**FINAL REPORT CONSOLIDATED INCINERATION FACILITY
METALS PARTITIONING TEST (U)**

by
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**SAVANNAH RIVER SITE
SAVANNAH RIVER TECHNOLOGY CENTER**

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**FINAL REPORT:
CONSOLIDATED INCINERATION FACILITY METALS
PARTITIONING TEST (U)**

by

Dan B. Burns

August 31, 1993

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SUMMARY

Test burns were conducted at Energy and Environmental Research Corporation's rotary kiln simulator, the Solid Waste Incineration Test Facility, using surrogate CIF wastes spiked with hazardous metals and organics. The primary objective for this test program was measuring heavy metals partition between the kiln bottom ash, scrubber blowdown solution, and incinerator stack gas. Also, these secondary waste streams were characterized to determine waste treatment requirements prior to final disposal.

These tests were designed to investigate the effect of several parameters on metals partitioning.

- Incineration Temperature
- Waste Chloride Concentration
- Waste Form (solid or liquid)
- Chloride Concentration in the Scrubber Water

Tests were conducted at three kiln operating temperatures. Three waste simulants were burned, two solid waste mixtures (paper, plastic, latex, and one with and one without PVC), and a liquid waste mixture (containing benzene and chlorobenzene). Toxic organic and metal compounds were spiked into the simulated wastes to evaluate their fate under various combustion conditions. Kiln offgases were sampled for volatile organic compounds (VOC), semi-volatile organic compounds (SVOC), polychlorinated dibenzo[p]dioxins and polychlorinated dibenzofurans (PCDD/PCDF), metals, particulate loading and size distribution, HCl, and combustion products. Stack gas sampling was performed to determine scrubber capture efficiency for both metals and particulates. Kiln bottom ash and offgas scrubber blowdown were characterized to determine additional treatment requirements prior to final waste disposal.

Significant test results are summarized below.

Metals Partitioning

Mercury was the most volatile metal tested. No mercury remained in the kiln bottom ash, and the split between the blowdown and stack gas was dependent upon incineration conditions.

Lead, cadmium, thallium, and silver exhibited semi-volatile behavior. These metals partitioned between the kiln ash, blowdown, and stack gas with ratios dependent upon incineration conditions.

Chromium, nickel, barium, antimony, and arsenic exhibited nonvolatile behavior at incineration temperatures. Greater than 90 wt% of the metal remained in the kiln bottom ash for all test conditions.

Incineration temperature had a significant effect on volatile and semi-volatile metals partition, and no effect on nonvolatile metals partition. As incineration temperatures were increased, the fraction of volatile and semi-volatile metals leaving the kiln increased.

Three metals tested, lead, cadmium, and mercury showed a relationship between chloride concentration in the waste and metals partition. Increasing the waste chloride concentration resulted in a larger metal fraction in the kiln offgas and stack offgas.

Feeding the metals to the kiln in liquid form versus solid form resulted in an increase of metals partition to both the blowdown and stack gas for all metals.

Organics Destruction

The spiked principal organic hazardous constituents (POHCs) destruction and removal efficiency (DRE) was greater than 99.99998, independent of waste type or incineration temperature. The liquid waste (95% benzene) was burned without detectable benzene levels in the incinerator offgas. The high chloride solid waste produced the largest concentrations and numbers of both VOCs and SVOCs. Detected VOCs included chloromethane, chloroform, carbon tetrachloride, benzene, toluene, and xylene. Detected SVOCs included benzyl alcohol and polyaromatic hydrocarbons (PAHs) such as naphthalene, fluorene, and pyrene.

Scrubber Particulate Capture Efficiency

Hydrosonic scrubber particulate capture efficiencies were less than 80%. Reasons for this performance include the large particulate fraction less than one micron, the low particulate concentration in the incinerator offgas, and scrubber operating parameters were not optimized for these conditions. Although particulate collection efficiencies were low, the maximum particulate concentration in the stack gas was 0.058 gr/dscf.

INTRODUCTION

In 1996, the Savannah River Site plans to begin operation of the Consolidated Incineration Facility (CIF) to treat solid and liquid RCRA hazardous, and mixed wastes. The CIF will utilize a 13 million Btu rotary kiln incinerator and 5 million Btu secondary combustion chamber to treat both solid and liquid combustible waste. The air pollution control (APC) system consists of a liquid recirculating quench and steam-atomized scrubber for offgas cooling/cleaning, a cyclone separator and mist eliminator for liquid/gas separation, and final HEPA filtration prior to atmospheric discharge through the facility stack.

