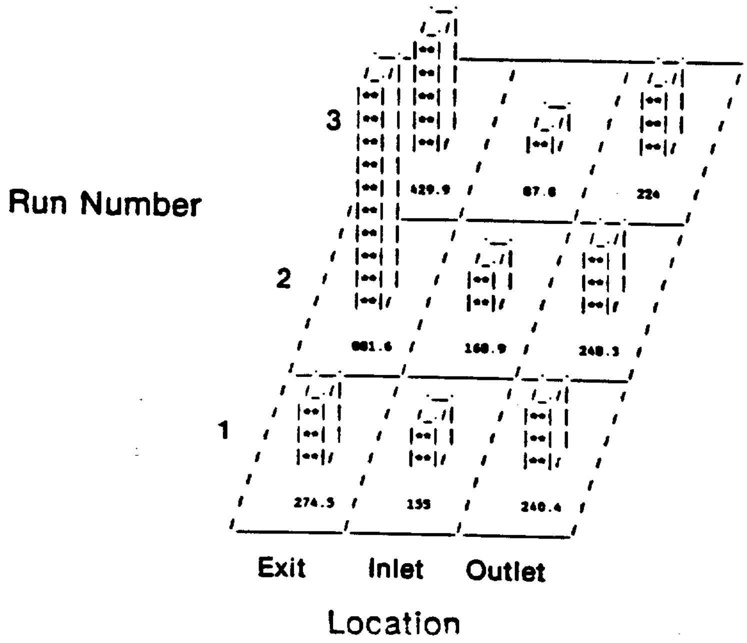

Figure 7-37. Comparison of CDF Concentrations by Location, Start of Campaign

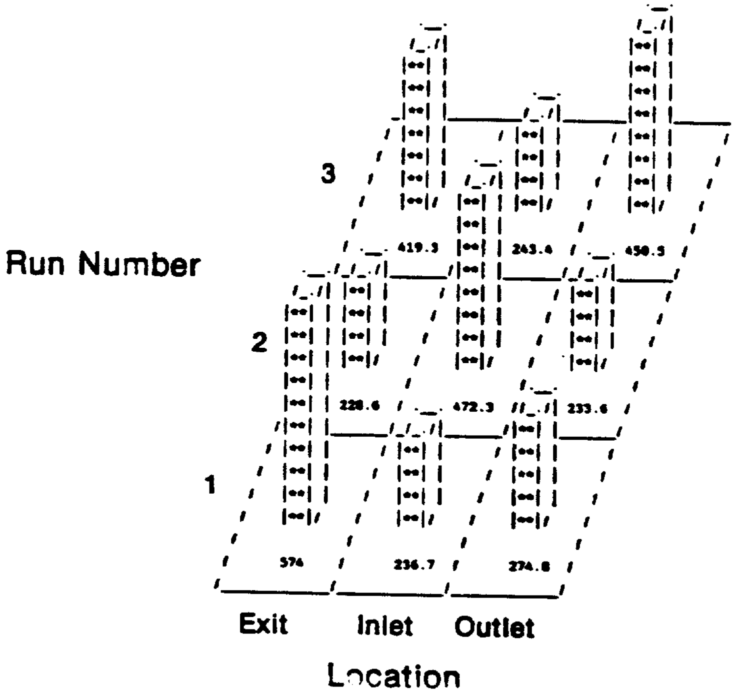

Figure 7-38. Comparison of CDF Concentrations by Location, End of Campaign

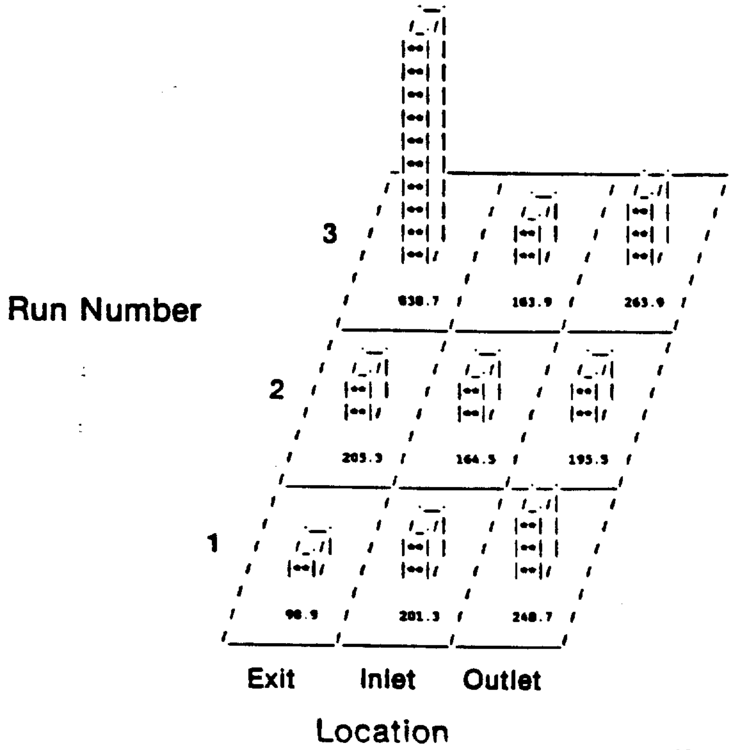

**Figure 7-39. Comparison of CDF Concentrations by Location, Mid-Range Secondary Chamber Temperature**

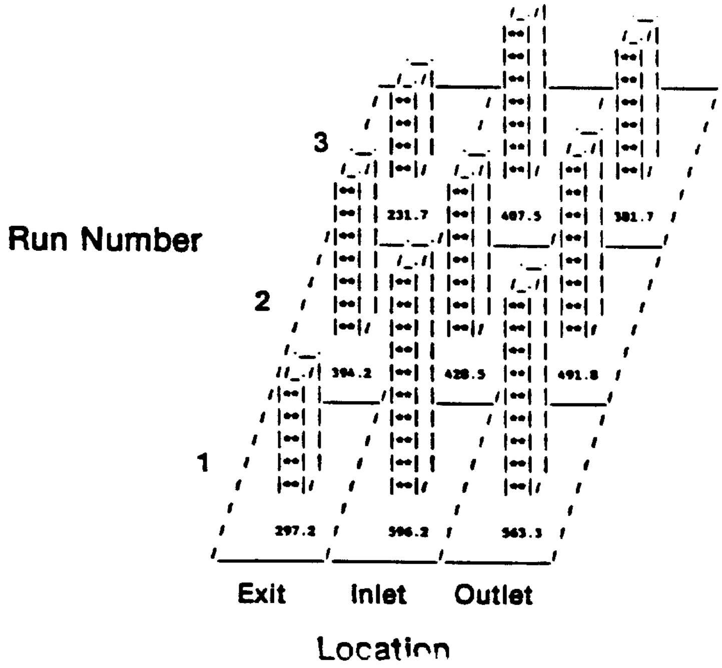

**Figure 7-40. Comparison of CDF Concentrations by Location, Low Secondary Chamber Temperature**

locations and at different operating conditions, although the end of campaign operating condition concentrations appear to vary somewhat at the ESP outlet location. CDD concentrations ranged from 81.8 to 216 ng/dscm at 7 percent $O_2$ at the ESP outlet for the end of campaign test runs. Again, this variation does not appear to be altering the trends between operating conditions which are consistent throughout. However, it could explain why the ANOVA results were not as strong for the CDD concentrations measured for the end of campaign operating condition.

The results of the Duncan's multiple range test for this second set of one-way ANOVAs is also given in Table 7-11. Duncan's multiple range test indicates that the secondary chamber exit had consistently below average CDD concentrations, whereas the ESP outlet always had higher than average CDD concentrations. The ESP inlet had average or above average CDD concentrations and always fell somewhere between the CDD concentrations measured at the secondary chamber exit and ESP outlet.

Results of the CDF analysis. It was found in ANOVA Model I that there were no significant differences in CDF concentrations between locations when averaged over operating conditions. The one-way ANOVAs were performed for each operating condition, again resulting in, at best, only marginally signficant differences between locations for each operating condition. No significant results were found for the end of campaign and mid-range secondary chamber temperature operating conditions; the significant levels were 0.7 and 0.57, respectively. The start of campaign and low secondary temperature operating conditions showed marginally significant results with significance levels of 0.09 and 0.10, respectively. This implies there is about a 90 percent certainty that there existed true differences between the CDF means measured at the secondary chamber exit, ESP inlet, and ESP outlet for the start of campaign and low secondary chamber temperature conditions.

Figures 7-33 through 7-36 show the CDF concentrations used for the second set of one-way ANOVAs. As before, the reliability of the ANOVA assumption that the CDF data represent replicates within each location comes into question.

Although the data shown in Figure 7-34 show the CDF concentrations behave relatively consistently by location within the low secondary chamber temperature operating condition, the other figures show some erratic behavior, especially for the mid-range secondary chamber temperature operating condition (Figure 7-35).

Duncan's test showed that differences only existed for the start of campaign operating condition, with the secondary chamber exit having the highest average CDF concentration (528.7 ng/dscm at 7 percent $O_2$) and the ESP inlet having the lowest average CDF concentration (137.2 ng/dscm at 7 percent $O_2$). Again, Duncan's test was used only to explore differences in locations within operating conditions, and does not report significant differences.

Conclusions of ANOVA Model II. The second set of ANOVA models was performed to investigate trends within each location and operating condition separately. Since the main effects of location and operating condition were significant for the CDD concentrations (ANOVA Model I), significant trends existed between operating conditions within each location (ANOVA Model IIA) and between locations within each operating condition (ANOVA Model IIB). The only trend which was not quite as strong as the others was the difference between locations at the end of campaign operating condition which was significant only at the 0.09 level. For the CDF concentrations, a significant difference between operating conditions was found at the ESP inlet and outlet. For the start of campaign and low secondary chamber temperature operating conditions, there were marginally significant differences between locations for CDF concentrations.

## ANOVA Conclusions

The first set of ANOVA models analyzed differences in CDD and CDF concentrations, separately, between locations and operating conditions. Both location and operating condition and the interaction of the two were significant for CDD concentrations; whereas, neither of the main effects were found to be significant for CDF concentrations.

The second set of ANOVA models analyzed the operating condition effect separately for each location, and then, conversely, the location effects separately for each operating condition. Each ANOVA model was found to be significant for CDD concentrations; the differences between locations for the end of campaign operating condition was only marginally significant at the 0.09 level. The only trends which were significant for the CDF concentrations were the differences between operating conditions at the ESP inlet and outlet. Differences between locations were found to be only marginally significant for the start of campaign and low secondary chamber temperature operating conditions with significance levels of 0.09 and 0.10, respectively.

The differences between end of campaign and start of campaign test conditions, and the differences between low secondary chamber temperature and mid-range secondary chamber temperature operating conditions were explored with Duncan's multiple range tests. These differences are shown in Table 7-10.

Comparing the start and end of campaign results, Duncan's test showed that the CDD and CDF means measured at the ESP outlet were lower than average for both of these operating conditions. The CDD averages at the ESP inlet behaved the same as the averages measured at the ESP outlet; whereas, the CDF concentrations at the start of campaign were lower than those at the end of campaign. Duncan's test also showed there was no signficant difference in CDD and CDF averages between the start of campaign and end of campaign operating conditions at the secondary chamber exit.

The differences between the low secondary chamber temperature and the mid-range secondary chamber temperature operating conditions were much more pronounced for both the CDD and CDF concentrations. The low secondary chamber temperature operating condition consistently had higher than average CDD concentrations, whereas; the mid-range secondary chamber temperature operating condition always had a lower than average CDD concentration. For the CDF concentrations, the low secondary chamber temperature operating condition had a higher average at the ESP inlet and the ESP outlet. The mid-range secondary chamber temperature operating condition was shown to have a lower than average

CDF concentration only at the ESP outlet. The secondary chamber exit showed no significant differences in CDF concentrations between operating conditions.

Again, the multiple range test in this study is used only to explore differences in operating condition and location effects on CDD and CDF concentrations, and is not strictly used to interpret significant differences. A consistent operating condition effect for all locations may exist but may be masked due to the variability of the CDD and CDF concentrations. It is important to note that this analysis does not take into account error associated with sampling and analysis. A statistical method which simultaneously considers CDD and CDF concentrations is useful, in that the assumption that the test runs are replicates within each operating condition can be explored. If they are not replicates, the question of the effect of operating condition or location on CDD and CDF concentrations cannot be answered.

## Cluster Analysis

Cluster analysis was performed to determine whether CDD and CDF concentrations were jointly distinguishable on the basis of operating conditions for the three locations. Each test run is represented in the cluster analyses by both the CDD and CDF concentrations.

A cluster analysis groups or clusters test runs with similar CDD and CDF concentrations at each location. If the operating conditions were sufficiently altered to have an effect on CDD and CDF concentrations, test runs within an operating condition should cluster together. In other words, if the three CDD and CDF concentrations for the start of campaign operating condition are true replicates, and they are sufficiently different from the concentrations for the other conditions, these three test runs (Runs 1, 2, and 3) will form a single cluster. Conversely, if there is little difference between CDD and CDF concentrations among different operating conditions compared to the variability of the replicates within any one test condition, test runs within operating conditions will split apart and form clusters with other test runs from other conditions.

The cluster analysis was done to determine which of the test runs were most similar. Ideally, Runs 1, 2, and 3 would cluster together, forming the start of campaign operating condition; Runs 4, 5, and 6 would cluster together, forming the mid-range secondary chamber temperature operating condition; Runs 7, 8, and 9 would cluster together forming the end of campaign operating condition; and Runs 10, 11, 12 would cluster together forming the low secondary chamber temperature operating condition. If these do not cluster together that does not necessarily mean that the test runs within each operating condition are not replicates. It only reports which test runs are most similar.

The cluster presented in this section are the results of Ward's minimum variance clustering method. This method was selected because past analyses have shown it to be especially effective when used with highly variable data.(12,13) Ward's method clusters test runs in stages. The first stage assigns the 12 test runs to 12 separate clusters. The second stage of clustering groups the two most similar test runs, that is, similar by magnitude for both CDD and CDF concentrations, forming 11 clusters. The comparison is between CDD to CDD and CDF to CDF concentrations, at each stage of clustering. The total sum of squares (as in ANOVA) is calculated for each possible combination of clusters at each stage of clustering. The combination (two clusters or two test runs) with the smallest total sum of squares is joined in a cluster. At each of the following stages, a test run (or cluster) is joined with another test run (or cluster). This process continues until the final stage of clustering, when all the test runs are combined into one single cluster.

### Dendrograms

At each stage of clustering, a measure of the distance between the two joined clusters is derived. Simply stated, this measure is the average sum of squared CDD and CDF concentration differences between all the test runs in the two clusters. A small distance measure indicates that the CDD and CDF concentrations in the two joined clusters are similar. A large measure indicates that less similar clusters were joined together.

The dendrograms in Figures 7-41 through 7-43 graphically display the relative similarity of the joined clusters at each stage of clustering for the three cluster analyses. The average distance between the clusters is delineated along the y axis, and the test runs are designated on the x axis.

Figure 7-41 shows that Runs 5 and 8 are joined in the first stage of clustering at the secondary chamber exit, because they are the most similar test runs in terms of CDD and CDF concentrations. The average distance between these two test runs is smaller than for any other pair of test runs; the lines joining these two test runs are the shortest in the figure, reflecting their relative similarity. Test Runs 3 and 9 and test Runs 2 and 6 are joined in the next two stages of clustering. As is shown in the figure, none of the test runs within an operating condition is similar based on the CDD and CDF concentrations measured at the secondary chamber exit.

Figure 7-42 presents the results of the cluster analysis for the CDD and CDF concentrations measured at the ESP inlet. As is shown in the figure, the mid-range secondary chamber temperature operating condition test runs (Runs 4, 5, and 6) are joined with a distance of about 0.25. The start of campaign operating condition test runs (Runs 1, 2, and 3) are joined at a distance measure of 0.42, and the low secondary chamber temperature operating condition tests (Runs 10, 11, and 12) are joined at a distance measure of 0.83. The end of campaign condition tests (Runs 7, 8, and 9) are the last to join, at distance measure of about 1.38.

As shown in Figure 7-43, three of the four operating conditions for the ESP outlet form clusters with distance measures similar to those at the ESP inlet. The mid-range secondary chamber temperature condition test runs joined at a distance measure of 0.24 and the end of campaign operating condition test runs joined at a distance measure of 1.39. The low secondary chamber temperature condition test runs form a cluster at a distance measure of about 0.82. The start of campaign condition test runs were joined at lower distance measures than at the ESP inlet with a measure of 0.10. The test runs at this location show the most similarity within each operating condition.

### Analysis of Clusters

The dendrograms for each location (Figures 7-41 through 7-43) were reviewed for similarities. As shown in the figures, a cut-off point of 0.70 will create three clusters at each location. Table 7-12 shows the test runs in each cluster for the three locations. As can be seen in the table, the test runs within the four operating conditions do not form the expected four clusters; in fact, only three clusters are formed. Test runs within operating conditions are quite dispersed among the clusters at the secondary chamber exit. The first cluster contains Runs 1, 4, 5, 8, 10, and 12, the second cluster contains Runs 3, 7, 9, and 11, and the third cluster contains Runs 2 and 6. No cluster contains all the test runs for a given operating condition at this location.

The ESP inlet and outlet data each show a cluster which contains all the test runs for two operating conditions, start of campaign and mid-range secondary chamber temperature. Figures 7-44 through 7-46 chart the CDD and CDF concentrations for each test run cluster for each location. Although there clearly is more similarity in CDD and CDF concentrations within the three sets of clusters than within the four sets of operating conditions, this does not necessarily mean the test runs within each operating condition are not replicates. As stated above, the cluster analysis shows which test runs are the most similar. Whereas the test runs within each operating condition may not have been the most similar test runs, they can be replicates. Overall, most of the test runs were relatively consistent within operating conditions, except for the end of campaign operating condition test runs which tended to vary considerably (especially for CDF concentrations). The secondary chamber exit location test runs also appeared to vary more than the other locations.

### Comparing Cluster Results to ANOVA II Results

The cluster analysis results can be compared to the ANOVA results. At the secondary chamber exit, the ANOVAs showed that operating condition had no effect on CDF concentrations, but did have an effect on CDD concentrations. The cluster analysis showed that none of the test runs was joined by operating

## Table 7-12.

## TEST RUNS WITHIN CLUSTERS BY LOCATION

### Secondary Chamber Exit

| Cluster | Test Runs |
|---|---|
| 1 | 1, 4, 5, 8, 10, 12 |
| 2 | 3, 7, 9, 11 |
| 3 | 2, 6 |

### ESP Inlet

| Cluster | Test Runs |
|---|---|
| 1 | 1, 2, 3, 4, 5, 6, 7, 9, |
| 2 | 8, 11, 12 |
| 3 | 10 |

### ESP Outlet

| Cluster | Test Runs |
|---|---|
| 1 | 1, 2, 3, 4, 5, 6, 7, 8 |
| 2 | 9, 12 |
| 3 | 10, 11 |

condition at the secondary chamber exit. This result is consistent with the Duncan results for CDF concentrations. However, the Duncan difference in CDD concentrations is not supported by the cluster analysis.
At the ESP inlet, the cluster analysis showed that the start of campaign operating condition could be grouped into cluster 1 and the low secondary chamber temperature condition could be grouped into clusters 2 and 3 for CDD and CDF concentrations. The Duncan results also distinguished the start of campaign and low secondary chamber temperature conditions for CDD and CDF concentrations. If a cut-off point of 0.9 is used, the low secondary chamber temperature operating condition runs and Run 8 are different from the other operating conditions.

At the ESP outlet, it appears that the low secondary chamber temperature condition and Run 9 are different from the other operating conditions if a cut-off point of 0.9 is used. Again, Duncan's test showed that the low secondary chamber temperature condition differed significantly from the other operating conditions for both CDD and CDF concentrations.

## CONCLUSIONS OF STATISTICAL ANALYSES

There are location and operating condition effects on total CDD concentrations. The ESP outlet appeared to have the strongest location effect on CDD concentrations; the CDD concentrations were significantly higher at this location. The operating condition which seemed to have the strongest effect was the low secondary chamber temperature condition, which had a much higher CDD concentration than the other operating conditions at each of the locations.

For CDF concentrations, neither location nor operating condition were significant main effects. However, the effects of operating condition were significant at the ESP inlet and ESP outlet. Location had only a marginally significant effect for the start of campaign and low secondary chamber temperature operating conditions.

Finally, except for CDF concentrations at the secondary chamber exit, there were considerable differences in CDD and CDF concentrations between mid-range secondary chamber temperature and low secondary chamber temperature operating conditions for all locations. Duncan's test, however, showed that there were no differences between the start and end of campaign operating conditions, except for CDF concentrations at the ESP inlet. At the ESP inlet, the start of campaign operating condition had a lower than average CDF concentration.

## RELATIONSHIP OF CDD AND CDF WITH OPERATING VARIABLES AND COMBUSTION GAS VARIABLES

In addition to comparing the CDD and CDF concentrations by location and operating condition, the statistical and engineering analysis also attempted to relate CDD and CDF concentrations with the continuously monitored operating variables and combustion gas variables. To make this comparison, it was necessary to reduce the large quantity of continuously monitored data into single numbers. The numbers are termed single value representations (SVRs). Derivation of SVRs is described below.

A correlation analysis of the SVRs of the combustion gases monitored at the secondary chamber exit were correlated with CDD and CDF concentrations measured at the secondary chamber exit. Likewise, a correlation analysis of the SVRs of the combustion gases that were monitored at the ESP outlet were correlated with the CDD and CDF concentrations measured at the ESP inlet and outlet. The SVRs of the process variables were correlated with the CDD and CDF concentrations measured at the secondary chamber exit. Appendix B contains these complete correlation matrices.

### Single Value Representations

The CEM data monitored at the secondary chamber exit and the process variable data were collected once every 10 seconds. The CEM data at the ESP outlet were monitored once every 20 seconds. A single CDD and CDF measurement was also made over the comparable test period, which typically lasted three to four hours. There is no way of knowing when during the test period CDD and CDF were formed, since the sampling method effectively averages the CDD and CDF emissions over the test period.

The CEM and process variables give a much more detailed picture of operating conditions during the test period than the single CDD and CDF numbers since, for example, in one four-hour test there would be 1,440 10-second measurements collected at the secondary chamber exit and 720 20-second readings taken at the ESP outlet for each single CDD and CDF measurement. To attempt to correlate the CEM and process data with the CDD and CDF measurements, the information contained in the 1,440 readings measured at the secondary chamber exit and the 720 readings measured at the ESP outlet have to be summarized into a single value that captures as much information on the important factors in the combustion process as possible (i.e., those factors that might be related to differences in CDD and CDF emissions).