The CIF will treat wastes that contain hazardous heavy metals regulated by RCRA. Thus, all secondary waste (kiln ash and scrubber blowdown) and facility stack emissions must comply with all RCRA regulatory requirements. Currently, heavy metals behavior in thermal treatment systems is a primary area of interest in hazardous waste incineration. Of specific interest to the CIF is waste feed metals partition to the three facility output streams, kiln bottom ash, scrubber blowdown, and the stack gas. Hazardous metals concentrations in the bottom ash and blowdown must be known to insure successful secondary waste treatment prior to final disposal. Kiln bottom ash will be solidified in portland cement prior and placed in onsite mixed waste burial

vaults. This wasteform must pass strict leaching tests (Toxicity Characteristic Leaching Procedure, TCLP) before placement in the burial vault. Typical and worst case ash compositions must be known to determine formulations that will pass TCLP. The scrubber blowdown must also be treated for permanent disposal. Blowdown treatment process development is ongoing, and accurate waste compositions are required to develop a successful process.

To provide the required information for successful secondary waste treatment, test burns were conducted in a pilot scale rotary kiln incinerator equipped with a wet offgas scrubber. The test objectives are listed below.

- Characterize metals partition between kiln bottom ash, scrubber blowdown, and stack gas.
- Measure Destruction and Removal Efficiency (DRE) for CIF Principal Organic Hazardous Constituents (POHCs).
- Measure kiln chloride emissions.
- Collect kiln bottom ash and scrubber blowdown for characterization and future treatment tests.

Three simulated waste mixtures were used in this test program. Wastes were incinerated at both the CIF design operating temperatures and two planned trial burn temperatures. Toxic organics and heavy metals were added to the waste mixtures to determine their fate under the various test conditions.

EXPERIMENTAL TEST FACILITY

EQUIPMENT

All testing was conducted at the Energy and Environmental Research's (EER) Santa Ana test site known as the EER Solid Waste Incineration Test Facility (SWIFT). This test facility was selected because an existing SRTC pilot-scale scrubber, prototypic of the CIF offgas scrubber, could be added to the SWIFT to simulate CIF air pollution control system (APCS) performance. A schematic of the SWIFT, with sampling locations, is presented in Figure 1. The primary combustion chamber (PCC) has a 30" ID by 24" long rotary section for solids treatment. PCC offgas passes through a secondary combustion chamber (SCC) before entering the offgas system. The SWIFT uses natural gas burners in both the PCC and SCC. The PCC has an Eclipse 82 MVTA burner with a 450,000 Btu/hr capacity. The SCC has an Eclipse 51.5 MVTA burner with a 150,000 Btu/hr capacity. The system is operated under negative pressure maintained by an induced draft fan which discharges to the facility stack.

FIGURE 1
Solid Waste Incineration Test Facility (SWIFT)

Solid waste is charged to the kiln manually through a refractory gate. The gate is opened to allow a bucket containing the waste feed to enter the kiln and deposit the waste in the center of the rotating section. After the waste is dropped into the kiln, the bucket is withdrawn and the refractory gate closed. The entire procedure takes approximately five seconds. A removable plug in the kiln barrel allows access for cleaning and ash removal. Ash can be removed from the kiln only when the system is shut-down.

High Btu organic liquid waste was burned in the kiln by a vortex burner designed, fabricated, and installed by EER. The burner replaced the 82 MVTA natural gas burner in the PCC during liquid waste incineration. The hazardous metals solution was injected directly into the center of the PCC through a water-cooled atomization nozzle for the liquid waste tests. No solids were burned during the liquid waste tests, thus the kiln was held stationary.

To simulate the CIF system, SRTC provided a Model 20 Hydro-Sonic air-atomized scrubber and cyclone separator APCS. Before entering the scrubber, hot combustion gases were cooled below the adiabatic saturation temperature (180°F) by a single nozzle counter-current flow quench in the duct leading to the scrubber. Both scrubber and quench liquids were fed from a single 55 gallon polyethylene drum, which also served as a blowdown shipping container at the conclusion of each test run.

INSTRUMENTATION

The SWIFT was equipped with numerous temperature, pressure, and flow instruments. Waukeec flowmeters and standard rotameters were used to measure the flow of natural gas, air, and supplemental oxygen to PCC and SCC burners. A rotameter was used for measurement of both liquid waste and metals solution flows during liquid waste tests. PCC pressure was measured and controlled by a damper on the facility ID fan. The facility was equipped with thermocouples to measure gas temperatures at the PCC and SCC exit and scrubber inlet. Thermocouples were also embedded in the PCC refractory to monitor kiln wall temperature. One thermocouple extended through the wall to contact the ash bed once with each kiln revolution to measure kiln bed temperature.

In addition to temperature, pressure, and flow instruments, the SWIFT was equipped with an offgas continuous emissions monitoring system (CEMS). The CEMS measures dry volume percents of O₂, CO₂, NO_x, CO, and SO₂. Instrument readings were continuously recorded by strip charts. The CEMS was used to monitor both the PCC and SCC flue gases.

OFFGAS SAMPLING

Facility offgas was sampled upstream of the scrubber to measure uncontrolled emissions of the following:

- volatile organics
- semivolatile organics
- polynuclear aromatic hydrocarbons (PAH)

- polychlorinated dioxins and furans (PCDD/PCDF)
- heavy metals
- particulate loading and size distribution
- HCl

Stack gas samples were taken downstream of the scrubber to measure controlled emissions of:

- particulate loading
- heavy metals

Offgas sampling was conducted using manual sampling methods developed by the EPA. Specific equipment, sampling, and analytical methodology are dependent on the emission species of interest. All methods employed a basic EPA Method 5 sampling train. The flue gas sample was drawn isokinetically through a nozzle and heated probe. Downstream of the probe was a heated filter to collect noncondensable particulate. The filter assembly was followed by a series of chilled impingers for water vapor and condensable material collection. Following the impingers was a metering system to measure sample gas flow, and a pump. Methods and procedures used for each emission species are listed in Table 1.

TABLE 1
Summary of Analytical Procedures

Sample Train	Analyte	Analytical Technique	Reference Procedure
MM5 Organic	PCDD/PCDF	HRGC/MS	EPA Method 23
MM5 Organic	SV Organics	GC/MS	EPA SW846 M8270
MM5 Organic	PAH	HRGC/MS	CARB 429
VOST	Volatile Organics	GC/MS	EPA SW846 M8240
HCl	HCl	Ion Chromatography	EPA Method 26
Metals/Particulates	Particulates	Gravimetric	EPA Method 5
Metals/Particulates	Sb, Ba, Be, Cd	ICAP	EPA SW846 M6010
Metals/Particulates	Cr, Pb, Ni, Ag	ICAP	EPA SW846 M6010
Metals/Particulates	As, Hg, Se, Ti	AA	EPA SW846 M7470
Cascade Impactor	Particle Size	Gravimetric/PADRE	EPA 600/2-77-004

EXPERIMENTAL PLAN

The test plan (Table 2) contained nine runs using three waste types and three operating conditions. All tests were conducted with simulated waste mixes. The three waste compositions are presented in Table 3. Two waste types, E and F, represent typical SRS combustible wastes. The difference between Type E and F wastes was the PVC concentration in the mix, which is known to significantly effect metals volatility. Type E waste contained 10 wt% PVC and Type F

waste contained no PVC. Type G waste simulated typical high Btu liquid organic waste. This waste contained benzene and chlorobenzene.

TABLE 2
Metals Partitioning Test Plan

Run	Waste Type	PCC Temperature (°F)	SCC Temperature (°F)	Salt in Scrubber Water
1	E	1832	2012	Y
2	E	1832	2012	Y
3	E	1832	2012	N
4	F	1832	2012	N
5	E	1600	1800	Y
6	F	1600	1800	Y
7	G	1832	2012	Y
8	G	1600	1800	Y
9	E	1400	1600	Y

TABLE 3
Simulated Waste Compositions (Wt %)

Component	Solid Waste Mix Waste Type E	No PVC Solid Waste Waste Type F	Liquid Waste Waste Type G
Paper [C ₆ H ₁₀ O ₂]	45	55	0
Polyethylene [C ₂ H ₂]	25	25	0
Latex [(C ₅ H ₈) ₂₃ S]	20	20	0
PVC [C ₂ H ₃ Cl]	10	0	0
Benzene [C ₆ H ₆]	0	0	95
Chlorobenzene [C ₆ H ₅ Cl]	0	0	5

To simulate the hazardous constituents in SRS waste, toxic metals and organics were spiked into the simulated waste feed. To evaluate organic destruction efficiency, two POHCs (Principal Organic Hazardous Constituents) planned for use in the CIF trial burn (hexachloroethane and hexachlorobenzene) were added to the solid waste at a concentration of 0.6 wt% each. Metals spiking solutions were prepared by mixing water soluble, nonchlorinated metal compounds with deionized water. Metals spiking solution preparation was complicated by the apparent interactions between some metal compounds which formed precipitates. These precipitates were acceptable (though not desirable) only in spiking the solid wastes (Types E and F). Antimony, arsenic, and barium were eliminated from the metals spike for the liquid waste tests (Type G) to prevent precipitation. The metals solution was added directly to the solid waste. For the liquid waste tests, the metals solution was injected directly into the PCC flame zone through an

atomizing nozzle. The average metals concentrations for both solid and liquid waste are presented in Table 4. Target metals concentrations were based on the CIF RCRA permit limits.

TABLE 4
Average Metals Concentrations in Waste Feed
(mg metal/kg waste feed)

Metal Compound	Solid Waste (Type E & F)	Liquid Waste (Type G)
Antimony, $C_4H_4KO_7Sb$	538	0
Arsenic, $Na_2HAsO_4 \cdot 7H_2O$	38	0
Barium, $Ba(C_2H_3O_2)_2 \cdot H_2O$	85,741	0
Cadmium, $Cd(NO_3)_2 \cdot 4H_2O$	9	10
Chromium, $Cr(NO_3)_3 \cdot 9H_2O$	1,860	2,267
Lead, $Pb(NO_3)_2$	7,426	9,114
Mercury, $Hg(NO_3)_2 \cdot H_2O$	446	542
Nickel, $Ni(NO_3)_2 \cdot 6H_2O$	7,297	8,963
Silver, $AgNO_3$	5,435	6,663
Thallium, $TlC_2H_3O_2$	545	663

Three temperature conditions were included in the test plan. The predominant temperature condition was the design flowsheet CIF operating temperatures (PCC = 1832°F; SCC = 2012°F). The other two temperatures (PCC = 1600°F; SCC = 1800°F and PCC = 1400°F; SCC = 1600°F) tested are planned operating temperatures for the CIF trial burn. Temperature is a variable of interest because metal volatility is a function of process temperature.