Numerous single value representations can be examined. Each has its own strengths and weaknesses and each will obscure or emphasize different facets of the CEM data that may or may not relate to CDD and CDF emissions. For example, the arithmetic mean is often used as a single value representation of a set of numbers, but the mean is an indicator of central tendency and can obscure a lot of information such as a trend in the data or the amount of variation in the data over the test period. Table 7-13 lists the single value representations of the data used in this analysis with a brief description of what they represent. The mathematical formulas for each of the SVRs as well as an explanation of what each SVR describes are given below.

Measures of Central Tendency. The arithmetic, geometric, and logarithmic means were used to correlate measures of central tendency. The arithmetic mean is simply the average, xbar, of a number of observations. That is, it is the sum of the observations divided by the number of observations. The geometric mean is the product of the observations raised to the power of 1/n , where n is the total number of observations, and the logarithmic mean is the sum of the logarithm of the observations divided by the number of observations. Each of these can be represented as follows:

$$\text{Arithmetic mean} = \frac{x_1 + x_2 + \ldots x_n}{n}$$

## Table 7-13.

## SINGLE VALUE REPRESENTATIONS OF CEM AND OPERATING VARIABLES USED IN THIS ANALYSIS

| Singe Value Representation (SVR) | Use |
|---|---|
| arithmetic mean | central tendency |
| logarithmic mean | central tendency |
| geometric mean | central tendency |
| standard deviation | variability |
| variance | variability |
| coefficient of variation | variability |
| sum of squares | variability |
| minimum | low value |
| 1st percentile | low value |
| 5th percentile | low value |
| 10th percentile | low value |
| lower quartile | low value |
| upper quartile | high value |
| 90th percentile | high value |
| 95th percentile | high value |
| 99th percentile | high value |
| maximum | high value |

Geometric mean $= (x_1 \, x_2 \, . \, . \, . \, x_n)^{1/n}$

$$\text{Logarithmic mean} = \frac{\log(x_1) + \log(x_2) + . \, . \, . + \log(x_n)}{n}$$

As stated previously, different SVR's describe different facets of the distribution of the CEM measurements. For example, if an CEM measurement is normally distributed, the arithmetic mean is the same as the median (the 50th percentile) and the mode (the most frequently occurring value). However, if the CEM values are lognormally distributed and for example, skewed to the right, the arithmetic mean would not be the best representation of the most frequently occurring value. The arithmetic average would fall into the tail of the distribution and would, therefore, not be the best measure of central tendency. Rather, the geometric mean would be closer to the mode and thus provide better indications as to the central tendencies, as shown in Figure 7-47.

Measures of Dispersion. The standard deviation, variance, coefficient of variation, and sum of squares are all measures of dispersion or variability. The sum of squares is sum of the square of each CEM observation. The sample variance is the sum of the squared difference between each observation and the arithmetic mean, divided by n - 1, where n is the total number of observations. The standard deviation is the square root of the variance.

Another measure often used in describing the dispersion of a population is the coefficient of variation (c.v.). The coefficient of variation is the sample standard deviation divided by the arithmetic mean, that is, it is the standard deviation expressed as a fraction or percentage of the mean. The c.v. is a relatively stable value used to describe the variation, since the mean and standard deviation often tend to change together.

$$\text{Sum of Squares} = \sum_{i=1}^{n} x_i^2$$

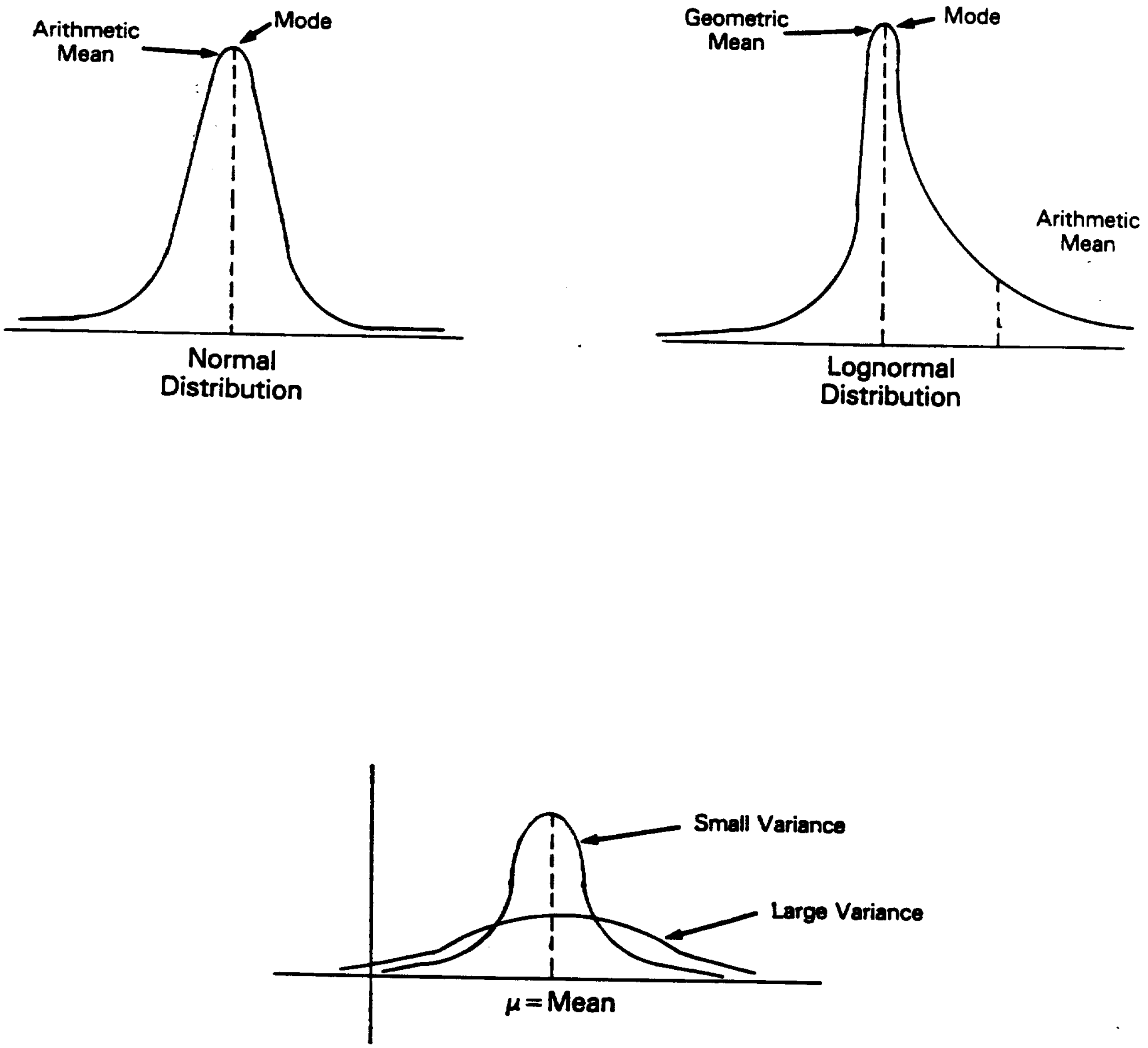

Figure 7-47. Measures of Central Tendency and Dispersion

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$$\text{Variance} = s^2 = \frac{\sum_{i=1}^{n} (x_i - \bar{x})^2}{n - 1}$$

$$\text{Standard Deviation } (s) = \left(\frac{\sum_{i=1}^{n} (x_1 - \bar{x})^2}{n - 1}\right)^{1/2}$$

$$\text{Coefficient of Variation} = \frac{s}{\bar{x}}$$

If values tend to be concentrated towards the mean then the variance is small, whereas if the values tend to fall far from the mean, the variance is large. Figure 7-47 illustrates a comparatively small and large variance.

Measures of Extreme Values. Since series of extreme values sometimes follow regular patterns or behaviors, a correlation analysis of CEM extreme values was done. Percentiles are used to describe these extreme values.

Often, the area under a density curve is subdivided by the use of ordinate values such that the area to the left of the ordinate is a percentage of the total area. The values corresponding to such areas are called percentiles. Thus, for example, the area to the left of the ordinate of $x_a$ in Figure 7-48 is a.

In particular, the area to the left of $x_{.10}$ would be .10 or 10% and would be called the 10th percentile (or the 1st decile) and the area to the left of $x_{.90}$ would be the 90th percentile. The median would be called the 50th percentile (or 5th decile) as shown below. Thus, the 1st percentile, 5th percentile, 10th percentile (1st decile), and 25th percentile (lower quartile) are measures of low values of the distribution. Likewise, the 75th percentile (upper quartile), the 90th percentile and 99th percentile are measures of high values of the distribution. Figure 7-48 shows example percentile plots.

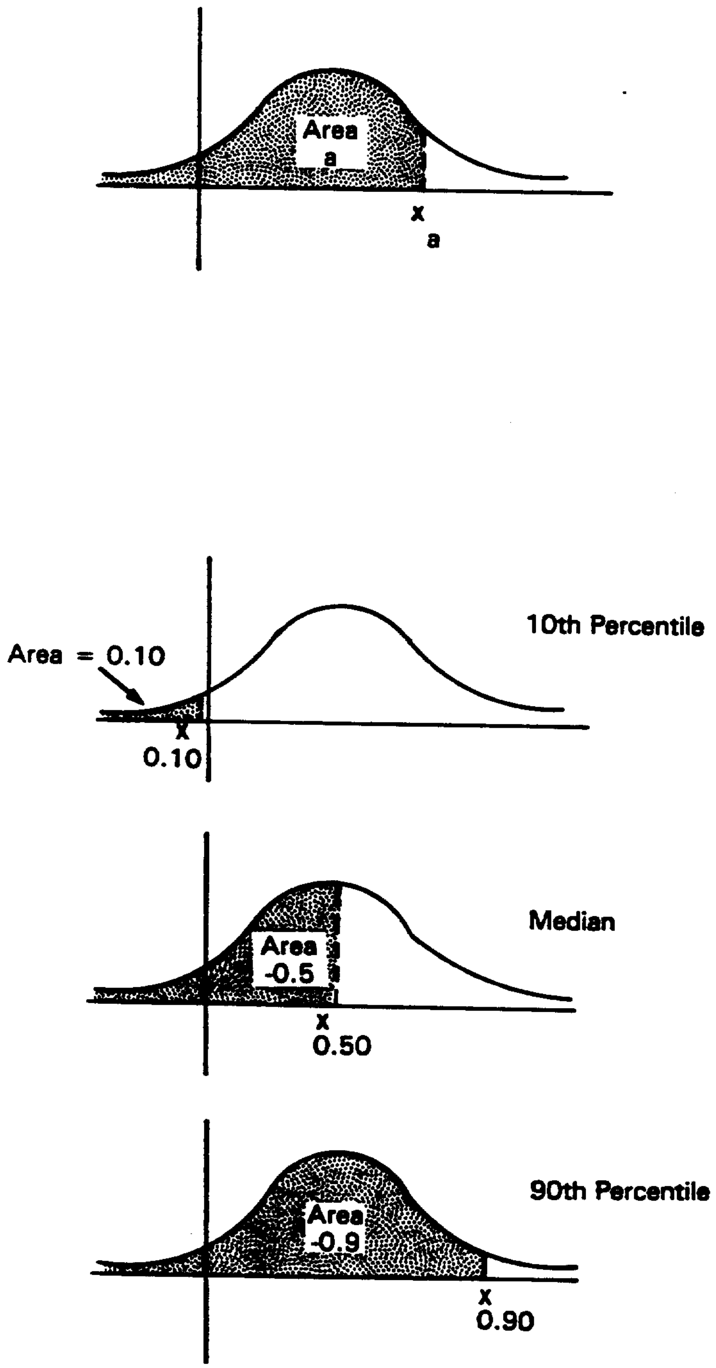

Figure 7-48. Measures of Extreme Values

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Not all SVRs for all CEM variables can be clearly interpreted from a combustion or CDD and CDF formation standpoint. However, to simplify the analysis, all SVRs listed were computed for all continuously monitored variables and were used in the statistical analysis.

## Correlation of SVRs of Plant Operating Variables and CEM Data with CDD and CDF Data

Single value representations of CO, $CO_2$, $NO_x$, $SO_2$ and THC (secondary chamber exit only) concentrations adjusted to 7 percent $O_2$ were calculated for each test run and location. The data measured at the secondary chamber exit were corrected using $O_2$ values at the secondary exit and the data collected at the ESP outlet were corrected using $O_2$ values at the ESP outlet. These SVRs were correlated with the following three sets of CDD and CDF values, all of which were adjusted to 7 percent $O_2$:

- 2378-TCDD and -TCDF isomers;
- sum of all 2378-substituted isomers; and
- sum of all homologues.

Single value representations of eight process variables were calculated for each test run, including: secondary chamber temperature, primary chamber temperature, boiler outlet temperature, boiler inlet temperature, boiler draft pressure, upper chamber pressure, lower chamber pressure, and boiler differential pressure. These values (unadjusted) were correlated with unadjusted CDD and CDF concentrations measured at the secondary chamber exit.

Finally, single value representations of $O_2$ were calculated for each test run and location. The $O_2$ SVRs at the secondary chamber exit were correlated with CDD and CDF concentrations measured at the secondary chamber exit; the $O_2$ SVRs at the ESP outlet were correlated with CDD and CDF concentrations measured at the ESP inlet and ESP outlet. In these correlations, the CDD and CDF concentrations (ng/dscm) were not adjusted to 7 percent $O_2$. Correcting the concentrations to 7 percent $O_2$ when comparing with $O_2$ could potentially mask any relationships that may exist.

Table 7-14 lists the correlations of SVRs with CDD and CDF concentrations with a correlation coefficient above 0.8 which appear to be valid, linear relationships. These relationships are statistically significant at the 0.05 level, meaning that there is at most a 5 percent chance the apparent correlation is due to noise in the data. As can be seen in the table, all of the combustion gas variables ($O_2$, CO, $CO_2$, THC, and $SO_2$) correlate strongly with the CDD and CDF measurements. The combustion gas variable which correlated with the CDD and CDF measurements most frequently was CO. It is interesting to note that it was the SVRs representing extreme values of CO (i.e., P90, P95, and P99) that correlated most frequently with the CDD and CDF levels measured, indicating that it is extreme variations in CO concentrations that indicate changes in CDD and CDF concentrations at this facility. Scatter plots were made of selected correlations to determine if any outliers were driving the correlations. Figures 7-49, 7-50, and 7-51 show total CDD, 2,3,7,8-substituted CDD, and 2,3,7,8-substituted CDF, respectively, versus CO at the secondary chamber exit. As is shown in the figures, in general, the start of campaign and mid-range secondary chamber temperature test series group together and the end of campaign and low secondary chamber temperature test series group together. In addition, the figures all show positive correlations of CO with the CDD measurements, indicating the higher the CO concentration, the higher the CDD concentration. Figures 7-52 and 7-53 present THC versus total CDD and 2,3,7,8-substituted CDD, respectively, at the secondary chamber exit. As shown in the figures, the test runs do not group by test condition but are scattered with Run 10 driving the correlations. These calculated test run averages are near the limit of quantitation of these analyzers and may reflect noise around the baseline. Scatter plots of other selected correlations are provided in Appendix F.

## EFFECT OF PLANT OPERATING CONDITIONS ON CDD AND CDF HOMOLOGUE DISTRIBUTION

The relationship between total CDD and CDF measured and plant operating conditions (as captured in different test conditions) was discussed previously. In this section, relationships between the CDD and CDF homologue distributions and plant operating conditions are examined. Figures 7-54 through 7-59 summarize the mole fractions of mono- through octa-chlorinated CDD and CDF for the test conditions by location. Three-dimensional plots of

Table 7-14.

## PEARSON CORRELATION MATRIX FOR CDD AND CDF WITH COMBUSTION GAS VARIABLES AND PROCESS DATA ($|r| \geq 0.8$)[a]

| Parameter/loc. | Dioxin or Furan/loc. | N | SVR | Pearson Corr. Coeff. (r) | Sig. Level |
|---|---|---|---|---|---|
| CO/ESP outlet | 2378-TCDF/ESP outlet | 12 | P90 | 0.835 | 0.0007 |
| CO/ESP outlet | 2378-TCDF/ESP inlet | 12 | P99 | 0.845 | 0.0005 |
| $CO_2$/ESP outlet | 2378-TCDF/ESP inlet | 12 | P75 | 0.814 | 0.0013 |
| $CO_2$/ESP outlet | 2378-TCDF/ESP inlet | 12 | P90 | 0.845 | 0.0005 |
| $CO_2$/ESP outlet | 2378-TCDF/ESP inlet | 12 | P95 | 0.863 | 0.0003 |
| $SO_2$/ESP outlet | 2378-TCDD/ESP inlet | 4 | SS | 0.981 | 0.0192 |
| $SO_2$/ESP outlet | 2378-TCDD/ESP inlet | 4 | MIN | 0.992 | 0.0083 |
| $SO_2$/ESP outlet | 2378-TCDD/ESP inlet | 4 | P1 | 0.959 | 0.0409 |
| $SO_2$/ESP outlet | 2378-TCDD/ESP inlet | 4 | P5 | 0.957 | 0.0435 |
| CO/ESP outlet | TOTAL CDF/ESP inlet | 12 | AMEAN | 0.835 | 0.0007 |
| CO/ESP outlet | TOTAL CDD/ESP inlet | 12 | LMEAN | 0.805 | 0.0016 |
| CO/ESP outlet | TOTAL CDD/ESP outlet | 12 | P75 | 0.811 | 0.0014 |
| CO/ESP outlet | TOTAL CDD/ESP inlet | 12 | P90 | 0.904 | 0.0001 |
| CO/ESP outlet | TOTAL CDD/ESP outlet | 12 | P90 | 0.898 | 0.0001 |
| CO/ESP outlet | TOTAL CDF/ESP outlet | 12 | P90 | 0.834 | 0.0007 |
| CO/ESP outlet | TOTAL CDD/ESP inlet | 12 | P95 | 0.897 | 0.0001 |
| CO/ESP outlet | TOTAL CDF/ESP inlet | 12 | P95 | 0.876 | 0.0002 |
| CO/ESP outlet | TOTAL CDD/ESP outlet | 12 | P95 | 0.805 | 0.0016 |
| CO/ESP outlet | 2378-Sub. CDF/ESP inlet | 12 | AMEAN | 0.845 | 0.0005 |
| CO/ESP outlet | 2378-Sub. CDD/ESP inlet | 12 | LMEAN | 0.803 | 0.0017 |
| CO/ESP outlet | 2378-Sub. CDF/ESP inlet | 12 | LMEAN | 0.802 | 0.0017 |
| CO/ESP outlet | 2378-Sub. CDF/ESP outlet | 12 | LMEAN | 0.834 | 0.0007 |
| CO/ESP outlet | 2378-Sub. CDF/ESP outlet | 12 | P75 | 0.897 | 0.0001 |
| CO/ESP outlet | 2378-Sub. CDD/ESP inlet | 12 | P90 | 0.886 | 0.0001 |
| CO/ESP outlet | 2378-Sub. CDF/ESP inlet | 12 | P90 | 0.845 | 0.0005 |
| CO/ESP outlet | 2378-Sub. CDD/ESP outlet | 12 | P90 | 0.860 | 0.0003 |

Table 7-14.

PEARSON CORRELATION MATRIX FOR CDD AND CDF WITH COMBUSTION GAS VARIABLES AND PROCESS DATA ($|r| \geq 0.8$)[a] (continued)

| Parameter/loc. | Dioxin or Furan/loc. | N | SVR | Pearson Corr. Coeff. (r) | Sig. Level |
|---|---|---|---|---|---|
| CO/ESP outlet | 2378-Sub. CDF/ESP outlet | 12 | P90 | 0.905 | 0.0001 |
| CO/ESP outlet | 2378-Sub. CDD/ESP inlet | 12 | P95 | 0.854 | 0.0004 |
| CO/ESP outlet | 2378-Sub. CDF/ESP inlet | 12 | P95 | 0.883 | 0.0001 |
| $O_2$/ESP outlet | Total CDD/ESP inlet | 12 | SS | 0.802 | 0.0017 |
| SCE temp. | Boiler inlet temp. | 9308 | -- | 0.856 | 0.0001 |
| Boiler draft | 2378-TCDD/SCE | 6 | CV | 0.964 | 0.0019 |
| CO/SCE | 2378-TCDD/SCE | 6 | P90 | 0.860 | 0.0282 |
| $CO_2$/SCE | 2378-TCDD/SCE | 6 | P90 | 0.831 | 0.0402 |
| $CO_2$/SCE | 2378-TCDD/SCE | 6 | P95 | 0.874 | 0.0228 |
| LC pres. | 2378-TCDD/SCE | 6 | STD | 0.871 | 0.0237 |
| LC pres. | 2378-TCDD/SCE | 6 | VAR | 0.935 | 0.0063 |
| LC pres. | 2378-TCDD/SCE | 6 | CV | 0.964 | 0.0019 |
| LC pres. | 2378-TCDD/SCE | 6 | P10 | -0.857 | 0.0293 |
| PC temp. | 2378-TCDD/SCE | 6 | VAR | 0.848 | 0.0329 |
| PC temp. | 2378-TCDD/SCE | 6 | MIN | -0.893 | 0.0164 |
| PC temp. | 2378-TCDD/SCE | 6 | P1 | -0.894 | 0.0161 |
| PC temp. | 2378-TCDD/SCE | 6 | P5 | -0.893 | 0.0164 |
| PC temp. | 2378-TCDD/SCE | 6 | P10 | -0.880 | 0.0207 |
| PC temp. | 2378-TCDD/SCE | 6 | P75 | 0.884 | 0.0193 |
| PC temp. | 2378-TCDD/SCE | 6 | P90 | 0.899 | 0.0148 |
| PC temp. | 2378-TCDD/SCE | 6 | P95 | 0.854 | 0.0306 |
| PC temp. | 2378-TCDD/SCE | 6 | P99 | 0.956 | 0.0029 |
| $SO_2$/SCE | 2378-TCDD/SCE | 6 | MAX | 0.884 | 0.0195 |
| THC/SCE | 2378-TCDD/SCE | 6 | AMEAN | -0.879 | 0.0211 |
| THC/SCE | 2378-TCDD/SCE | 6 | MIN | -0.883 | 0.0196 |
| THC/SCE | 2378-TCDD/SCE | 6 | P1 | -0.925 | 0.0082 |
| THC/SCE | 2378-TCDD/SCE | 6 | P5 | -0.922 | 0.0089 |
| THC/SCE | 2378-TCDD/SCE | 6 | P10 | -0.919 | 0.0096 |

## Table 7-14.

## PEARSON CORRELATION MATRIX FOR CDD AND CDF WITH COMBUSTION GAS VARIABLES AND PROCESS DATA $(|r| \geq 0.8)^a$ (continued)

| Parameter/loc. | Dioxin or Furan/loc. | N | SVR | Pearson Corr. Coeff. (r) | Sig. Level |
|---|---|---|---|---|---|
| THC/SCE | 2378-TCDD/SCE | 6 | P25 | -0.914 | 0.0107 |
| THC/SCE | 2378-TCDD/SCE | 6 | MEDIAN | -0.912 | 0.0113 |
| THC/SCE | 2378-TCDD/SCE | 6 | P75 | -0.876 | 0.0223 |
| UC pres. | 2378-TCDD/SCE | 6 | STD | 0.854 | 0.0303 |
| UC pres. | 2378-TCDD/SCE | 6 | VAR | 0.875 | 0.0225 |
| UC pres. | 2378-TCDD/SCE | 6 | MIN | -0.920 | 0.0094 |
| UC pres. | 2378-TCDD/SCE | 6 | P95 | 0.861 | 0.0277 |
| UC pres. | 2378-TCDD/SCE | 6 | P99 | 0.922 | 0.0089 |
| UC pres. | 2378-TCDD/SCE | 6 | MAX | 0.849 | 0.0326 |
| CO/SCE | Total CDD/SCE | 11 | AMEAN | 0.891 | 0.0002 |
| CO/SCE | Total CDD/SCE | 11 | P75 | 0.852 | 0.0009 |
| CO/SCE | Total CDD/SCE | 11 | P90 | 0.921 | 0.0001 |
| CO/SCE | Total CDD/SCE | 11 | MAX | 0.801 | 0.0031 |
| $CO_2$/SCE | Total CDD/SCE | 10 | SS | 0.806 | 0.0049 |
| THC/SCE | Total CDD/SCE | 10 | P1 | -0.858 | 0.0015 |
| THC/SCE | Total CDD/SCE | 10 | P5 | -0.870 | 0.0011 |
| THC/SCE | Total CDD/SCE | 10 | P10 | -0.875 | 0.0009 |
| THC/SCE | Total CDD/SCE | 10 | P25 | -0.883 | 0.0007 |
| THC/SCE | Total CDD/SCE | 10 | MEDIAN | -0.892 | 0.0005 |
| THC/SCE | Total CDD/SCE | 10 | P75 | -0.894 | 0.0005 |
| THC/SCE | Total CDD/SCE | 10 | P90 | -0.864 | 0.0013 |
| Boiler draft | 2378-Sub. CDD/SCE | 11 | CV | 0.819 | 0.0020 |
| CO/SCE | 2378-Sub. CDD/SCE | 11 | AMEAN | 0.800 | 0.0031 |
| CO/SCE | 2378-Sub. CDF/SCE | 11 | P10 | 0.807 | 0.0027 |
| CO/SCE | 2378-Sub. CDF/SCE | 11 | P25 | 0.827 | 0.0017 |
| CO/SCE | 2378-Sub. CDF/SCE | 11 | MEDIAN | 0.851 | 0.0009 |
| CO/SCE | 2378-Sub. CDD/SCE | 11 | P75 | 0.838 | 0.0013 |

## Table 7-14.

## PEARSON CORRELATION MATRIX FOR CDD AND CDF WITH COMBUSTION GAS VARIABLES AND PROCESS DATA ($|r| \geq 0.8$)[a] (continued)

| Parameter/loc. | Dioxin or Furan/loc. | N | SVR | Pearson Corr. Coeff. (r) | Sig. Level |
|---|---|---|---|---|---|
| CO/SCE | 2378-Sub. CDF/SCE | 11 | P75 | 0.896 | 0.0002 |
| CO/SCE | 2378-Sub. CDD/SCE | 11 | P90 | 0.930 | 0.0001 |
| CO/SCE | 2378-Sub. CDF/SCE | 11 | P90 | 0.917 | 0.0001 |
| CO/SCE | 2378-Sub. CDD/SCE | 11 | MAX | 0.801 | 0.0030 |
| $SO_2$/SCE | 2378-Sub. CDD/SCE | 10 | MAX | 0.847 | 0.0020 |
| $SO_2$/SCE | 2378-Sub. CDF/SCE | 10 | MAX | 0.854 | 0.0017 |
| THC/SCE | 2378-Sub. CDD/SCE | 10 | AMEAN | -0.877 | 0.0009 |
| THC/SCE | 2378-Sub. CDD/SCE | 10 | P1 | -0.903 | 0.0003 |
| THC/SCE | 2378-Sub. CDD/SCE | 10 | P5 | -0.908 | 0.0003 |
| THC/SCE | 2378-Sub. CDD/SCE | 10 | P10 | -0.911 | 0.0002 |
| THC/SCE | 2378-Sub. CDD/SCE | 10 | P25 | -0.915 | 0.0002 |
| THC/SCE | 2378-Sub. CDD/SCE | 10 | MEDIAN | -0.925 | 0.0001 |
| THC/SCE | 2378-Sub. CDD/SCE | 10 | P75 | -0.929 | 0.0001 |
| THC/SCE | 2378-Sub. CDD/SCE | 10 | P90 | -0.885 | 0.0007 |
| THC/SCE | 2378-Sub. CDD/SCE | 10 | P95 | -0.803 | 0.0051 |
| $O_2$/SCE | $CO_2$/SCE | 8664 | -- | -0.942 | 0.0001 |

---

[a] Correlations of CEMs (except $O_2$) with CDD or CDF, data corrected to 7 percent $O_2$. Correlations of process data with CDD or CDF, data not corrected to 7 percent $O_2$. Correlations of $O_2$ with CDD or CDF, data not corrected to 7 percent $O_2$.

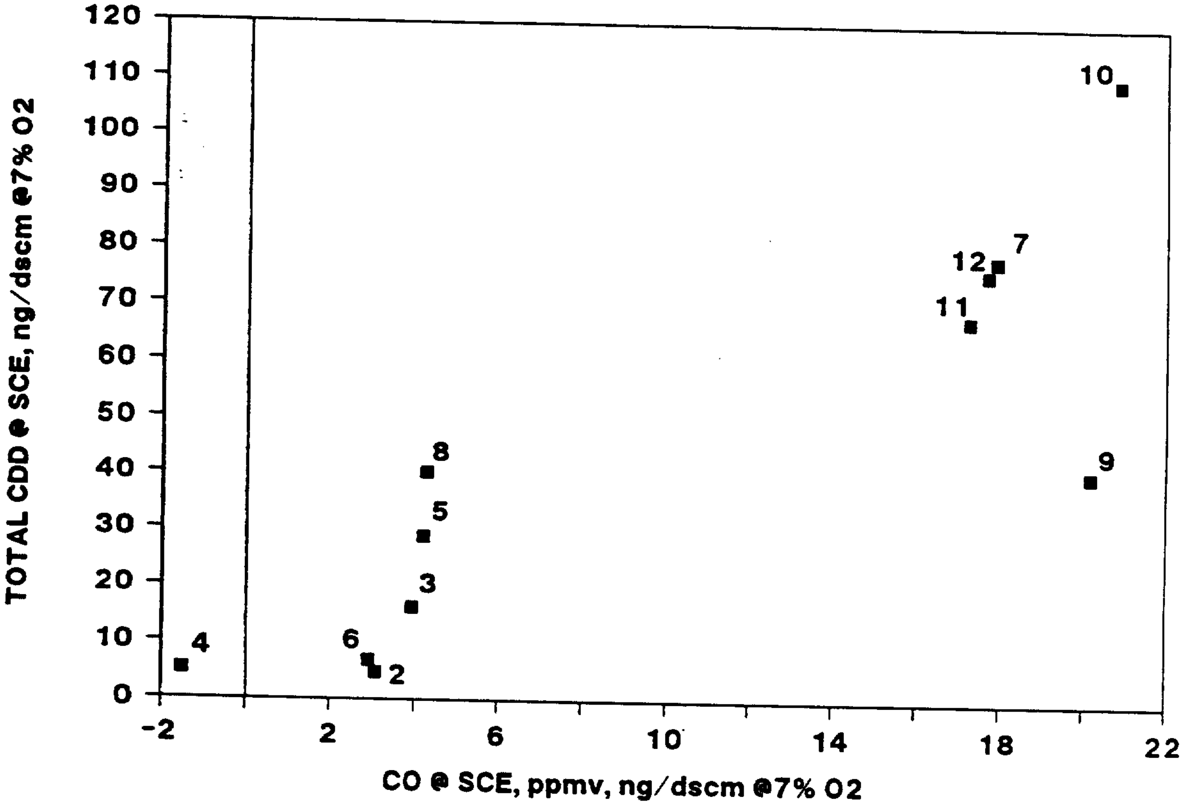

Figure 7-49. Total CDD Concentrations vs. Carbon Monoxide at the Secondary Chamber Exit (r = 0.921)

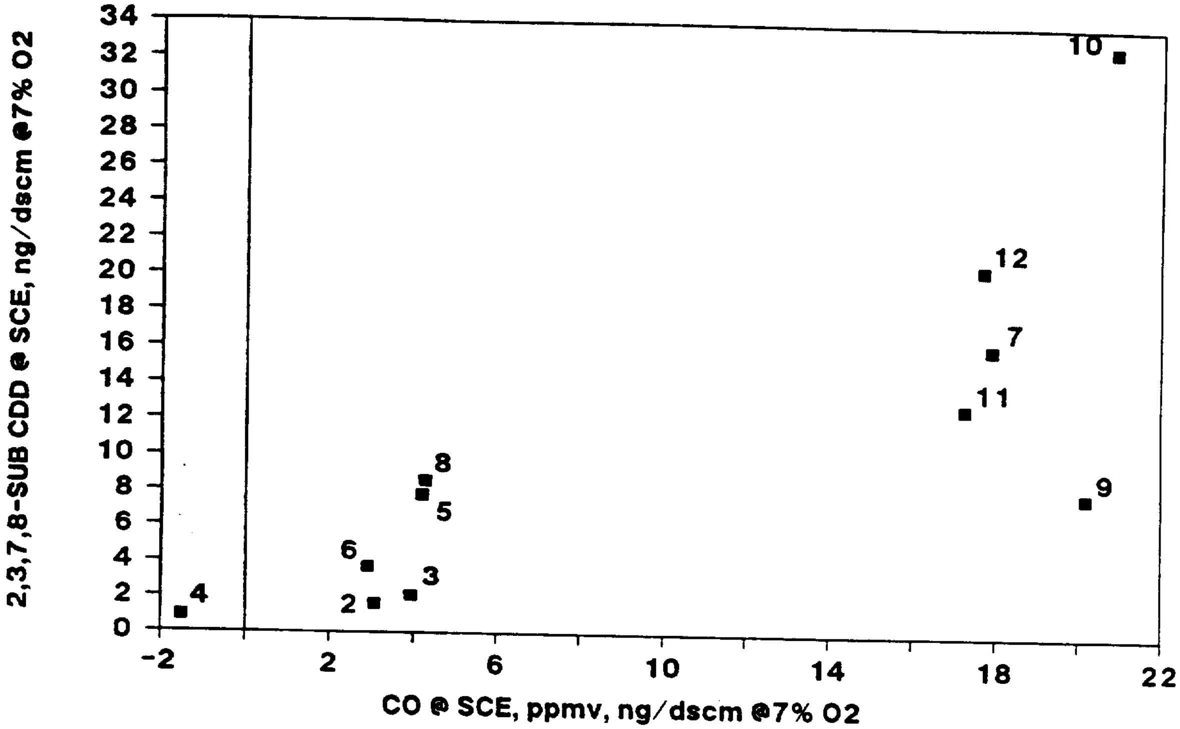

Figure 7-50. 2,3,7,8 - Substituted CDD vs. Carbon Monoxide at the Secondary Chamber Exit (r = 0.930)

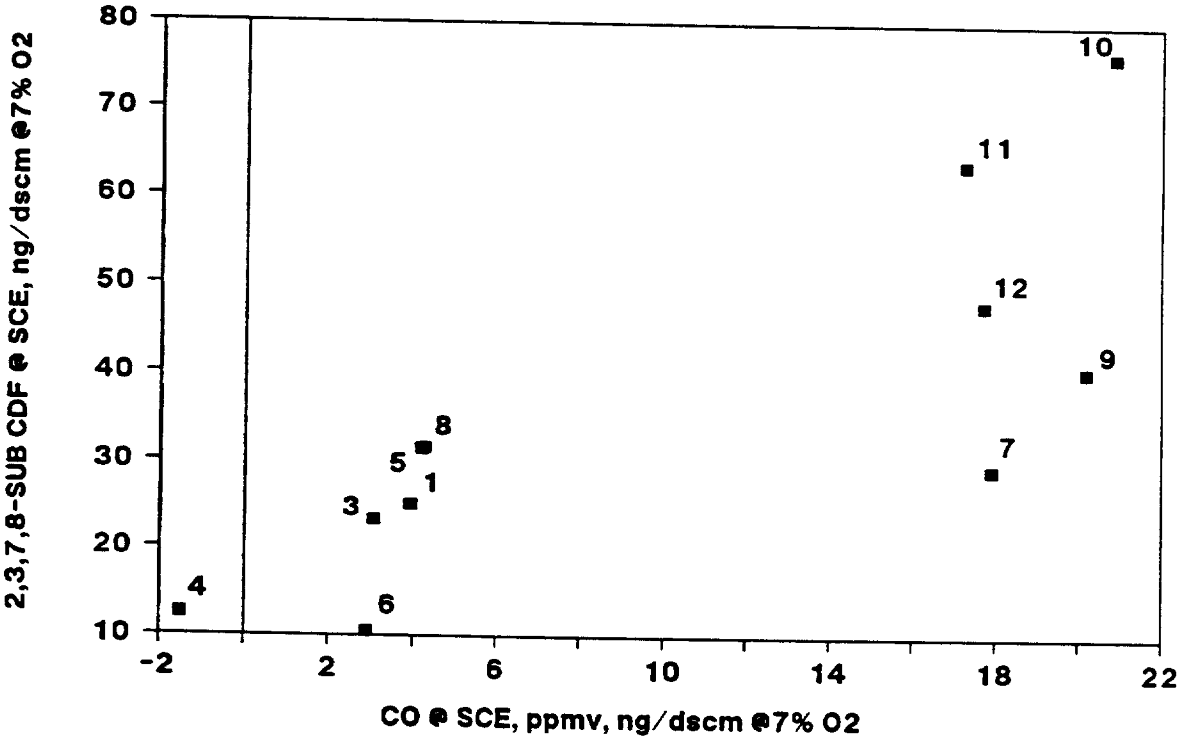

Figure 7-51. 2,3,7,8 - Substituted CDF vs. Carbon Monoxide at the Secondary Chamber Exit (r = 0.917)

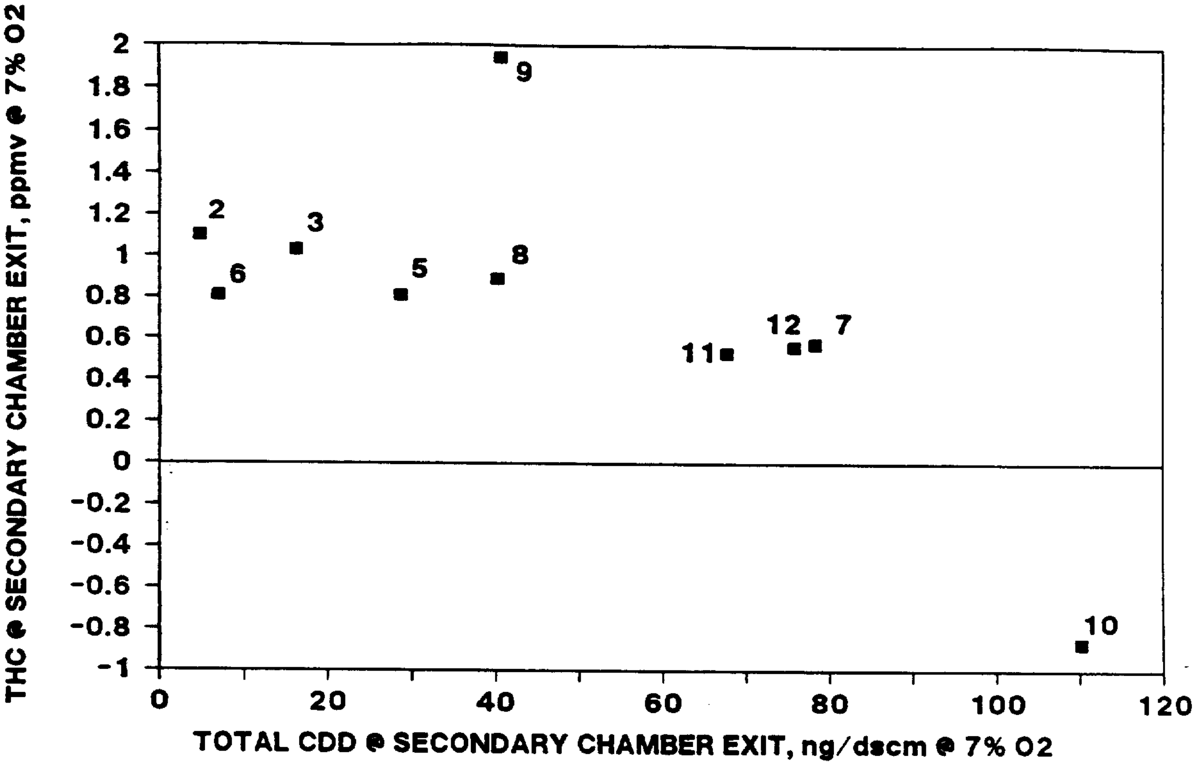

Figure 7-52. Total Hydrocarbons vs. Total CDD at the Secondary Chamber Exit

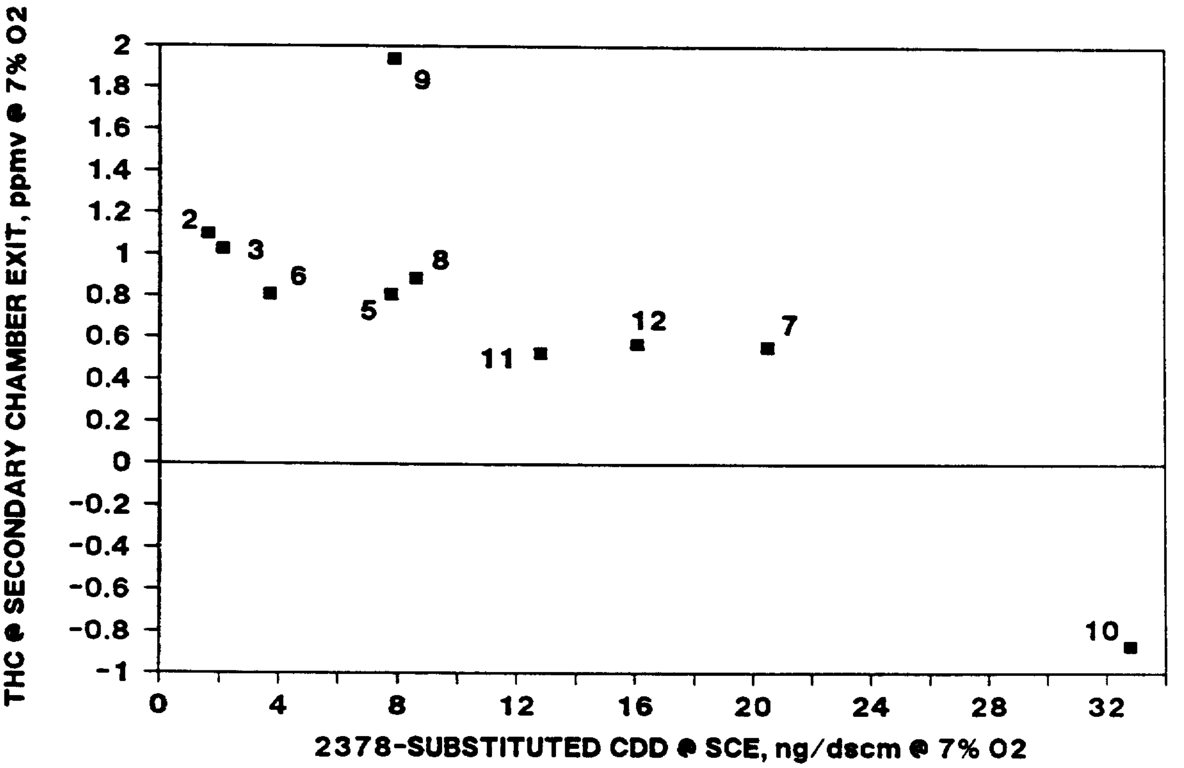

Figure 7-53. Total Hydrocarbons vs. 2378-Substituted at the Secondary Chamber Exit