The remaining variable in the test matrix is NaCl in the scrubber water. Salt concentration in the quench and scrubber is an operating variable determining, in part, the waste blowdown quantity generated by CIF operation. The average NaCl concentration in the scrubber will be approximately 2 wt%. Several runs were conducted with 2 wt% NaCl in the scrubber solution. Two runs, 3 and 4, were conducted with no NaCl in the scrubber solution to determine if salt in the scrubber or quench solutions impacts metals partition or metal scrubbing efficiency.

EXPERIMENTAL TEST PROCEDURE

Prior to testing, the waste feed batch size and charge rate limits had to be determined. Test waste charges were fired in the SWIFT at each nominal test condition to establish these limits. The charge size limit was found to be 125 grams of solid waste plus an equal weight of water packed into a 28 gram cardboard box. The water helped to slow the burning, thereby allowing a larger charge size without causing oxygen deficit in the PCC during waste burning. The water was supplied by the metals spiking solution. Three minutes was found to be a sufficient burn time for each charge.

The basic procedure followed for conducting each run is outlined below:

1. Set facility operating conditions (temperature, pressure, flows, etc.)
2. Start CEMS recorders
3. Allow flue gas and incinerator wall temperature to reach steady state.
4. Begin sampling with manual sampling trains.
5. Wait one minute (to ensure proper operation of sampling trains).
6. Begin waste feeding.
7. Periodically record flue gas and solids temperature.
8. Record all test observations.
9. End of test.
 - Discontinue sampling with manual trains
 - Turn off burners
 - Recover ash residue as soon as possible (usually 10 minutes)
 - Recover scrubber blowdown in 55 gallon drum

RESULTS AND DISCUSSION

Test results fall into six areas of interest, metals partitioning between the kiln bottom ash, scrubber blowdown, and stack gas, offgas particulate characterization, HCl emissions, organics emissions, kiln bottom ash characterization, and scrubber blowdown characterization. Experimental results for each area is discussed in detail below.

Metals Partitioning

The primary test objective was determining waste feed heavy metals partition between the kiln bottom ash, scrubber blowdown, and stack gas. The impact of incineration temperature, waste chloride concentration, waste form, scrubber water chloride concentration, and offgas particulate concentration was measured. When subjected to incineration conditions, metal compounds in waste feed can either remain with the bottom ash, exit the kiln in a volatile form, or exit the kiln with entrained fly ash. Metal volatility can be determined for a given set of conditions by equilibrium analysis. The metal volatility temperature is the temperature at which the effective equilibrium vapor pressure of all species containing the metal is 10^{-6} atmospheres. This vapor pressure was selected because it represents a measurable amount of vaporization. The lower the volatility temperature, the more volatile the metal. Volatility temperatures, based on equilibrium calculations, have been successfully used to predict general trends in metals partitioning.² Table 5 presents the calculated volatility temperatures for all metals used in this study. Volatilized metals can condense on flue gas particulate after entering the APC system, where temperatures are considerably below average incinerator temperatures. This behavior has been observed to cause metals enrichment in the collected fly ash.³

TABLE 5
Metal Volatility Temperature⁴

Metal	Volatility Temp (°F)	Volatility Temp (°F) with chlorides present
Chromium	2935	2930
Nickel	2210	1280
Silver	1660	1160
Barium	1560	1660
Thallium	1330	280
Arsenic	1292	1292
Antimony	1220	1220
Lead	1160	5
Cadmium	417	417
Mercury	57	57

Ten metals were spiked into the waste feed for these tests: mercury, lead, cadmium, chromium, nickel, silver, arsenic, thallium, barium, and antimony. The average metal composition in each waste type is presented in Table 4. The actual waste compositions for each run is included in Appendix A. Partition factors were determined by measuring the metal concentration in the kiln bottom ash, scrubber blowdown, and stack gas generated during each test run. Since equipment configuration prevented recovery of all kiln bottom ash (preventing mass balance closure), a theoretical ash wt%, based on waste feed analyses, was used to calculate the total kiln ash mass generated in each run. The mass of ash entrained into the APCS (from offgas particulate sampling) was subtracted from the total theoretical ash mass to obtain the kiln bottom ash mass for each run. Since no solid waste was burned in runs 8 and 9, or any measurable ash recovered, partition for these runs is limited to the offgas blowdown and stack gas. The spreadsheet for calculating partition factors is included in Appendix B.