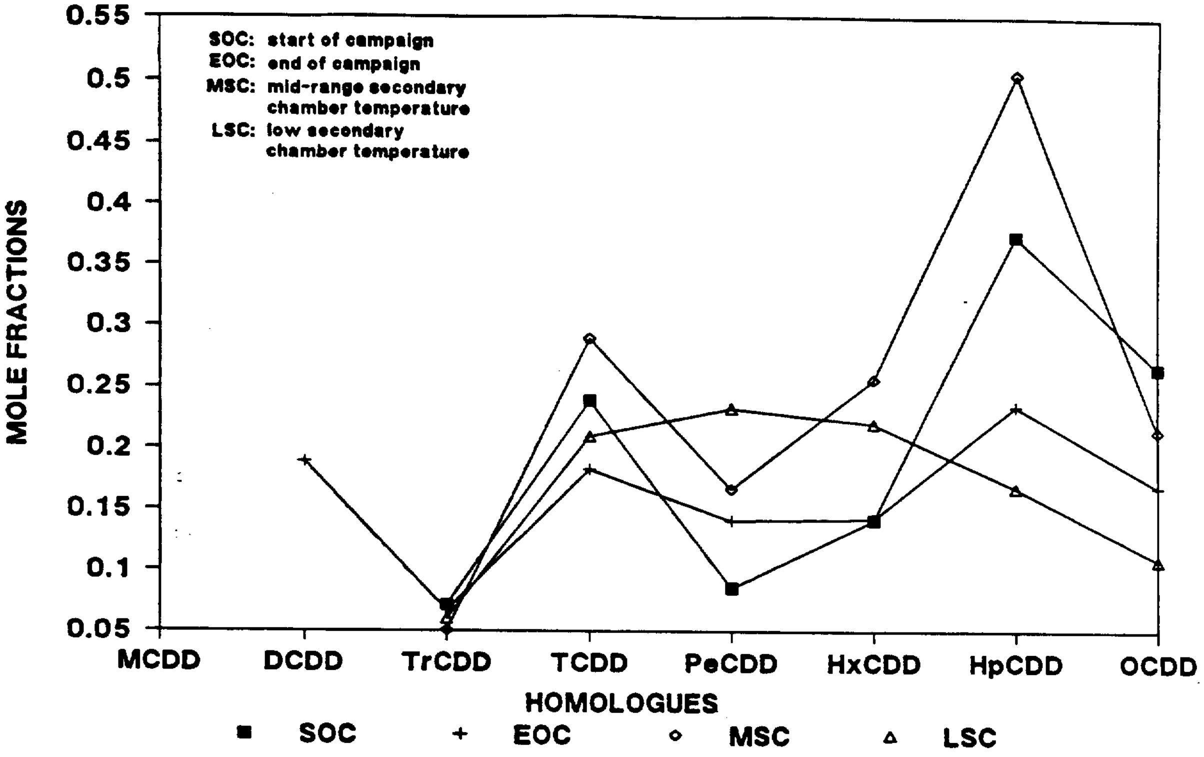

Figure 7-54. CDD Mole Fractions at the Secondary Chamber Exit by Test Condition

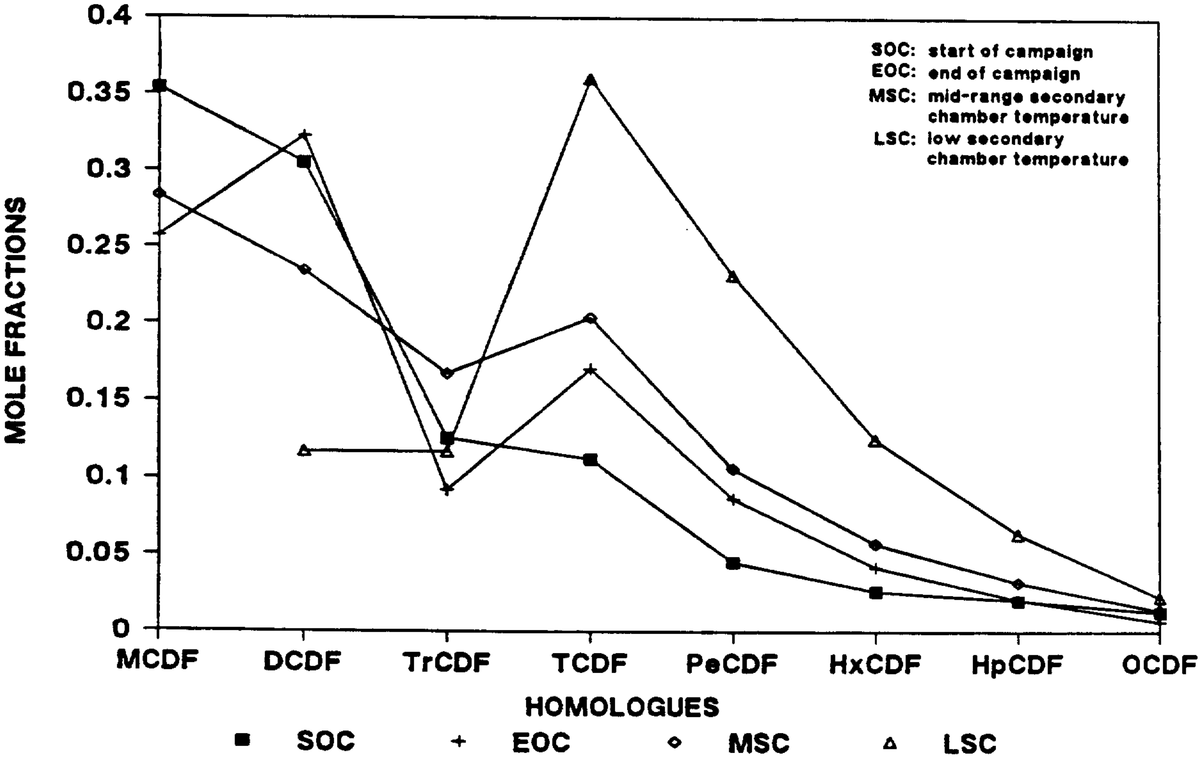

Figure 7-55. CDF Mole Fractions at the Secondary Chamber Exit by Test Condition

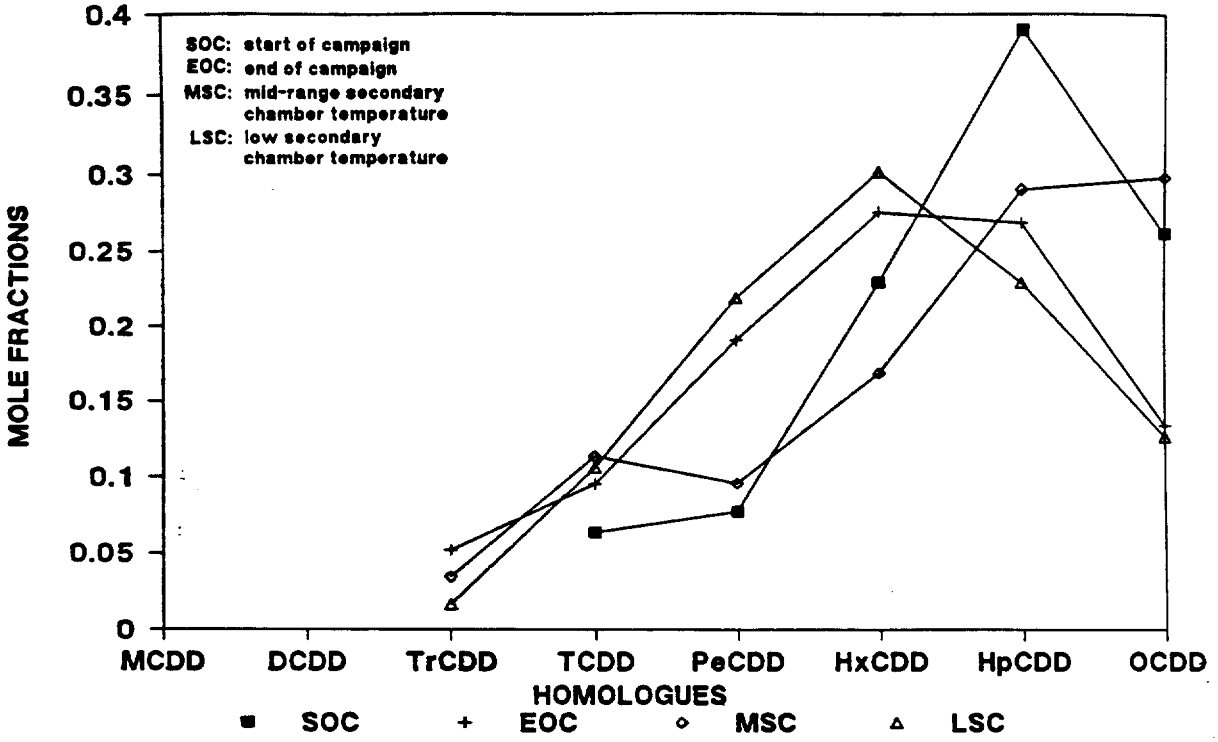

Figure 7-56. CDD Mole Fractions at the ESP Inlet by Test Condition

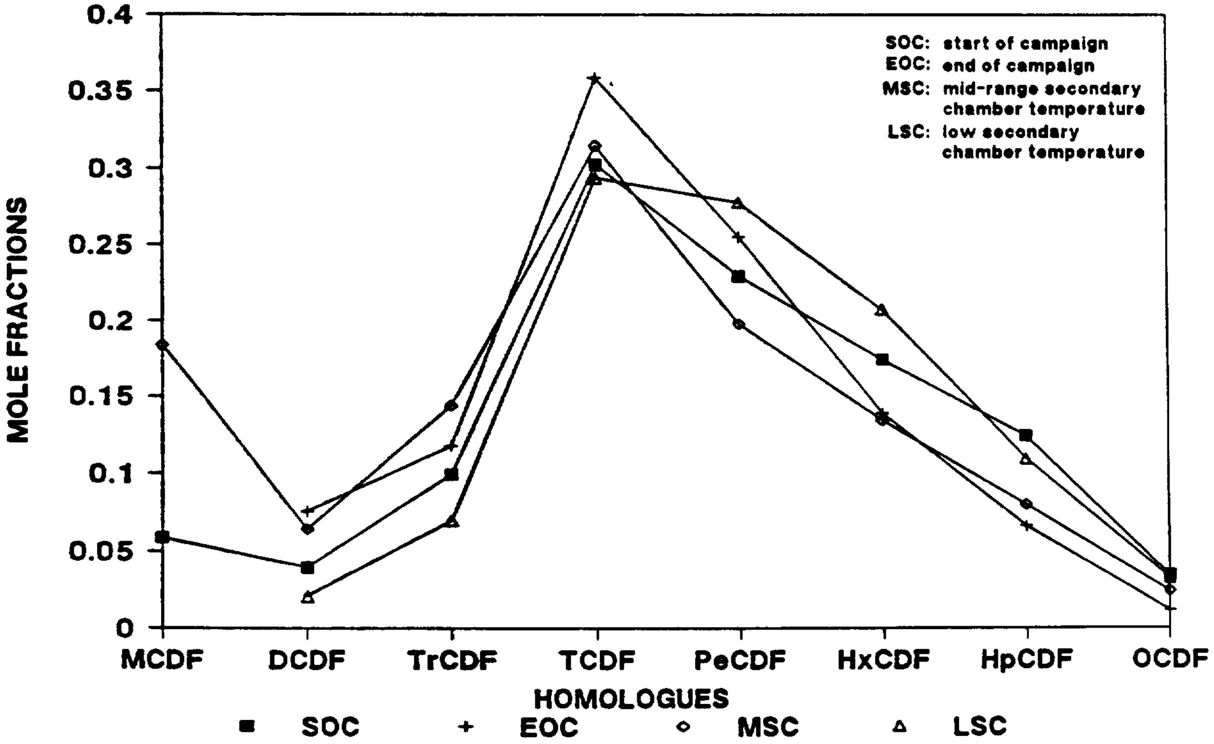

Figure 7-57. CDF Mole Fractions at the ESP Inlet by Test Condition

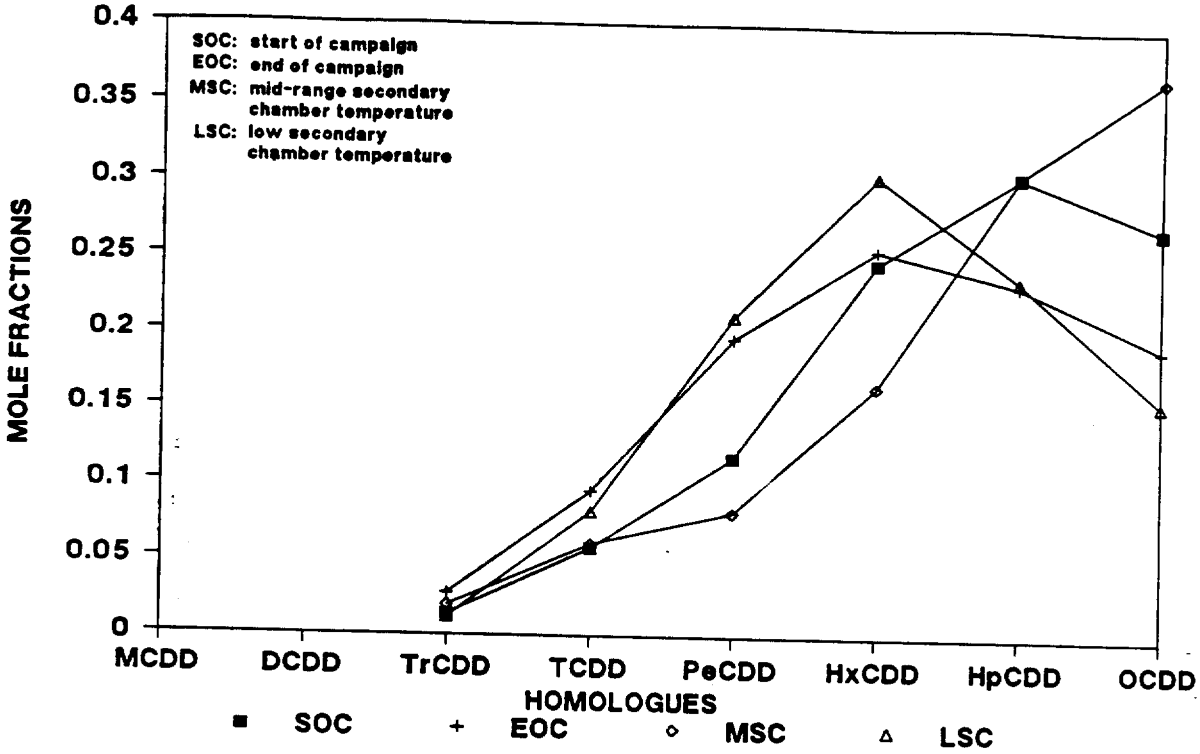

Figure 7-58. CDD Mole Fractions at the ESP Outlet by Test Condition

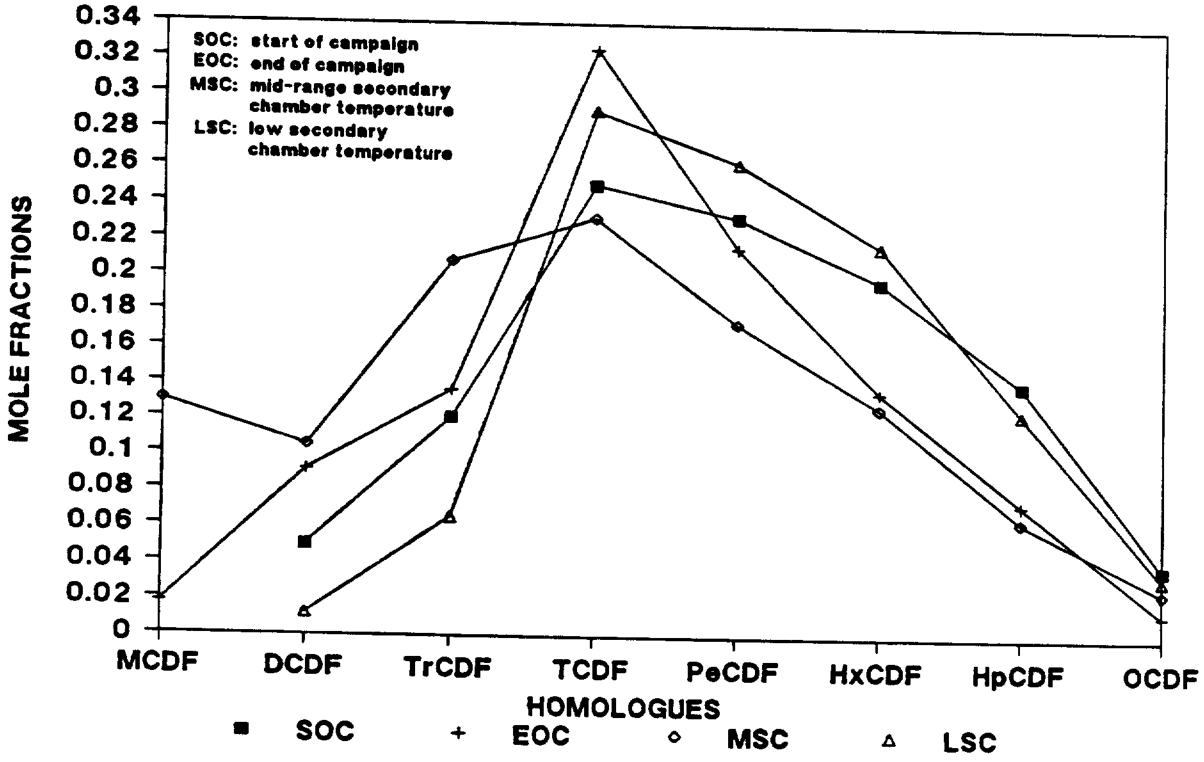

Figure 7-59. CDF Mole Fractions at the ESP Outlet by Test Condition

the homologue mole fractions are presented in Appendix C. As is shown in the figures, the lower molecular weight CDD homologues appear to chlorinate between the secondary chamber exit and ESP inlet, forming more hexa- and hepta-chlorinated homologues; the CDD homologue distribution pattern between the ESP inlet and outlet is similar. The lower molecular weight CDF homologues also appear to be chlorinating to form higher molecular weight homologues between the secondary chamber exit and ESP inlet. However, the most prevalent homologue is TCDF, which is generally considered to be the most toxic of the homologues. As with the CDD homologue distribution, the CDF homologue distribution is similar between the ESP inlet and outlet.

## LOCATION EFFECTS ON HOMOLOGUE DISTRIBUTIONS

As was shown previously, location is an important variable in the analysis of total CDD and CDF concentrations measured. This section explores the location effects on CDD and CDF homologue distribution.

Figures 7-60 through 7-67 present the homologue mole fraction distribution across the sampling locations by test condition. The figures show a discernible shift toward more highly chlorinated homologues from the secondary chamber exit through the ESP outlet for CDF; the CDD chlorination pattern varies for the different operating conditions. To further examine the possible location effects on homologue distribution, the average degree of chlorination was calculated, based on the mole fractions and number of chlorines for each homologue. Figures 7-68 and 7-69 show the average degree of chlorination for CDD and CDF, respectively. These figures summarize the information and show the trends observed in the other figures.

As noted in the discussion on location effects on total CDD and CDF concentrations, there is a significant difference in the concentrations measured at the different sampling locations for CDD only. As shown in the figures, a difference in the degree of chlorination between locations and in changes in chlorination patterns is observed for both CDD and CDF; however, these changes are much more prominent for CDF. This may explain why significant differences were not shown for CDF concentrations between the sampling locations.

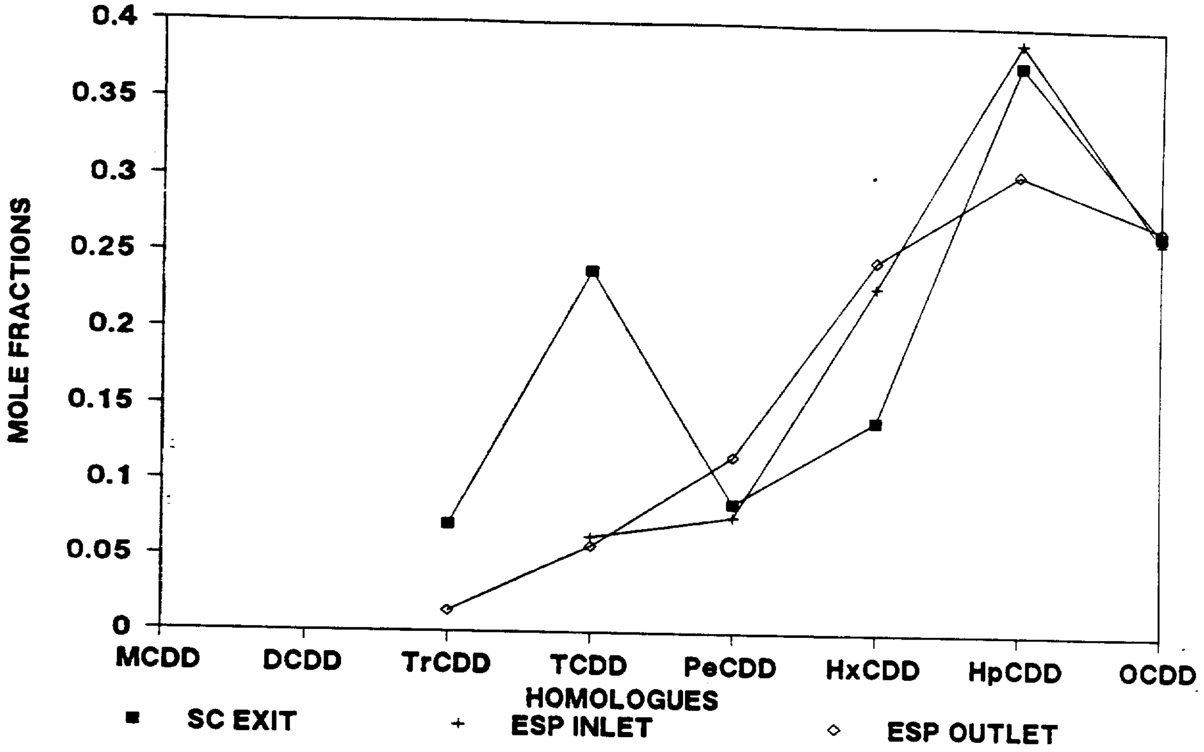

Figure 7-60. Start of Campaign CDD
Mole Fractions by Location

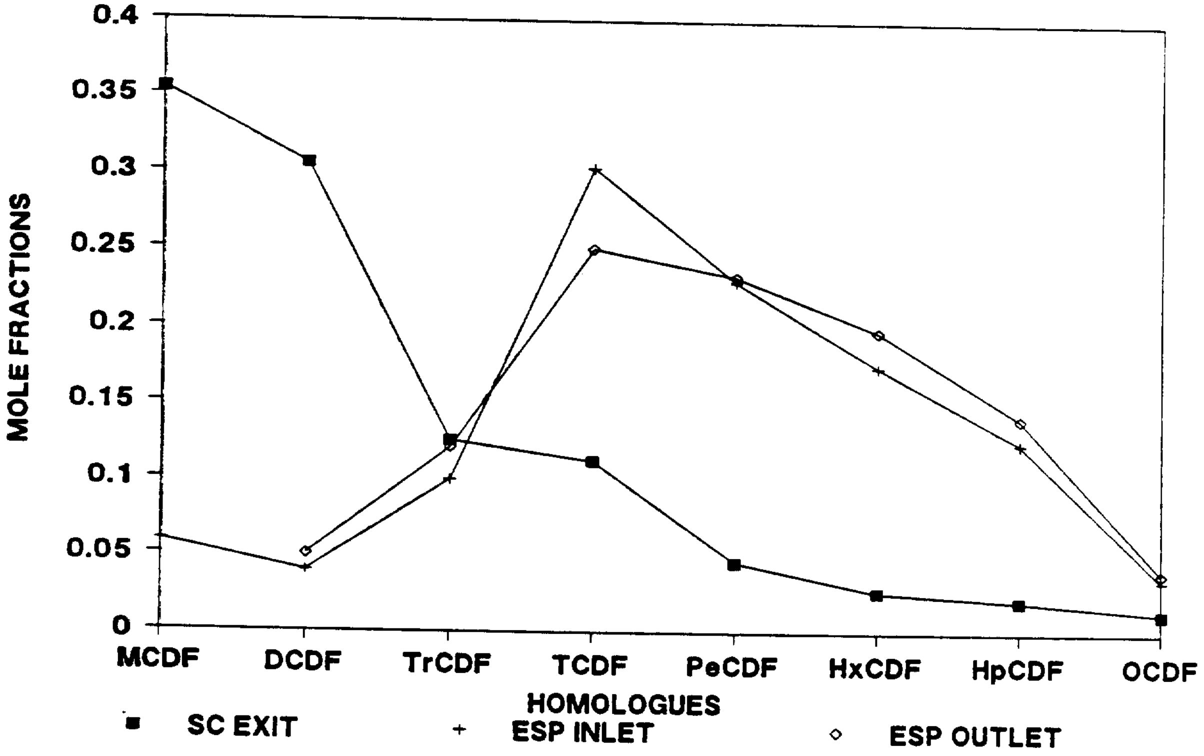

Figure 7-61. Start of Campaign CDF
Mole Fractions by Location

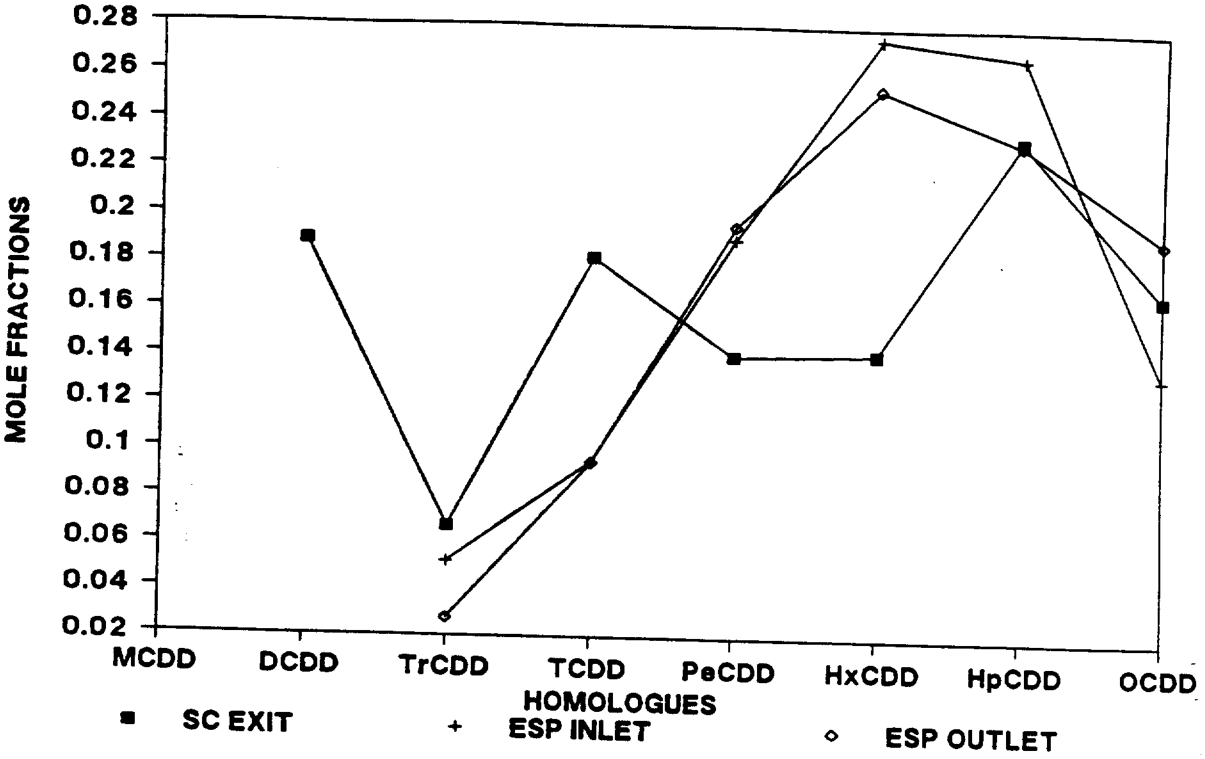

Figure 7-62. End of Campaign CDD
Mole Fractions by Location

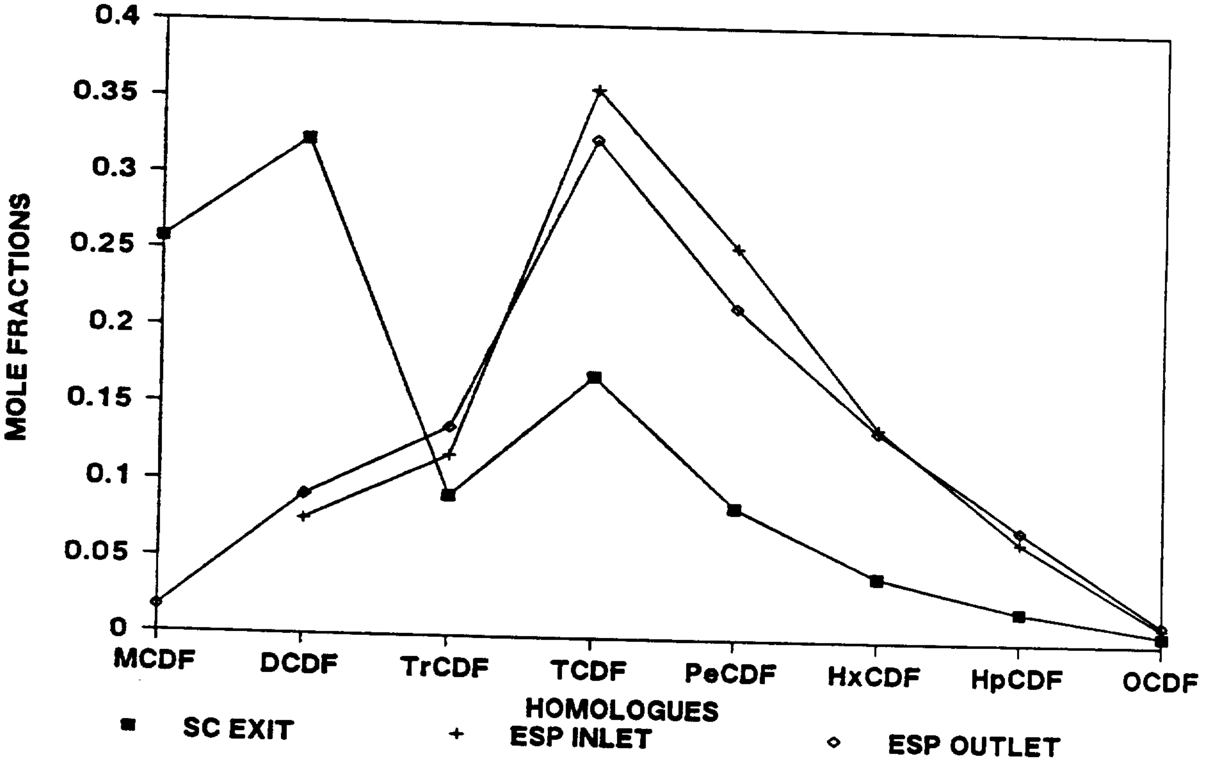

Figure 7-63. End of Campaign CDF
Mole Fractions by Location

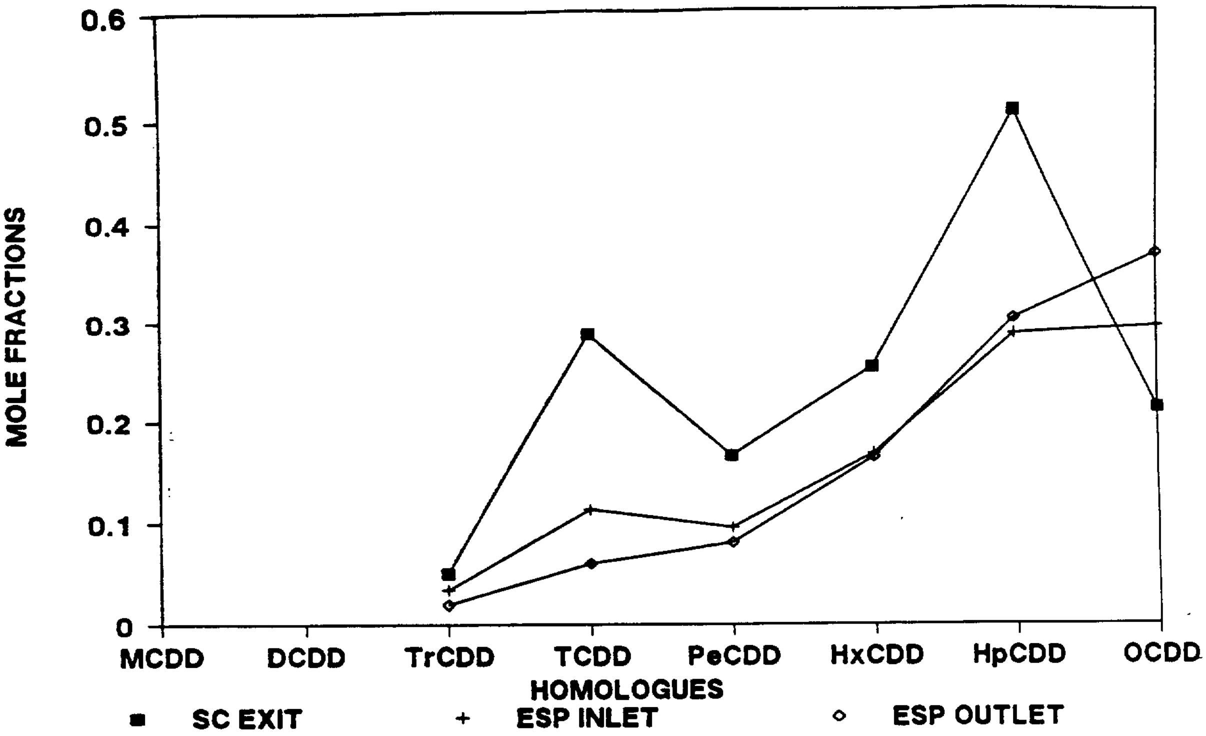

**Figure 7-64. Mid-Range Secondary Chamber Temperature CDD Mole Fractions by Location**

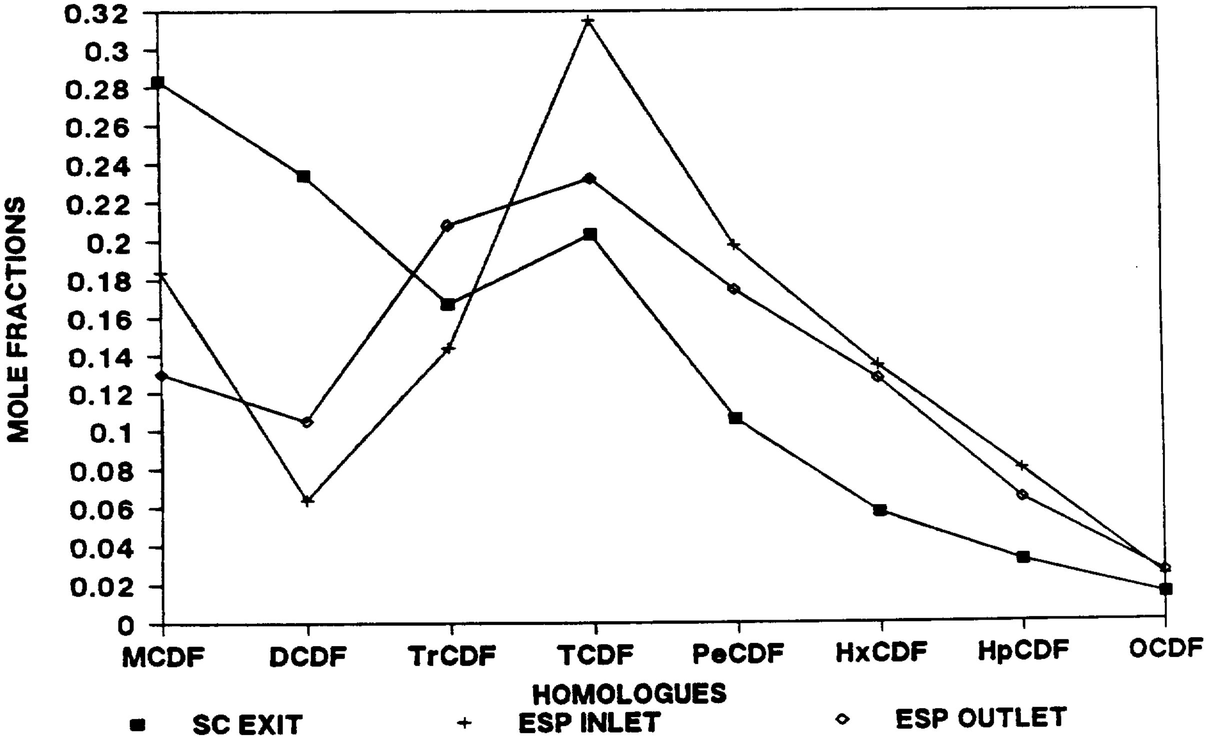

**Figure 7-65. Mid-Range Secondary Chamber Temperature CDF Mole Fractions by Location**

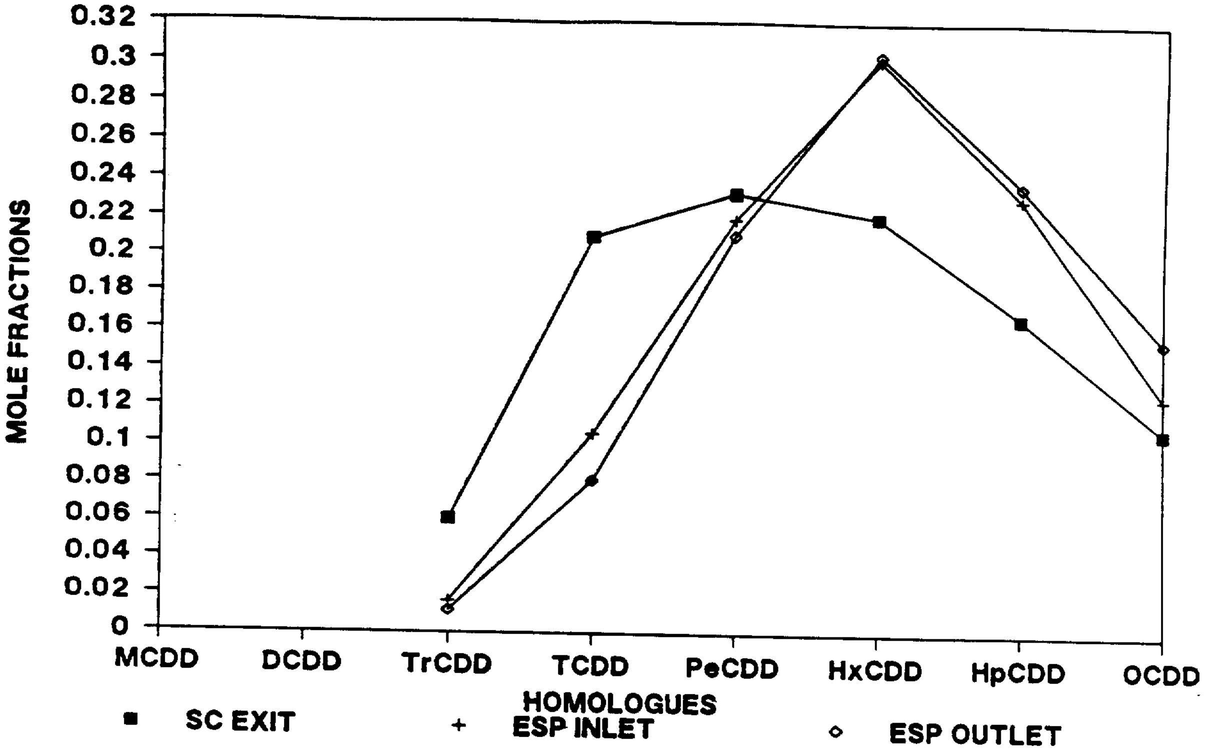

Figure 7-66. Low Secondary Chamber Temperature CDD Mole Fractions by Location

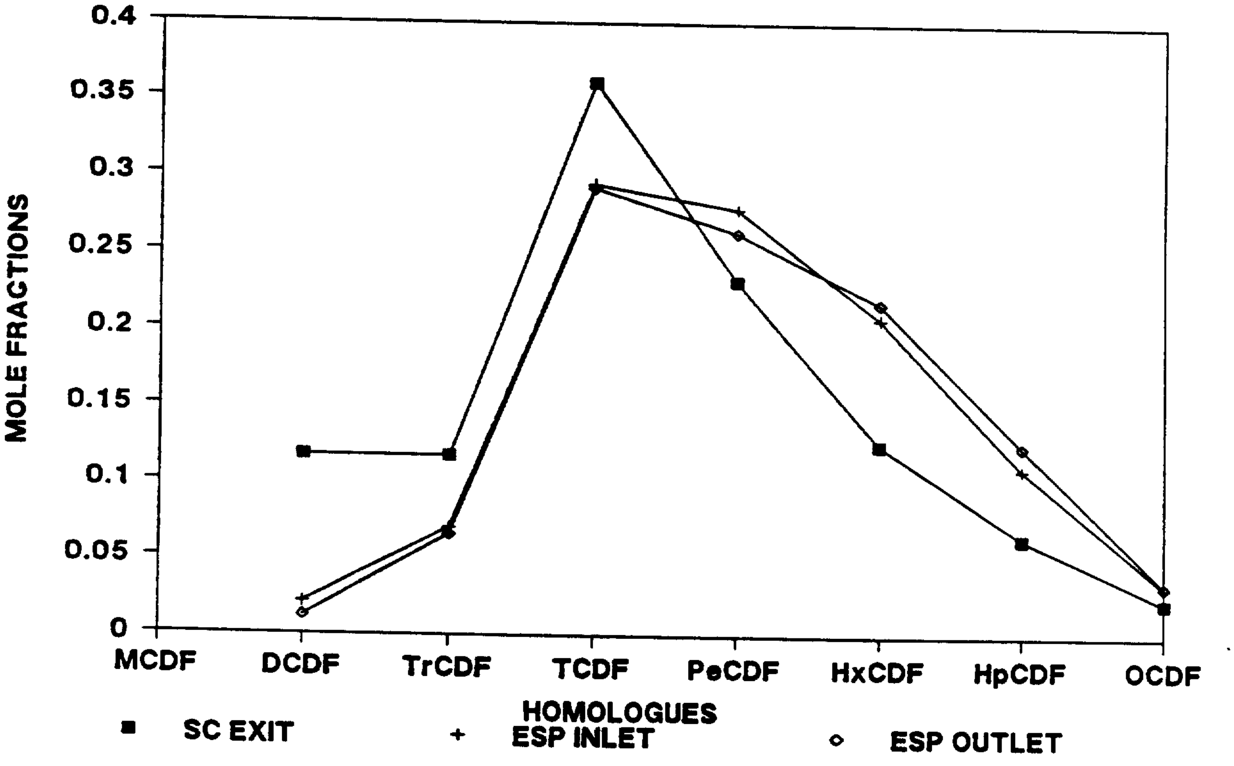

Figure 7-67. Low Secondary Chamber Temperature CDF Mole Fractions by Location

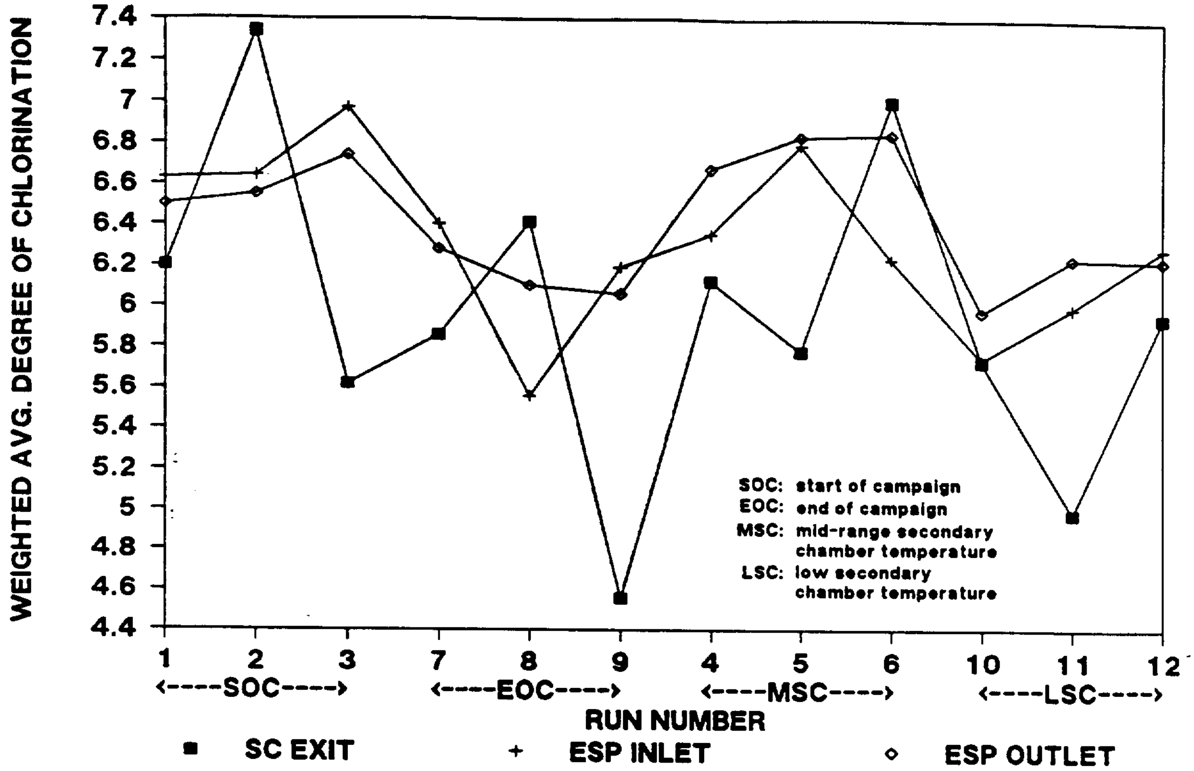

Figure 7-68. CDD Degree of Chlorination by Run Number and Location

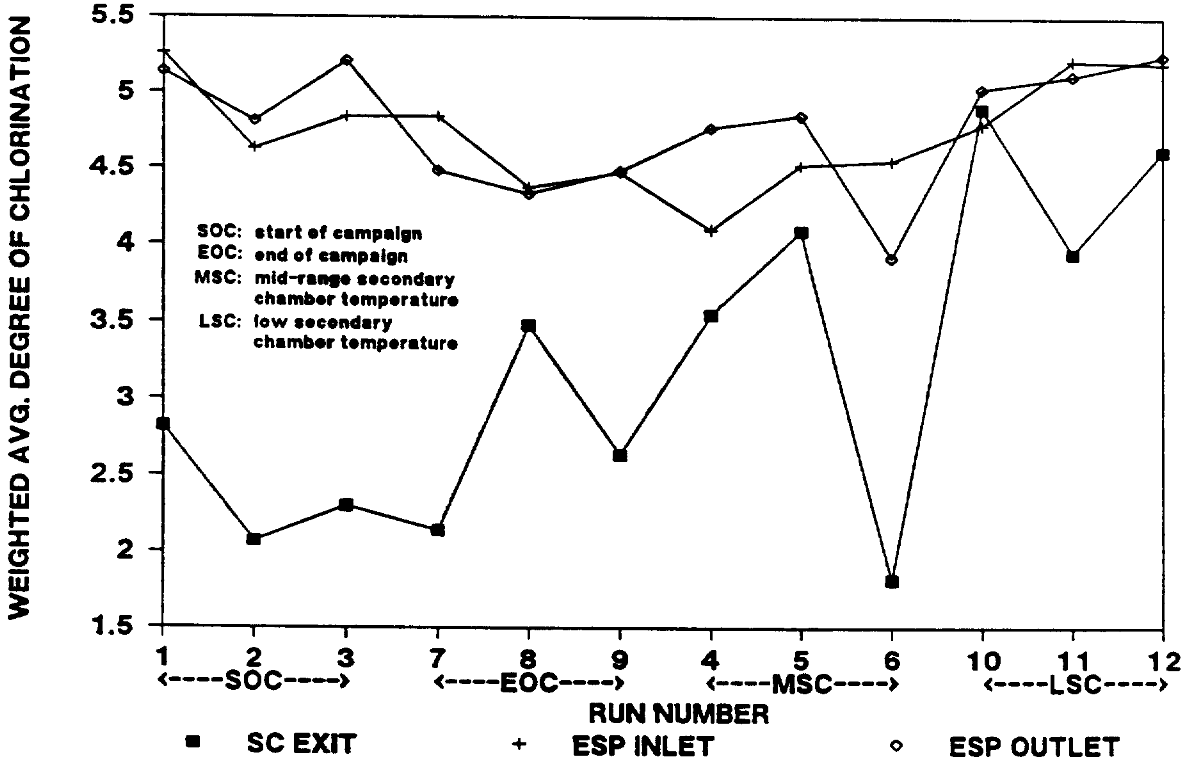

Figure 7-69. CDF Degree of Chlorination by Run Number and Location

Several plausible explanations may be constructed concerning the differences observed in CDD and CDF homologue distributions. The most obvious explanation would be differences in reaction rates and mechanisms. This may be operating together with other phenomena, such as aberrations caused by measurement methods, to obscure relationships in the CDD and CDF measurements.