All metals partition data was normalized by the total mass balance closure achieved. Testing of this type typically has metals mass balance closures between 30 and 200 percent.¹ Mass balances for these tests are discussed in detail later in this section. Since perfect mass balance closures were not observed, it is difficult to interpret data presented as a percent-of-feed fractional distribution, since mass balance closure varied from run to run. Variable closure was removed from the data by normalizing with the total closure achieved. Therefore, data is presented in terms of metal percent measured in the outlet streams (ash, blowdown, and stack), instead of metal percent in the waste feed. Use of normalized distributions is the best method of quantifying metal partitioning, given the variable and less than perfect metals mass balance closure. The overall partition for each metal for all nine runs is shown in Figure 1.

Figure 1
Metals Partition

Mercury Discharge Distributions

Lead Discharge Distributions

Cadmium Discharge Distributions

Figure 1 (cont.)
Metals Partition

Chromium Discharge Distributions

Nickel Discharge Distributions

Silver Discharge Distributions

Figure 1 (cont.)
Metals Partition

Arsenic Discharge Distributions

Thallium Discharge Distributions

Barium Discharge Distributions

Figure 1 (cont.)
Metals Partition

The following general observations can be made from the charts in Figure 1. The metals divide into three general groups. The first group contains volatile metals. These metals completely volatilize from the kiln and enter the APCS. A fraction is removed by the APCS, and a fraction remains in the stack gas. Mercury was the only metal falling into this group with a volatility temperature less than 100°F. As expected, no mercury remained in the kiln bottom ash. All mercury vaporized, exited the kiln, passed through the APCS, and a fraction exited with the stack gas. This behavior is illustrated in the charts of Figure 1 and has been observed in other studies.³

The second group contains semi-volatile metals. Depending on incineration conditions, a fraction of the metal remains in the kiln bottom ash, while the remainder enters the APCS and is either captured by the scrubber or emitted with the stack gas. Lead, cadmium, thallium, and silver fall into this group. The metals volatility temperatures in the presence of chlorides range from 5 to 1160°F. Since all runs contained chloride, either in the PVC or the organic POHC spiked in the waste, the volatility temperature with chlorides present must be used.

The third group contains nonvolatile metals. The metals volatility at incineration temperatures is so low, metals concentration in the vapor phase is negligible, and all metal remains in the kiln ash. A small fraction of metal can be found in the blowdown due to particulate entrainment to the APCS. Chromium, nickel, barium, antimony, and arsenic are in this group. These metals calculated volatility temperatures are higher than the semi-volatile metals. Other studies have documented their relative nonvolatile behavior in the incineration environment.^{7,8}

These tests were designed to investigate the effect of several parameters on metals partitioning. These parameters include:

- Incineration Temperature
- Waste Chloride Concentration
- Waste Form (solid or liquid)

- Chloride Concentration in the Scrubber Water
- Offgas Particulate Concentration (total and submicron)

The effects of each parameter is discussed below.

Incineration Temperature

As expected, incineration temperature did have a significant effect on the partition of several metals. For these tests, both the primary combustion chamber (PCC) and secondary combustion chamber (SCC) were incremented together to match the two planned CIF trial burn conditions (PCC temperatures of 1400 and 1600°F) and the facility design operating temperature (PCC temperature of 1832°F). These tests did not investigate the PCC and SCC temperature effects separately, because previous studies demonstrated SCC temperature has minimal impact on metals partition.^{7,8} The PCC temperature effect was expected to be most pronounced for metals with a volatilization temperature near the kiln operating temperature. As kiln temperature increased, volatile metals concentration would be expected to increase, and a larger fraction of metal should exit the kiln to the offgas. The partition of metals with volatilization temperatures significantly above the kiln temperature should remain unchanged.

As expected, the semi-volatile metals partition was dependent on kiln temperature. Silver and lead showed the most significant relationship between kiln temperature and metal partition for solid waste. The plots in Figure 2 show increasing kiln temperatures caused a decrease in the metal fraction in the kiln ash. Mercury, cadmium, and thallium also exhibited a noticeable kiln temperature effect. Although the metal partition to the kiln ash remained relatively constant (and very low) as the kiln temperature increased, the metal fraction out the stack increased and the metal captured by the scrubber decreased (See Figure 3). The data indicates that lead was not as volatile as the theoretical volatility temperature would have predicted. At low PCC temperatures, significant fractions of lead and silver remained in the kiln ash. At higher PCC temperatures the metals fraction in the kiln ash was significantly reduced. Mercury, cadmium, and thallium volatility resulted in very low ash fractions at both high and low PCC temperatures. The increase in partition to the stack for all these metals is most likely due to increased submicron particle generation at higher PCC temperatures. Volatilized metals condense on offgas particulate in the APCS which are then removed by the offgas scrubber. The scrubber has a lower collection efficiency for submicron particles. Thus, an increase in the submicron particle fraction would be expected to cause an increase in semi-volatile metals stack emissions. Offgas particle size and concentration data will be discussed in detail later.