### CDD AND CDF MEASURED IN FRONT HALF AND BACK HALF FRACTIONS OF THE MODIFIED METHOD 5 TRAIN

Analysis of front and back half fractions of the MM5 train was performed to provide information on the phase or particle size fraction in which the CDD and CDF were located. It should be noted that the particulate matter collected with the CDD and CDF samples was held at approximately 250°F on the filter, and was exposed to flue gases potentially containing precursors or hydrochloric acid for the entire testing period; therefore, even though the results of these observations may provide useful insight, this is not a conclusive analysis because of possible sorption, desorption, and reaction effects which may have occurred. Tables 7-15 and 7-16 summarize the front and back half CDD and CDF fractions for the ESP inlet and outlet. Figures 7-70 through 7-73 show the front and back half CDD and CDF weight fraction distributions graphically. The tables and figures show a definite shift in both CDD and CDF fractions from the front half of the train at the ESP inlet to the back half of the train at the ESP outlet. This implies that the particulate CDD and CDF are removed in the ESP and therefore, the gaseous CDD and CDF (back half) is caught in the train at the ESP outlet. However, there are uncertainties in the phase separation effectiveness of the sampling method. Because of the semivolatile characteristics of CDD and CDF congeners, it is possible that the filterable (front half) measurements do not represent particulate phase alone, and that the back half (non-filterable) measurements do not represent only gas phase CDD and CDF.

An analysis of variance, conducted with ESP inlet and outlet data only, showed no statistical difference between test runs for front half and back half CDD and CDF fractions, nor was there a statistical difference seen between run groups. However, location effects were confirmed as statistically significant

## Table 7-15.

## SUMMARY OF CDD AND CDF MEASURED IN THE FRONT HALF AND BACK HALF OF THE SAMPLING TRAIN AT THE ESP INLET

| RUN NUMBER | CDD |  | CDF |  | CDD + CDF |  |
|---|---|---|---|---|---|---|
|  | wt. % FH | wt. % BH | wt. % FH | wt. % BH | wt. % FH | wt. % BH |
| 1 | 22.9 | 77.1 | 12.7 | 87.3 | 15.5 | 84.5 |
| 2 | 69.2 | 30.8 | 65.0 | 35.0 | 66.2 | 33.8 |
| 3 | 35.1 | 64.9 | 17.1 | 82.9 | 21.8 | 78.2 |
| 4 | 12.6 | 87.4 | 16.1 | 83.9 | 15.2 | 84.8 |
| 5 | 46.2 | 53.8 | 21.8 | 78.2 | 27.8 | 72.2 |
| 6 | 31.9 | 68.1 | 22.0 | 78.0 | 24.0 | 76.0 |
| 7 | 65.2 | 34.8 | 56.5 | 43.5 | 58.4 | 41.6 |
| 8 | 68.7 | 31.3 | 63.4 | 36.6 | 64.4 | 35.6 |
| 9 | (a) | 100.0 | (a) | 100.0 | (a) | 100.0 |
| 10 | 56.2 | 43.8 | 50.7 | 49.3 | 52.7 | 47.3 |
| 11 | 35.2 | 64.8 | 34.6 | 65.4 | 34.8 | 65.2 |
| 12 | 48.6 | 51.4 | 43.7 | 56.3 | 45.6 | 54.4 |

[a] Not reported.

## Table 7-16.

## SUMMARY OF CDD AND CDF MEASURED IN THE FRONT HALF AND BACK HALF OF THE SAMPLING TRAIN AT THE ESP OUTLET

| RUN NUMBER | CDD | | CDF | | CDD + CDF | |
|---|---|---|---|---|---|---|
| | wt. % FH | wt. % BH | wt. % FH | wt. % BH | wt. % FH | wt. % BH |
| 1 | 2.7 | 97.3 | 0.3 | 99.7 | 1.2 | 98.8 |
| 2 | 9.7 | 90.3 | 3.2 | 96.8 | 5.5 | 94.5 |
| 3 | 10.1 | 89.9 | 3.8 | 96.2 | 6.1 | 93.9 |
| 4 | 3.3 | 96.7 | 0.4 | 99.6 | 1.5 | 98.5 |
| 5 | 7.7 | 92.3 | 1.1 | 98.9 | 3.4 | 96.6 |
| 6 | 7.4 | 92.6 | 0.5 | 99.5 | 2.3 | 97.7 |
| 7 | 3.2 | 96.8 | 0.2 | 99.8 | 1.2 | 98.8 |
| 8 | (a) | 100.0 | (a) | 100.0 | (a) | 100.0 |
| 9 | 1.4 | 98.6 | 0.2 | 99.8 | 0.6 | 99.4 |
| 10 | 3.6 | 96.4 | 1.4 | 98.6 | 2.4 | 97.6 |
| 11 | 2.7 | 97.3 | 0.8 | 99.2 | 1.6 | 98.4 |
| 12 | 1.3 | 98.7 | 0.2 | 99.8 | 0.7 | 99.3 |

[a] Not Reported.

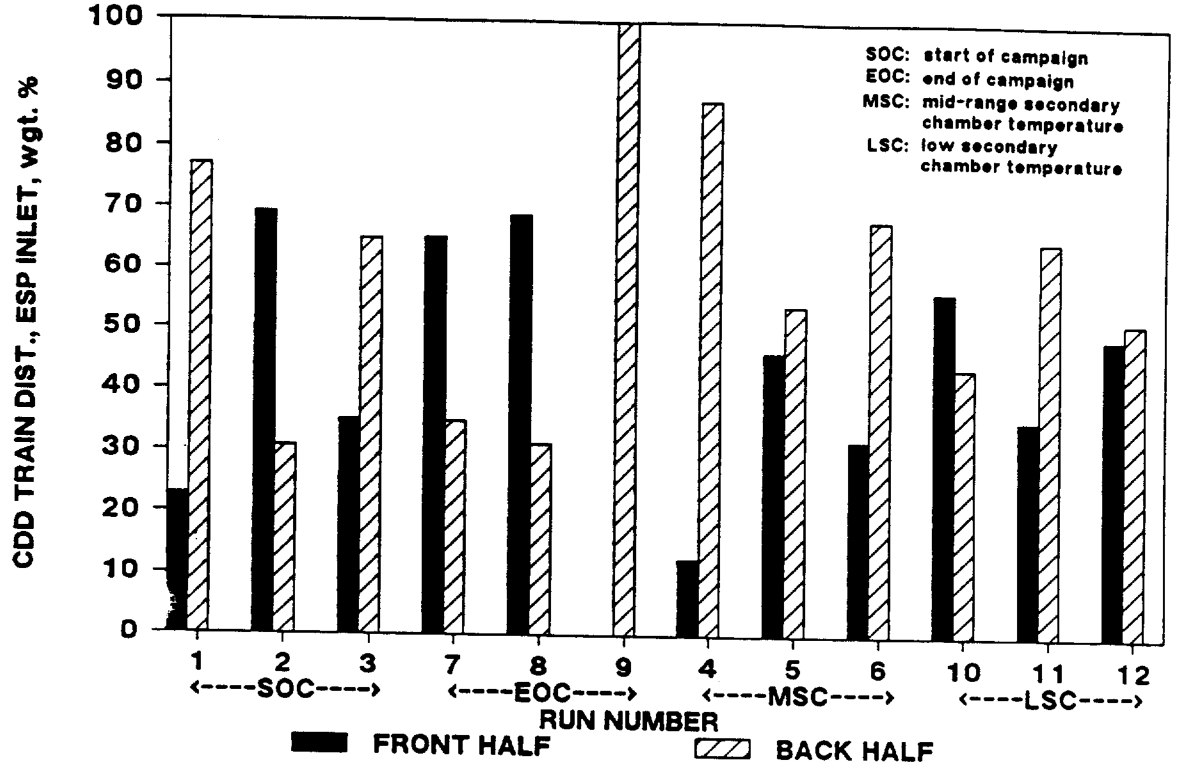

Figure 7-70. Front and Back Half CDD Distribution at the ESP Inlet by Run Number

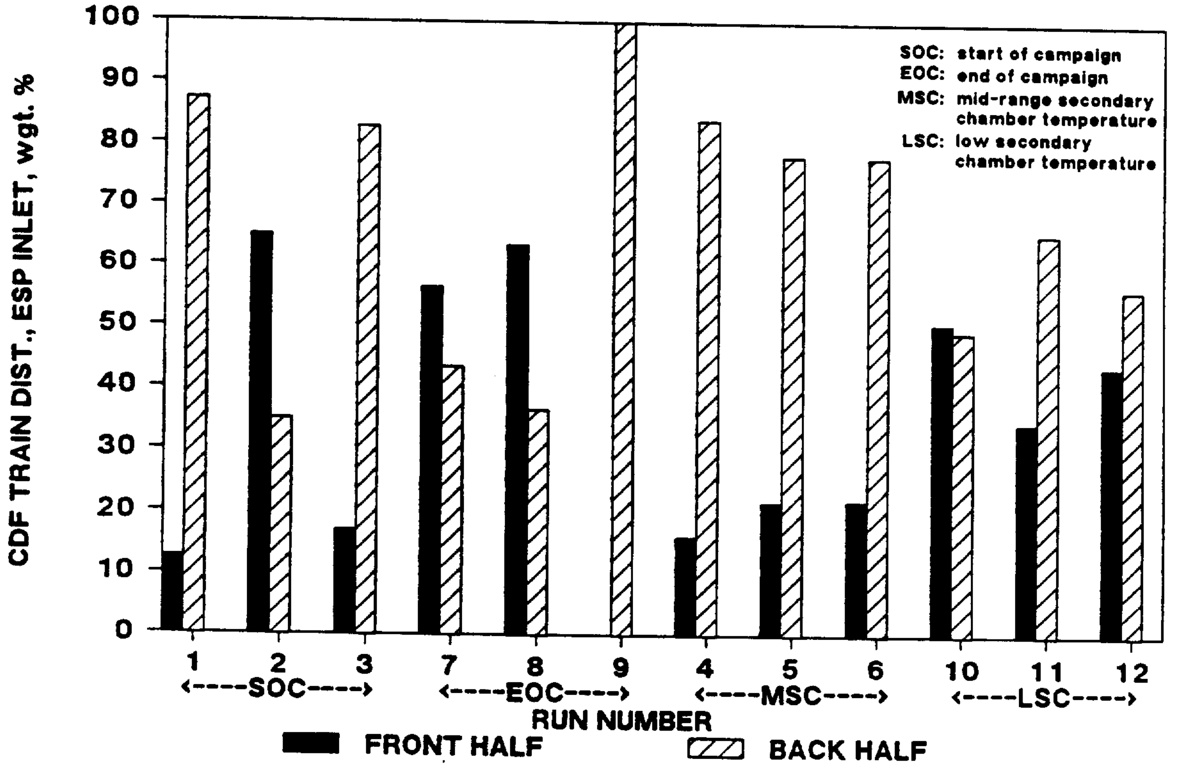

Figure 7-71. Front and Back Half CDF Distribution at the ESP Inlet by Run Number

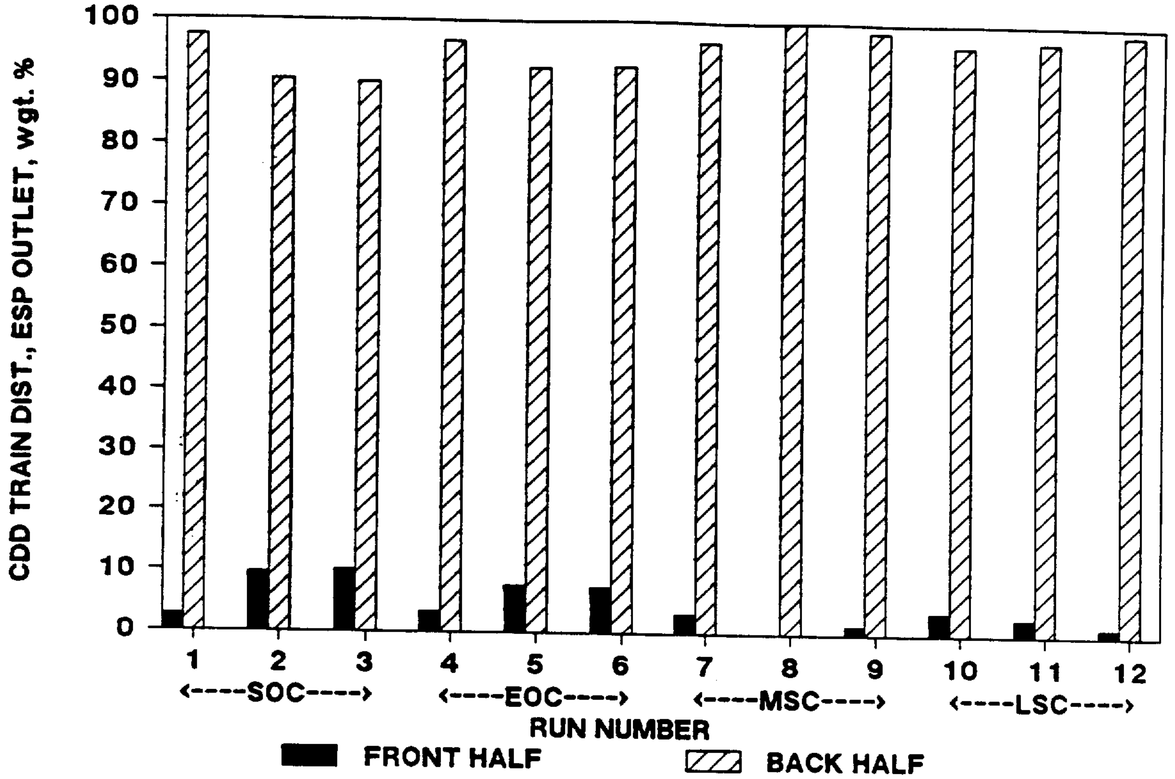

Figure 7-72. Front and Back Half CDD Distribution at the ESP Outlet by Run Number

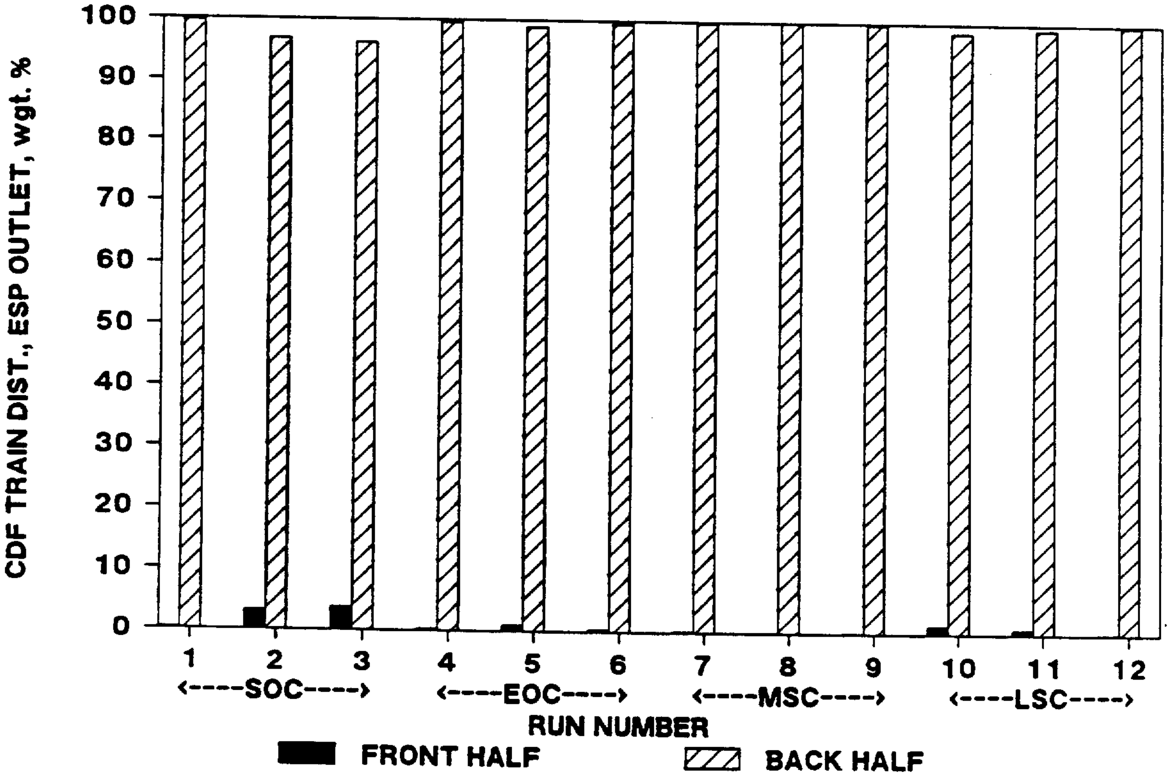

Figure 7-73. Front and Back Half CDF Distribution at the ESP Outlet by Run Number

for both CDD and CDF at the 0.0001 level. Since there were no significant differences in CDD front-half and back-half percentages between runs, and because total CDD and CDF did not correlate strongly and consistently with the CEM or plant operating variables (see Section 5), no further analysis of front-half and back-half fractions of CDD and CDF with respect to CEM or process data was pursued.

## ESP COLLECTION EFFICIENCY

An additional question posed as part of the study was: How does control device removal efficiency for CDD and CDF vary with plant operating conditions? This question can be addressed by focusing on comparisons of the ESP inlet and outlet CDD and CDF measurements. As discussed earlier, concentrations of CDD and CDF at these two locations are statistically different and, therefore, potentially meaningful comparisons of the two locations can be made.

For the purposes of this report, collection efficiency has been calculated using the following equation, which is based on CDD and CDF concentrations adjusted to 7% $O_2$.

$$\text{Efficiency Ratio} = \frac{(\text{Concentration}_{\text{ESP Inlet}} - \text{Concentration}_{\text{ESP Outlet}})}{\text{Concentration}_{\text{ESP Inlet}}}$$

Calculated removal efficiencies for total CDD, total CDF, and combined CDD and CDF based on mass rates are presented in Figure 7-74. Particulate removal efficiencies based on mass rates for the same test conditions are shown in Figure 7-75. As expected, the CDD and CDF removal efficiencies are negative, due to formation rather than removal of CDD and CDF by the ESP. In addition, the CDD and CDF removal efficiencies, while different in magnitude, are similar for all test runs, indicating that removal efficiency was not affected

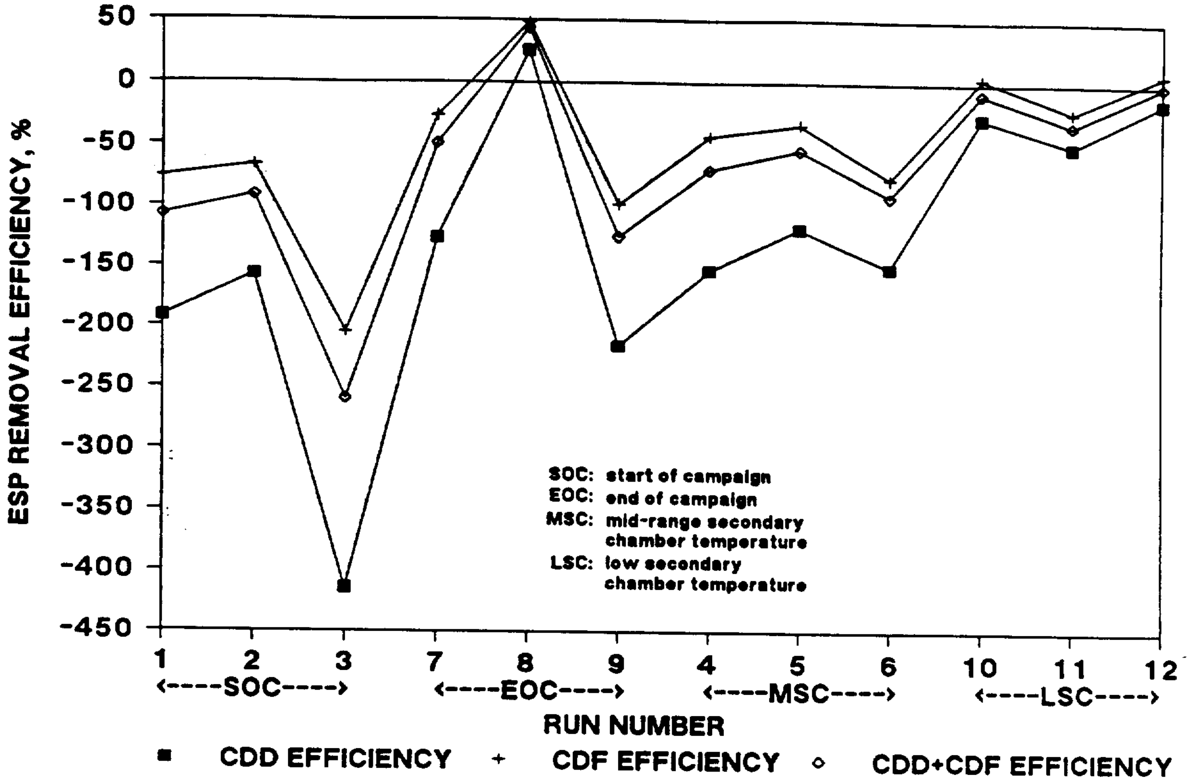

Figure 7-74. ESP CDD and CDF Removal Efficiency by Run Number

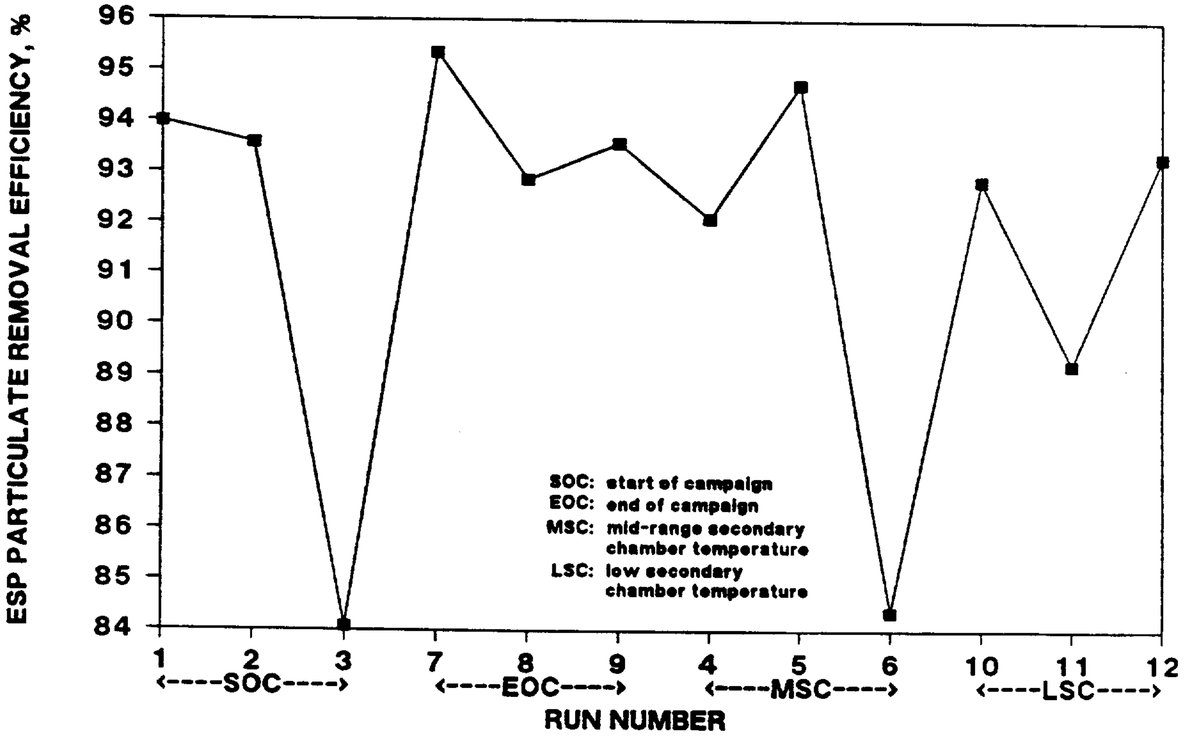

Figure 7-75. ESP Particulate Removal Efficiency by Run Number

by the different operating conditions. The particulate removal efficiency ranged between 84 and 95 percent. Excluding Runs 3 and 6, the efficiency did not vary significantly between test runs.

An ANOVA and scatter plots were used to detect if there were any differences between run groups. The averages with Duncan's results are presented in Table 7-17. Although the ANOVA results show that there is no significant difference between operating conditions for the CDD and CDF efficiency values, Duncan's tests showed that differences did exist for the CDD removal efficiencies. According to Duncan's test, the low secondary chamber temperature condition had a higher than average ESP removal efficiency and the start of campaign operating condition had a lower than average ESP removal efficiency.

To attempt to explain the differences in ESP removal efficiency by run group, further analyses of the differences in flue gas parameters between runs were performed. Factors affecting ESP performance for particulate matter were selected for consideration in the analysis. In general, the performance of an ESP for control of particulate matter depends on: 1) the amount of available collecting surface, 2) flue gas flowrate, 3) particulate resistivity, 4) particle size distribution, 5) flue gas velocity distribution, 6) rapping intensity and frequency, and 7) electric field strength. Because the individual effects of these factors on ESP performance are difficult to model, ESP performance is typically predicted from an empirical, three-parameter equation.

Classically, the performance of an ESP for control of particulate matter has been predicted with the Deutsch-Anderson equation:

$$n = 1 - \exp\,[-W_e(A/V)]$$

where,

$n$ = collection efficiency

$W_e$ = average migration velocity, ft/m

$A$ = collecting plate area, $ft^2$

$V$ = flue gas flowrate, $ft^3/m$

## Table 7-17

## REMOVAL EFFICIENCIES AVERAGED BY OPERATING CONDITION[a]

| Operating Condition | CDD | N | CDF | N |
|---|---|---|---|---|
| Start of Campaign | -2.0445 | 3 (L) | -.8574 | 3 |
| End of Campaign | -.9091 | 3 | -.1688 | 3 |
| Low S.C. Temp. | -.2810 | 3 (H) | -.0097 | 3 |
| Mid-range S.C. Temp. | -1.1299 | 3 | -.3447 | 3 |

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[a] The letters in parentheses represent the results of Duncan's multiple range tests (H = high and L = low).

The ratio A/V is known as the specific collection area (SCA) and is usually expressed in $m^2/(m^3/s)$ or $ft^2/1000$ acfm. The actual collection area during ESP operation depends on the actual flue gas flowrate which will be a function of the flue gas temperature, excess air level and boiler load. Increases in temperature and excess air level will decrease the SCA and may, therefore, lower the collection efficiency for particulate matter.

The average migration velocity or precipitation rate is a function of particle size distribution and resistivity, flue gas velocity distribution, rapping intensity and frequency, and electrical field strength. Figure 7-76 shows the dependence of precipitation rate on particle resistivity. Figure 7-77 shows that the resistivity of flyash from a municipal waste incinerator is dependent on temperature. Particle resistivity will also vary depending on the fuel sulfur content, which was not considered in the analysis. The flyash resistivity graph shows that the ESP temperature at the Oswego unit is not in the maximum resistivity range shown for municipal waste combustor ash.

Other variables including configuration and type of electrode, the rapping cycle and the gas flow distribution also have marked impacts on ESP particulate removal efficiency. However, these variables were not changed from run to run for this test program; therefore, these effects cannot be tested. One further factor that affects ESP performance for particulate matter is the voltage applied to the ESP electrodes. Proper voltage ensures an adequate corona for charging the particles while minimizing problems of sparking. The use of an automatic power supply control is desirable in many applications because of the varying flyash and flue gas properties brought on by various boiler loads and fuel properties. Automatic controls allow the ESP to respond more effectively to these changes by reducing sparking and current losses. Several of the above-mentioned factors known to be important for particulate control efficiency were investigated for their effect on CDD and CDF control efficiency at the Oswego facility. These include the effect of gas temperature and gas flowrate. However, there were no strong linear associations between control device efficiency for CDD and CDF and the variables considered.

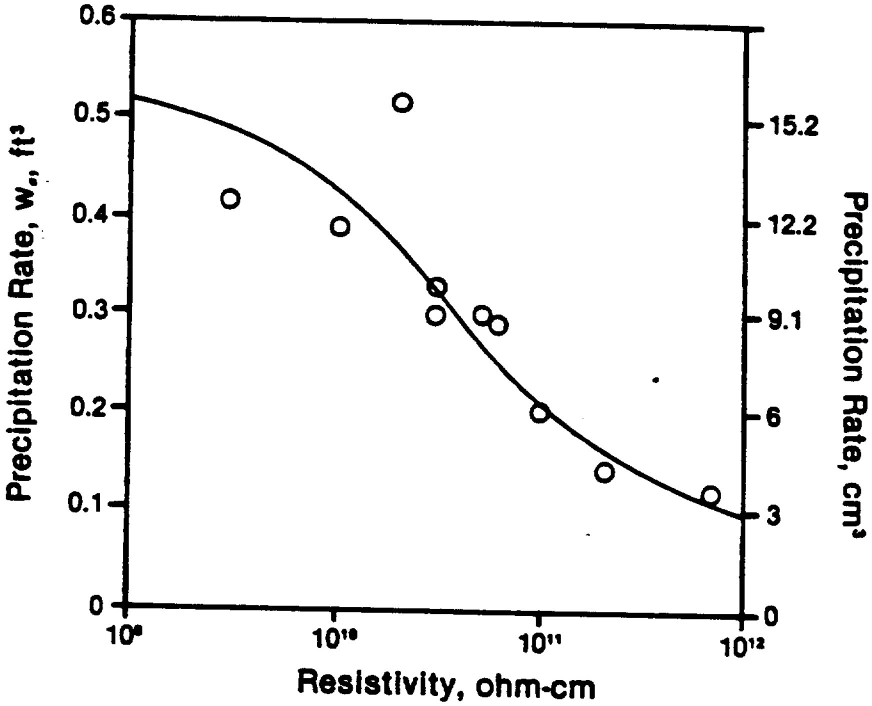

**Figure 7-76. Relationship of Particle Resistivity and Precipitation Rate**

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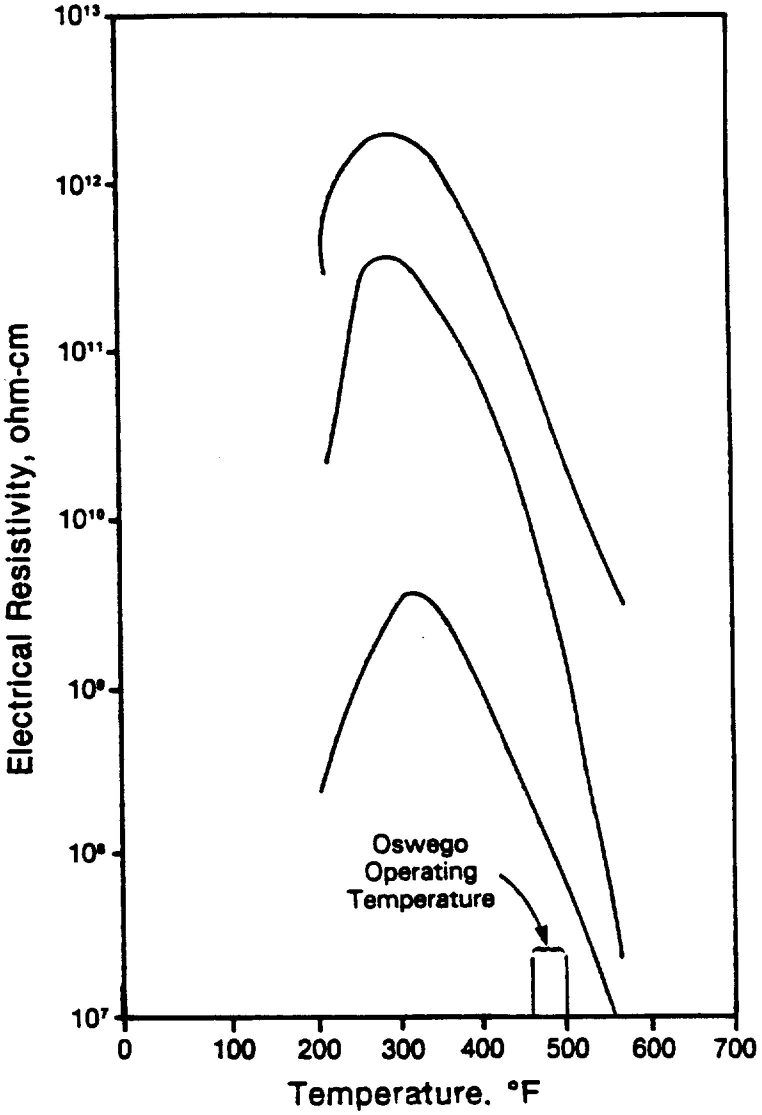


Figure 7-77. Electrical Resistivity of Flyash from Three MSW Incinerators and Boilers

2881102R

## REFERENCES

1. Midwest Research Institute. Municipal Waste Combustion Study: Emission Data Base for Municipal Waste Combustors. EPA/530-SW-87-021b. Prepared for the U. S. Environmental Protection Agency, June 1987.

2. Kelly, W. "Measurement of Dioxins and Furans in Combustion Flue Gases Results and Problems." Presented at Environment Canada Conference, 1987.

3. Visalli, J.R. "A Comparison of Dioxin, Furan and Combustion Gas Data from Test Programs at Three MSW Incinerators." Hazardous Waste Management. December 1987.

4. Ahling, B. and A. Lindskog. Emission of Chlorinated Organic Substances from Combustion. In: Pergamon Series on Environmental Science, Volume 5, 1982. pp. 215-225.

5. Buser, H. R. and C. Rappe. Formation of Polychlorinated Dibenzofurans (PCDFs) from the Pyrolysis of Individual PCB Isomers. Chemosphere, 8(3):157-174, 1979.

6. Dow Chemical. The Trace Chemistries of Fire - A Source of and Routes for the Entry of Chlorinated Dioxins into the Environment. Dow Chemical U.S.A, 1978. 46 pp.

7. Rappe, C., S. Marklund, P.A. Bergqvist and M. Hansson. Polychlorinated Dioxins (PCDDs), Dibenzofurans (PCDFs) and Other Polynuclear Aromatics (DCPNAs) Formed During PCB Fires. Chemica Scripta, 20:56-61, 1982.

8. Stieglitz, L. and H. Vogg. "New Aspects of PCDD/PCDF Formation in Incineration Processes." Preliminary Proceedings, Municipal Waste Incineration, October 1-2, 1987, Montreal, Quebec.

9. Clark, M. "Air Pollution Control Status Report." Waste Age. November 1987. pp.102-117.

10. Hagenmaier, H., M. Kraft, H. Brunner, and R. Haag. "Catalytic Effects of Flyash from Waste Incineration Facilities on the Formation and Decomposition of Polychlorinated Dibenzo-p-dioxins and Polychlorinated Dibenzofurans." Environmental Science and Technology, November 1987, Volume 21, No. 11, pp.1080-1084.

11. Vogg, H. and L. Stieglitz. Chemosphere. 1986. Volume 15, p.1373.

12. Milligan, G. W. "An Examination of the Effect of Six Types of Error Perturbation of Fifteen Clustering Algorithms" Psychometrika, 1980, 45, pp.325-342.

13. Milligan, G. W. "A Review of Monte Carlo Tests of Cluster Analysis," Multivariate Behavioral Research, 1981, 16, pp.379-407.

14. Roeck, D. R. and R. Dennis. Technology Assessment Report for Industrial Boiler Applications: Particulate Collection. EPA-600/7-79-178h. Prepared for the U. S. Environmental Protection Agency. December 1979. p.29.

15. Reference 13, p.34.

# Section 8

# DESCRIPTION OF SAMPLING AND ANALYTICAL METHODS

The manual and continuous gas sampling methods which were used during this program to obtain flue gas samples and characterize incinerator operating conditions are described in this section. Manual gas sampling methods were used to: 1) obtain flue gas samples at the secondary chamber exit, ESP inlet and ESP outlet for CDD, CDF, and precursor analyses, 2) determine HCl concentrations in the flue gas at the secondary chamber exit, ESP inlet and ESP outlet, and 3) determine particulate matter concentrations in the flue gas at the ESP inlet and outlet. Manual methods were also used to measure the flue gas velocity, volumetric flow, and moisture content at all three sampling locations and to obtain flue gas samples for molecular weight determination. Continuous sampling was conducted to determine flue gas CO, $CO_2$, $O_2$, $SO_2$, and $NO_x$ concentrations at the secondary chamber exit and ESP outlet. In addition, moisture, THC, and temperature were monitored continuously at the secondary chamber exit. The sampling and analytical methods are described below.

## FLUE GAS CDD AND CDF DETERMINATION

Manual flue gas sampling for CDD and CDF was conducted according to the latest draft of the ASME chlorinated organic compound sampling protocol with several modifications. Necessary changes to the protocol that were implemented for this program are discussed in the appropriate sections below.

The ASME sampling method is a modified version of EPA Method 5 (MM5) that includes a solid sorbent module (XAD) for trapping vapor phase organics. The protocol was modified to include: 1) the use of a horizontal condenser and 2) the use of methylene chloride and acetone for final recovery of CDD and CDF. These deviations have been approved by both EPA and NYSDEC and have been used in the National Dioxin Study Tier 4 program conducted for the EPA and a joint test at the Westchester Resco facility which involved NYSDEC and the EPA's Office of Solid Waste. The horizontal condenser was used because it lowers the profile of the train and reduces breakage; the XAD trap following the condenser is maintained in a vertical position. No problems of channeling have been noted. In one of the Tier 4 test series, a backup XAD trap was used to determine if any breakthrough occurred due to the horizontal condenser, however, no CDD or CDF was detected in the second trap. Methylene chloride was substituted because it has been shown to be a better solvent for recovery of the higher molecular weight dioxins and is an acceptable solvent for EPA, NYSDEC, and Environment Canada NITEP tests.

The samples were collected isokinetically over a 3- to 4-hour test period (about one hour was devoted to switching ports and leakchecking the sampling train). Following sample recovery, the various parts of the sample (e.g., filter, solvent rinses, sorbent trap, etc.) were sent to HRI to quantify the 2,3,7,8-TCDD, 2,3,7,8-TCDF, mono- through octa-chlorinated CDD and CDF homologues, and target precursors present in the samples. The sampling rate was set at each sampling location to provide a minimum sample volume of 120 scfm. This sample is sufficient to allow detection of 1 part per trillion (ppt) of 2,3,7,8-TCDD in the flue gas at a minimum detection limit of 400 pg per resolvable peak.

The MM5 samples were collected simultaneously at the ESP inlet and outlet. Both trains were started at the same time, and sampling was interrupted if either train had to be stopped for port changes or filter replacement. The MM5 samples at the secondary chamber exit were collected concurrently with the ESP inlet and outlet MM5 samples, but sampling was not necessarily interrupted every time sampling at the other two locations was stopped. However, sampling at the secondary chamber exit was started at the same time as the ESP inlet and outlet tests, and was interrupted if extended shutdowns were expected. While the samples at the three locations were not collected on an exactly simultaneous basis, the time differences should not significantly affect the results or conclusions.

### Sampling Train Description

A schematic diagram of a typical MM5 CDD and CDF sampling train is shown in Figure 8-1. Flue gas is pulled from the stack through a stainless steel nozzle and glass-lined probe. Particulate matter is removed from the gas stream by means of a cyclone (for high particulate loading) followed by a glass fiber filter housed in a Teflon-sealed glass filter holder maintained at 248 ± 25°F. The filter holder contains a Teflon-coated stainless steel frit to support the filter. The gas passes through a sorbent trap for removal of organic constituents. The trap, which is illustrated in Figure 8-2, consists of separate sections for: 1) cooling the gas stream, and 2) adsorbing the organic compounds on Amberlite $XAD_2^R$ resin (XAD). A chilled impinger train is used to remove water from the flue gas and a dry gas meter is used to measure the sample gas flow.

Due to the high flue gas temperature at the secondary chamber exit sampling location, a water-cooled probe was required.

### Filter and XAD Preparation

Radian and the NYSDEC each prepared the glass fiber filters used at their respective sampling locations and the NYSDOH prepared and loaded the resin into the traps. The procedures outlined in the ASME protocol were followed. Filter preparation involved hexane extractions of the Whatman 934 AH filters.

### Glassware Preparation

All glass parts of the MM5 sampling train, including the sorbent tube, were precleaned prior to sampling according to the procedure listed in Table 8-1. Cleaned glassware was capped with precleaned foil or glass plugs until sample train assembly in the field. Following sample recovery, the glassware was reused at the same sampling location. Sealing greases were not used on the sample train.