The temperature effect was even more pronounced for liquid waste. Since no kiln bottom ash was recovered during liquid waste incineration, all metals divided between the scrubber blowdown and stack gas. For every metal (except silver with 100% partition to the blowdown), the metal fraction in the stack gas increased 2X to 5X at the higher PCC temperature. This behavior is likely due to the increase in offgas submicron particulate generation at higher kiln temperatures (70% submicron at 1832°F and 54% submicron at 1600°F). Figure 4 illustrates the increase in metals partition to the stack gas for liquid waste incineration at different kiln temperatures.

Figure 2
Partition as Function of Incineration Temperature
For Less Volatile Metals

Figure 3
Partition as Function of Incineration Temperature
For More Volatile Metals

Figure 4
Liquid Waste Stack Gas Partition vs. Kiln Temperature

Waste Chloride Concentration

To investigate the impact waste chloride concentration has on metal partition, two solid waste types were burned. One type contained 10 wt% PVC (Waste Type E), the other contained 0 wt% PVC (Waste Type F). Both wastes contained the organic chloride containing POHCs. The chloride concentration in the waste with PVC was approximately 6 wt%, while the waste without PVC contained 1.5 wt% chloride. Incinerating metals bearing waste with chlorides can result in the formation of metal salt compounds, which usually have a lower volatilization temperature than the metal oxide or hydroxide. For example, silver will normally vaporize as silver metal (volatility temperature = 1660°F), yet in the presence of chlorides, silver chloride is the principal vapor species (volatility temperature = 1160°F). Table 5 compares metal volatilization temperatures both with and without chlorides. Metals with lower volatilization temperatures in the presence of chlorides would be expected to have a greater partition to the APCS while burning chloride containing wastes.

Test data clearly shows a chloride effect on metal partition for three spiked metals (lead, mercury, and cadmium). Four metals, nickel, silver, thallium, and lead have lower calculated volatility temperatures in the presence of chlorides. Thus, increasing waste chloride concentration should increase the metals partition to the offgas. Of these four, only lead had a significant chloride effect (Figure 5). The chloride effect for silver and thallium was not clearly discernible due to data scatter. The large drop in volatility temperature for thallium in the presence of chlorides would have predicted a significant dependence between chloride concentration and thallium partition, yet this was not observed. The plot in Figure 6 shows chloride concentration had little effect on metal thallium partition. The reason a chloride effect was not observed for nickel is the volatility temperature in the presence of chloride is still too high to allow measurable quantities of nickel to enter the offgas.

Two metals, cadmium and mercury, had significant chloride effects at high PCC temperatures, although chlorides did not change the calculated volatility temperatures. Plots for both metals are shown in Figure 7. This data indicates that volatile metal chloride compounds appear to be forming that are not included in the equilibrium code used to calculate the metal volatility temperature. At the lower PCC test temperature, the chloride effect was significantly reduced. Previous tests have demonstrated increased cadmium and lead volatility in the presence of chlorides and no chloride effect for chromium, arsenic, and barium.⁹

Figure 5
Lead Partition vs. Waste Chloride Concentration

Figure 6
Thallium Partition vs. Waste Chloride Concentration

Figure 7
Mercury and Cadmium Partition vs. Waste Chloride Concentration

Waste Form (Solid or Liquid)

Both solid and liquid wastes will be incinerated in the CIF. To determine the effect waste form has on metal partition, both liquid and solid simulated wastes were burned. The metals spiking solution was added inside the waste boxes for the solid waste tests. The metals spiking solution was injected into the PCC burner flame (through an atomizing nozzle) for the liquid waste tests. To permit accurate metals spiking solution metering during the liquid waste tests, a few metal compounds were omitted (antimony, arsenic, and barium) to prevent metal compound precipitation. The waste form effect on metal partition was found to differ for volatile/semi-

volatile metals and non-volatile metals. The effect of waste form on mercury partition, the only volatile metal tested, is shown in Figure 8. The liquid waste mercury partition was similar to the high chloride solid waste. The liquid waste chloride content was approximately equal to the low chloride solid waste (1.5 wt%). Thus, it can be seen that the stack gas mercury fraction significantly increased when burning liquid waste mercury versus solid waste containing mercury.

Figure 8
Mercury Partition vs. Waste Form

The semi-volatile metals tested include lead, cadmium, and thallium. For these metals, the metal fraction in the stack gas increased when liquid waste was burned. The partition changed from 20-30% metal in the stack gas to approximately 50% stack gas partition when incinerating liquid waste. The balance of the metal was found in the scrubber blowdown since no ash remained in the kiln after liquid waste incineration. Figure 9 contains a representative plot showing the effect of waste form on semi-volatile metals.

Figure 9
Semi-Volatile Metals Partition vs. Waste Form

Nickel and chromium were the only non-volatile metals in the simulated liquid waste. Greater than 90% of the metal remained in the kiln bottom ash when solid waste was burned, yet 70-80% of the metal partitioned to the scrubber blowdown when liquid waste was burned. The balance of the metal exited with the stack gas. Figure 10 contains a representative plot showing the effect of waste form on non-volatile metals

Figure 10
Non-Volatile Metals Partition vs. Waste Form

Chloride Concentration in the Scrubber Water

The CIF will use a steam-atomized scrubber to remove particulates, acid gases, and metals from the kiln offgas. Scrubbed acid gas (primarily HCl) accumulation will cause the recirculating scrubber solution pH to decrease. Sodium hydroxide will be added to maintain a neutral pH scrubber solution. The neutralization reaction will cause salt (NaCl) to buildup in the solution. The average NaCl concentration in the scrubber will be approximately 2 wt% (since the current operating limit is 4 wt%). Several runs were conducted with 2 wt% NaCl in the scrubber solution. Two runs, 3 and 4, were conducted with no NaCl in the scrubber solution to determine if salt in the scrubber or quench solutions impacts metals partition.

The test data did not reveal any relationship between scrubber or quench solution salt concentration and metal partition. For every spiked metal, there was no significant difference in metals partition or metals removal efficiency when the salt concentration was 0 or 2 wt%.

Offgas Particulate Concentration (total and submicron)

Total particulate and sub-micron particulate concentration was measured at both the SCC outlet and stack. One mechanism for metals carryover out of the kiln is physical entrainment of metals enriched flyash. Metals that exit the kiln primarily by entrainment, could, in theory, have partitions related to kiln offgas particulate loading. Also, volatilized metals can condense on offgas particulate after leaving the high temperature SCC since gas temperatures drop very quickly in the offgas duct. Thus, even for semi-volatile metals, a correlation between metals partition and particulate concentration is possible. Identification of a correlation between metals partition to the offgas and offgas particulate concentration would be very useful because measuring offgas particulate loading is significantly easier than metals monitoring. Techniques exist for continuous, real time particulate monitoring (including sub-micron), not for continuous metals monitoring. Thus, correlating metals and particulate emissions would be very useful.

Extensive graphical analysis of the test data did not reveal a consistent correlation between metals partition and kiln offgas particulate concentration, total or submicron. Although uncontrolled particulate concentration ranged from 0.015 gr/dscf to 0.070 gr/dscf while burning solid wastes, there was no consistent metals partition trend observed for any metal. Reasons for no correlations include changes in waste chloride composition which alter the volatility temperature of several metals, thus changing the ratio of entrained to volatilized metals. Changes in kiln temperature also change this ratio. For the non-volatile metals, the percentage of metals partitioned out of the kiln was too low, under all conditions, to observe any correlation.

Metals Mass Balance

System mass balances for each spiked metal were calculated for every test run. These results are summarized in Table 6. The percent recovered is defined as the total mass of metal measured in the bottom ash, blowdown, and stack gas, divided by the total metal spiked in the waste feed. Calculation of total metal in both the blowdown and stack gas was conducted by multiplying the metal concentration by the total volume of blowdown or stack gas generated during each run. To calculate the total mass of metal in the kiln bottom ash, the ash metal concentration was multiplied by the theoretical quantity of generated kiln bottom ash. A calculated ash quantity was used because the configuration of the test equipment prevented recovery of all the bottom ash after each test run. This number was calculated using the ash analysis of the simulated waste feed material. Using the percent ash of the waste feed, the ash composition, and the quantity of ash carried over to the offgas system, a theoretical ash quantity remaining in the kiln was calculated for each run and used to complete the metals mass balance.

For these tests, metals mass balance closure ranged from 25 to 156%. These percent recoveries are typical of other metals mass balance closure for this type of test.¹ Careful review of the percent recoveries reveals several trends that should be corrected for in determining the actual mass balance closure obtained during these tests. The last column in Table 6 lists the corrected percent recovery for each metal which is discussed below.

Table 6
Metals Percent Recovery

METAL	Run Number									Average	Corrected Average
	1	2	3	4	5	6	7	8	9		
Lead	34	22	25	15	34	22	21	17	45	26	26
Mercury	64	51	30	13	24	18	33	45	-	35	35
Cadmium	309	200	189	47	251	58	47	36	270	156	47
Chromium	72	63	57	33	42	56	4	6	41	42	52
Nickel	102	81	84	46	91	79	6	15	81	65	81
Silver	25	11	20	16	46	35	12	12	46	25	25
Antimony	98	124	88	49	93	75	-	-	83	87	87
Arsenic	106	76	88	78	113	77	-	-	85	89	89
Barium	85	65	72	41	81	71	-	-	78	70	70
Thallium	76	58	61	57	65	63	52	59	67	62	62

All the percent recoveries average less than 100%, except for cadmium. The cadmium recoveries exceeded 100% only when Waste Type E was burned. While burning Waste Type F and G, cadmium recovery averaged 47%. The difference between Waste E and F is the inclusion of PVC in Waste E. It appears that the PVC used for these tests contained trace quantities of cadmium that resulted in recovery of more cadmium than was included in the waste spike. The corrected average recovery only takes into account runs using Waste Types F and G.