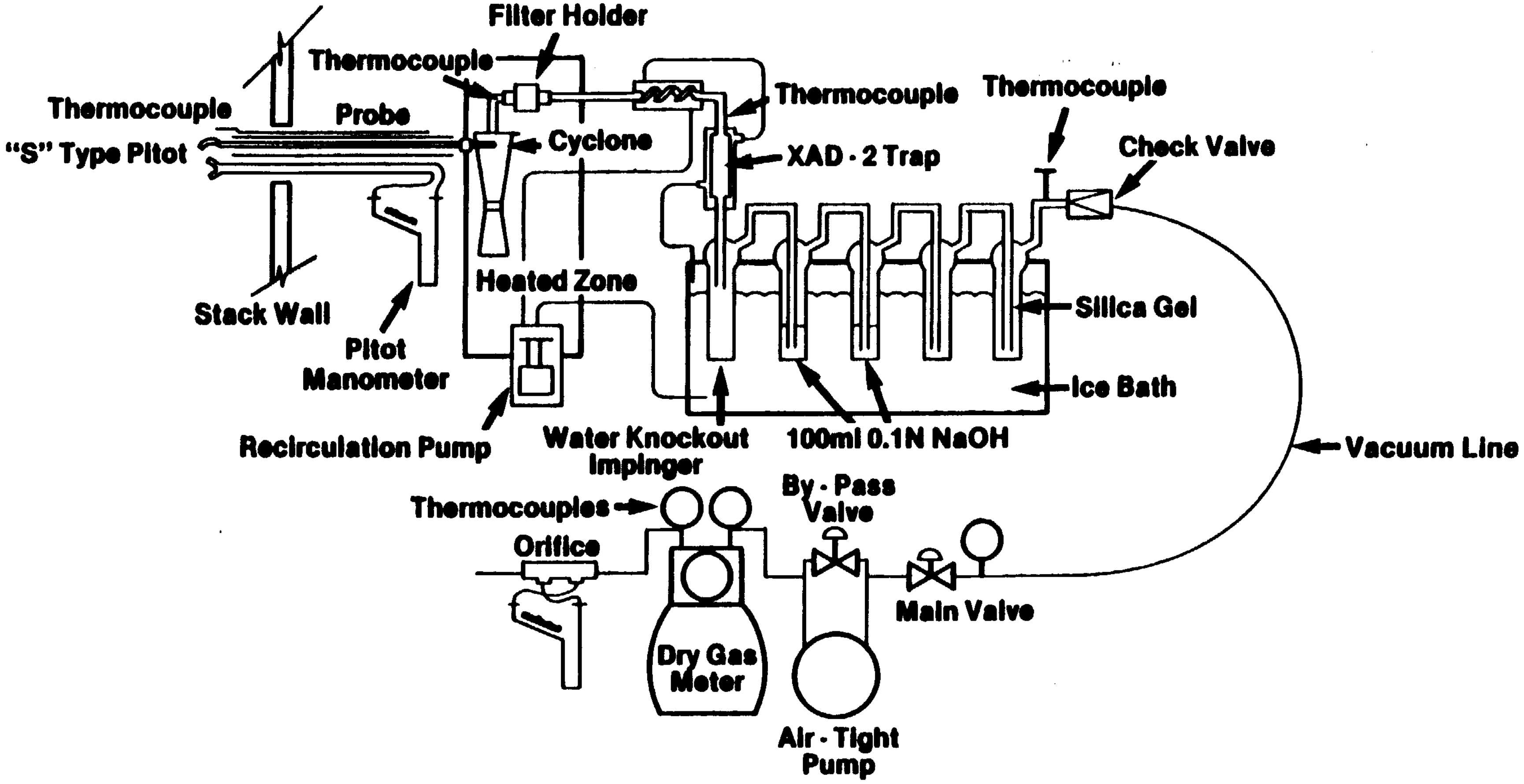
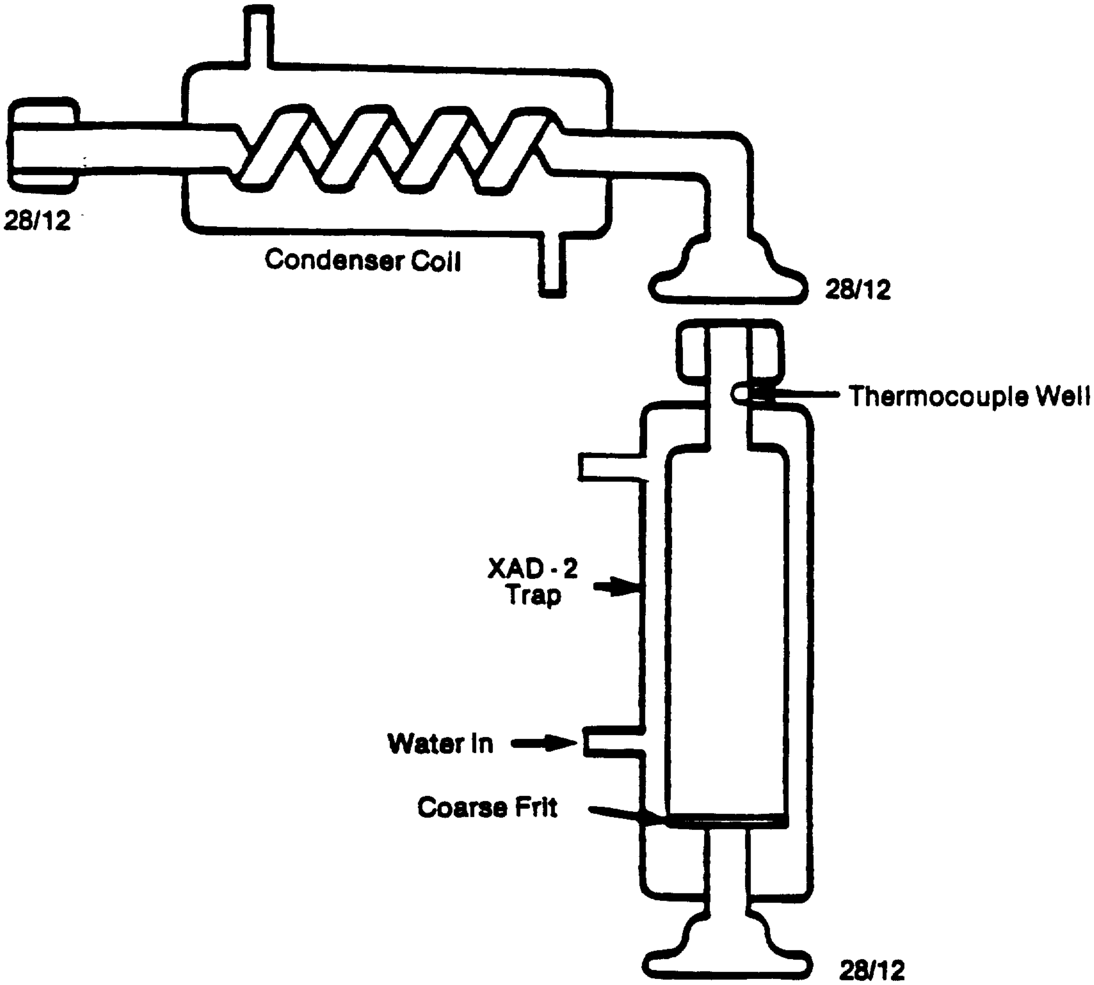


Figure 8-1. Modified Method 5 Train for CDD and CDF Sampling



XAD-2 Trap and Condenser Coil

Figure 8-2. Sorbent Trap Schematic

## Table 8-1

## GLASSWARE PRECLEANING PROCEDURE

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1. Soak all glassware in hot soapy water (Alconox) 50°C or higher.
2. $H_2O$ rinse (X3).[a]
3. Distilled/deionized $H_2O$ rinse (X3).
4. Heat at 550°F for 2 hours.
5. Distilled/deionized $H_2O$ rinse (X3).
6. Acetone rinse (pesticide grade) (X3).
7. Methylene chloride rinse (pesticide grade) (X3).
8. Oven dry at 110°F for 2 hours.
9. Cap glassware with clean glass plugs or hexane-rinsed aluminum foil.

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[a] (X3) = three times

Note: Use disposable gloves and adequate ventilation.

## Sample Train Operation

The sampling trains were operated according to the ASME protocol. Special attention was given to the following QC checks:

- The entire sample train was leakchecked to ensure that leakage did not exceed the lesser of: a) 4 percent of the average sampling rate, or b) 0.02 acfm.
- The probe exit and filter holder temperature were maintained at 248 ± 25°F during sampling. The probe temperature at the secondary chamber exit was regulated to some extent by controlling the cooling water flow. However, fine control was not possible due to the large temperature differential between the flue gas and ambient.
- Gas entering the sorbent module was maintained at or below 68°F.
- Isokinetic sampling was maintained within ±10 percent of actual flow.
- Stored resin was kept below 120°F at all times.
- The sampling train was leakchecked prior to the start of each run, after any shutdown, before every startup and at the end of the test. Sampling did not start until an acceptable leakcheck was attained.

## Sample Recovery

Recovery of the MM5 samples and assembly of the sampling trains were conducted in a mobile laboratory that was free from uncontrolled dust. Access to this area was limited to only those individuals involved in the recovery process.

Sample containers from a typical MM5 test run at the secondary chamber exit include those shown in Table 8-2. All CDD and CDF sample containers containing water were extracted for analysis by the designated lab within 7 to 14 days after sample collection. It should be noted that depending on the particulate loading and/or flue gas moisture content, the actual number of containers from each sample run varied. The need for three or more filters (and corresponding additional solvent rinses) was not unusual due to the high particulate loadings at the secondary chamber exit and ESP inlet.

## Table 8-2

## TYPICAL MM5 SAMPLING TRAIN COMPONENTS SHIPPED TO ANALYTICAL LABORATORY

| Container | Component |
|---|---|
| Component Number 1 | Filter(s) |
| Component Number 2 | Rinses[a] of nozzle, probe, transfer line (if used), cyclone (if used), and front half of filter holder |
| Component Number 3 | Rinses of back half of filter holder, condenser rinse, and water knockout trap (optional) |
| Component Number 4 | First impinger contents and rinse |
| Component Number 5 | Second, third and fourth impinger contents and rinses |
| Component Number 6, Sorbent Module | XAD-2 resin |

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[a] Rinses include acetone and methylene chloride combined in same container.

The solvents used for rinsing the nozzle, probe, filter holder, and cyclone (if used) included acetone and methylene chloride. The change from hexane as specified in the ASME protocol to methylene chloride was made to improve recovery of higher molecular weight (penta through octa) CDD and CDF homologues.

### Sample Train Blanks

Field blanks and laboratory proof blanks were recovered for each of the four operating conditions at the secondary chamber exit. Field blanks consisted of three portions of a sample train (impingers/sorbent trap, filter holder and probe) which were assembled at the sampling location as though to collect a sample, but flue gas was not pulled through the train. The train was then disassembled (into three portions) and returned to the mobile laboratory for recovery using the same procedure used to recover actual samples. The field blank was obtained using a train that had previously been used to collect at least one actual sample at each of the operating conditions from the test site.

Laboratory proof blanks were also obtained. Proof blanks were obtained from a complete set of MM5 sampling train glassware that had been cleaned according to the procedure presented in Table 8-1. The precleaned glassware, which consists of a probe liner, filter holder, condenser coil and impinger set, was rinsed with acetone and methylene chloride three times each. A proof blank was obtained before each test condition. Analysis of the rinse was used to check the effectiveness of the glassware cleaning procedure. Glassware used at a previous incinerator operating condition was cleaned with acetone and methylene chloride before use during a subsequent incinerator operating condition. Blanks of each solvent lot used at the test site were also saved for potential analysis.

### Sample Analysis

The recovered sample fractions were packed in appropriate shipping containers and transported by the NYSDEC to Albany, New York, for analysis by HRI. The samples were analyzed by the ASME/EPA/DOH Environmental Standards Workshop (October 1986 draft) protocol using high resolution gas chromatography followed by low resolution mass spectrometry (GC/MS).

## HCl DETERMINATION

HCl concentrations were determined by modifying the back half (after the $XAD_2$ resin trap) of the MM5 sampling train. For determining HCl concentrations, the following modifications were made to the MM5 train:

- Water in the first two impingers was replaced with 0.1 N NaOH.
- The recovered moisture and the NaOH in the impingers was saved for laboratory analysis by HRI.
- A portion of the NaOH solution was saved for blank analysis.

Aliquots of the recovered moisture and NaOH in the impingers were analyzed for chloride by ion chromatography.

## PARTICULATE GRAIN LOADING

Particulate sampling followed the procedures specified in EPA Reference Method 5. The sampling and analytical procedures are discussed in the following sections.

### Sampling Train Description

A schematic diagram of an EPA Method 5 sampling train is shown in Figure 8-3. Based on this method, a sample of the particulate-laden flue gas is extracted isokinetically from the stack using a stainless steel buttonhook nozzle and a glass probe. The particulate matter is removed from the gas by means of a glass fiber filter maintained at a temperature in the range of $248 \pm 25^{\circ}F$. A chilled impinger train is used to remove water from the flue gas. A pump and dry gas meter are used to control and monitor the gas flowrate.

### Sample Preparation

Method 5 requires that sample train glassware be cleaned with soap and water and dried with acetone to minimize particulates in the glassware. The

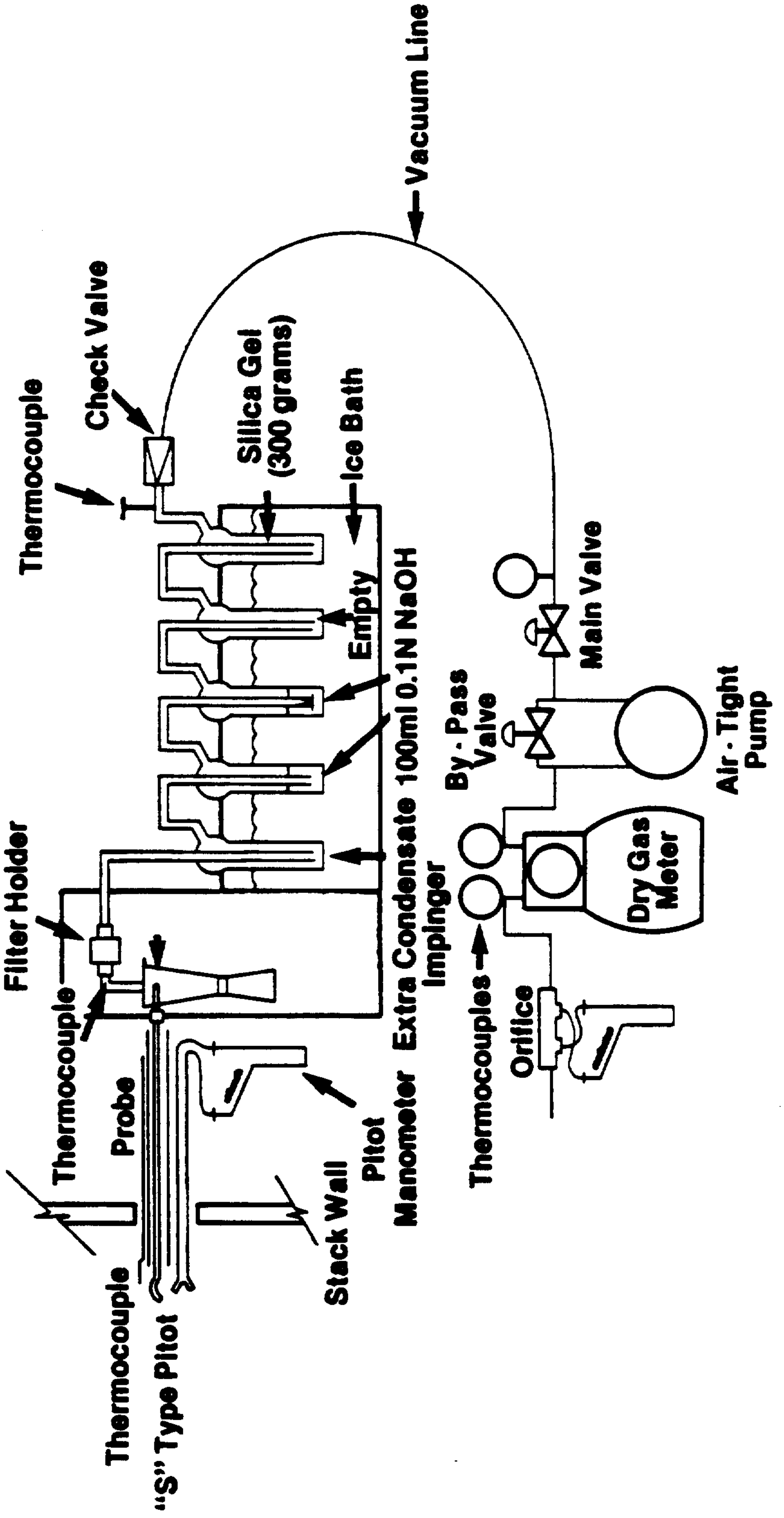

Figure 8-3. Method 5 Sampling Train

remaining preparation included calibration and leakchecking of all the train equipment including: meter boxes, thermocouples, nozzles, pitot tubes, and umbilicals.

### Sample Train Operation

Train leakrate determination, traversing, sampling time, and sampling rate were the same as described for the CDD and CDF trains.

### Sample Recovery and Analysis

To facilitate transfer from the sampling locations to the recovery area, the sampling train was disassembled into three sections: the probe with liner, the filter holder, and the impingers in their bucket. Each section was capped before removal to the recovery area. The sample fractions were recovered by rinsing the probe, cyclone, and front half of the filter housing with acetone. The filter was sealed in a petri dish. The acetone rinses were stored in amber glass bottles. The particulate weights were determined gravimetrically by the NYSDEC.

## VOLUMETRIC GAS FLOWRATE DETERMINATION

The volumetric gas flowrate was determined during this program using procedures described in EPA Method 2. Based on this method, the volumetric gas flowrate is determined by measuring the cross-sectional area of the duct and average velocity of the flue gas.

The average flue gas flowrate was calculated from the average gas velocity, pressure ($\Delta P$), temperature, wet molecular weight, and the absolute static pressure. Twenty-four traverse points were used to measure the average gas velocity at the secondary chamber exit and ESP inlet; 12 traverse points were used at the ESP outlet.

The velocity, pressure and temperature profile data were measured at each of the sampling points using S-type pitot tubes and K-type thermocouples. Inclined oil manometers of the proper range were used to measure the pressure drop ($\Delta P$) across the S-type pitots. A mercury or calibrated aneroid barometer was used to obtain barometric pressure readings at least twice a day. The static gas pressure was measured by disconnecting one side of the S-type pitot and then rotating the pitot so that it was perpendicular to the gas flow.

## FLUE GAS MOISTURE DETERMINATION

The moisture content of the flue gas was determined using the methodology described in EPA Method 4. Based on this method, a known volume of particulate-free gas is pulled through a chilled impinger train. The quantity of condensed water is determined gravimetrically and then related to the volume of gas sampled to determine the moisture content. During this project, the moisture content of the flue gas was determined during the operation of the MM5 and the M5 sampling trains.

## FLUE GAS MOLECULAR WEIGHT DETERMINATION

During CDD and CDF sampling at the secondary chamber exit, the integrated sampling technique described in EPA Method 3 was used to obtain a composite flue gas sample for fixed gas ($O_2$, $CO_2$) analysis. A small diaphragm pump and a stainless steel probe were used to extract a single point flue gas sample which was collected in a Tedlar bag. Moisture was removed from the gas sample by a water-cooled condenser so that the fixed gas analysis was on a dry basis. Fyrite$^R$ analyzers were used to determine the $CO_2$ and $O_2$ concentrations in the flue gas; nitrogen was determined by difference.

## CONTINUOUS GAS SAMPLING AND ANALYSIS PROCEDURES

Continuous monitoring for a number of flue gas parameters was conducted at the secondary chamber exit and ESP outlet. Carbon monoxide, carbon dioxide, oxygen, nitrogen oxides, sulfur dioxide, total hydrocarbons, flue gas moisture, and temperature, were monitored at the secondary chamber exit upstream of the manual MM5 sampling location. Carbon monoxide, carbon dioxide, oxygen, nitrogen oxides, and sulfur dioxide were monitored at the ESP outlet.

Continuous monitoring was performed throughout the 3- to 4-hour period that CDD and CDF sampling was conducted each test day. The primary intent of the continuous monitoring effort was to: 1) observe fluctuations in flue gas parameters, and 2) provide a measure of combustion conditions. While the continuous monitors were calibrated daily, no attempt was made to certify the monitors or monitoring locations through relative accuracy tests with EPA reference methods.

## PROCESS DATA

Process data were recorded continuously throughout each approximately 3 to 4-hour CDD and CDF sampling period. The parameters, shown in Table 8-3, included: incinerator charge rates, key incinerator temperatures, boiler steam flow, temperature and pressure, incinerator draft pressure, boiler differential pressure, and quench air flow and $\Delta$P.

Primary and secondary chamber temperatures were also recorded manually by Radian every 10 minutes (5 minutes for Run 1) throughout each test run to check the plant's instrumentation. In addition, the feed time, feed size, and operating ram (#1 and #2 transfer rams and loader ram) times were recorded for each feed cycle (approximately once every 6 to 7 minutes). The frequency of ash ram operation (approximately once every 40 minutes) was also recorded. Copies of process control system chart records for steam production, incinerator temperatures, and plant $O_2$ and CO were also collected.

## ASH SAMPLING

Incinerator bottom ash was sampled for each test run to determine ash burnout. The ash was sampled each time the ash ram operated (approximately every 40 minutes). The samples were then composited to provide a single daily sample. The bottom ash was sampled through the railing as the ash fell from the quench tank conveyor into a dedicated ash truck. The amount of ash collected in each grab was about 1/4 of a bucket (about two half-shovel loads) and processed into a composite sample. Crushing or grinding equipment was not used in the field, but each ash sample was well mixed. The samples were analyzed for loss-on-ignition by ASTM Methods D3173-73 and E830-81.

## Table 8-3

## KEY PROCESS PARAMETERS CONTINUOUSLY MONITORED

| Parameter | Location/Measurement |
|---|---|
| Temperature | Primary Chamber |
| | Secondary Chamber |
| | Boiler Inlet |
| | Boiler Outlet |
| | Quench Air[a] |
| Pressure | Primary Combustion Air |
| | Secondary Combustion Air |
| | Boiler Differential |
| | Incinerator Draft |
| | Quench Flow and P[a] |
| Load Indicators | Feed Charge Stroke Relay |
| | Grate Stroke Relay |
| | Charge Size Indicators |

[a] Quench air was not used during any of the testing periods.

ESP dust was sampled by collecting the entire ash stream produced during the CDD and CDF tests at the screw conveyor outfall to the quench tank. The total weight of ESP dust produced during the run was measured and then discarded.

## REFUSE SAMPLING

During each test run, the refuse charged to the incinerator was characterized by collecting and sorting a random loader charge of refuse. The sample loads were sorted into several categories including: metal/glass, wood, paper, plastic, cloth, miscellaneous combustibles (e.g., small pieces of paper, wood, etc.) and miscellaneous noncombustibles (e.g., dirt, etc.). Each fraction was weighed and the results were recorded. The noncombustibles (e.g., metals, glass, dirt, etc.) and other items that could not be shredded or processed into a laboratory sample were removed. Notations were made on sampling and weight record sheets when significant fractions of potential dioxin-containing wastes were not included in the fraction that was processed for analysis. However, no significant items were observed.

The remaining components, (i.e., plastics, paper, and other household wastes) were shredded several times to provide a representative, homogeneous sample and sent to HRI for CDD, CDF and precursor analysis.