Only two nonvolatile metals (chromium and nickel) were spiked in the Waste Type G (liquid waste) tests (runs 7 and 8). Recovery of these metals was much lower when liquid waste was burned. Since no ash was recovered during the liquid waste tests, the metals recovered included only metals in the blowdown and stack gas. It appears the majority of these metals remained in the kiln, yet the ash quantity was too small to recover and analyze. Since ash could not be recovered for these runs (7 and 8), the corrected average recovery only includes runs using Waste Types E and F (solid wastes).

In general, the mass balance closure was better for the nonvolatile metals. Nonvolatile metal mass balance closures averaged approximately 80%. The volatile and semi-volatile metal mass balance closures were not as high, averaging approximately 40%. This trend is not surprising. The volatile and semi-volatile metals would have the tendency to condense on the offgas duct walls and not be recovered or accounted for. The nonvolatile metals would remain in the kiln, to a much larger degree, and not be lost in the facility duct. To test for hold-up of metals in the facility duct, several samples were taken and analyzed for the presence of metals. These samples and the results are summarized below. All analytical results, except the rinse solutions, are qualitative.

- Duct Rinse Solutions: Metals detected are listed in order of increasing concentration
 - Quench Inlet Nitric Acid Rinse: Tl>Cr>Cd>Ni>Pb>Sb>As>Ag>Ba
 - Scrubber Nitric Acid Rinse: Pb>Tl>Cr>Ni>As>Ba>Cd
 - Scrubber Acetone Rinse: Tl>As
 - Scrubber Outlet Nitric Acid Rinse: Pb>Ba>Tl>Sb>Cr>Ag>As>Cd
- Duct Rinse Solids:
 - Quench Inlet Nitric Acid Rinse: Ag, Cr, Ni, Pb,
 - Scrubber Nitric Acid Rinse: Ag, Ba, Cr, Ni, Pb
 - Scrubber Acetone Rinse: Cr, Ni, Pb, Hg
 - Scrubber Outlet Nitric Acid Rinse: Cr, Ni, Pb
- Kiln Refractory: Ag, Ba, Cr, Ni, Pb
- Kiln Thermocouple Alumina Sheath: Ba, Cr, Ni, Pb
- Slag from Kiln Exit: Ag, Ba, Cr, Ni, Pb
- Kaowool Plug in Offgas Duct: Ag, Ba, Cr, Pb

Sample results showed measurable quantities of all metals remained in the test facility duct and equipment. The nonvolatile metals with the lowest recoveries (Cr, Ba, and Ni) were consistently found adhered to kiln surfaces. The semi-volatile metals with the lowest recoveries (Ag and Pb), were also found adhering to these surfaces. Offgas duct and equipment rinses found traces of all metals. Rinse solutions filtered solids contained the same metals found adhering to the kiln walls.

Another explanation for less than perfect metals mass balance closure is error in the analytical techniques. To check for analytical accuracy, spiked blanks for both the blowdown metals analysis and the multiple metals offgas trains were prepared and analyzed by the same methods. The percent recovery for each analytical method is the actual mass of metal measured divided by the mass of metal spiked, multiplied by 100. Table 7 shows the percent recovery for the analytical techniques used to determine metals concentration in the blowdown and stack gas.

Table 7
Analytical Method Percent Recovery

Metal	Blowdown Analysis % Recovery	Offgas Analysis % Recovery
Lead	84	87
Mercury	109	20
Cadmium	33	75
Chromium	117	97
Nickel	108	111
Silver	118	93
Antimony	95	68
Arsenic	99	103
Barium	115	110
Thallium	96	75

Table 7 shows the blowdown analysis accurately measured the concentration of all metals except cadmium. Thus, the low mass balance closure observed for cadmium was certainly due, in part, to the poor cadmium recovery of the analytical technique. One reason the recover is poor is the actual cadmium quantities being measured are very low (0.02 ppm) compared to the method detection limit (0.005 ppm). The low mass balance closure for mercury is likely due to mercury offgas analysis poor recovery. The low mercury volatility temperature would predict high mercury concentrations in the stack gas. The unaccounted for mercury was most likely in the stack gas. The offgas analysis recovery for all the other metals was very good.

Offgas Particulate Characterization

The kiln offgas particulate concentration and size distribution was measured as a function of waste type and kiln operating conditions. Also, scrubber particulate removal efficiencies were calculated by measuring particulate concentration in the facility stack gas in addition to the kiln offgas. Table 8 shows the kiln offgas and stack gas total particulate emission and overall scrubber particulate capture efficiency for each test. Scrubber particulate capture efficiencies (discussed in detail at the end of this section) were lower than expected. The primary reason for the low scrubber removal efficiencies is the low particulate concentration in the kiln offgas, significantly less than expected for the CIF (due to scale of test facility kiln). Also, the scrubber operating parameters were not optimized for these conditions.

Table 8
Particulate Concentrations and Scrubber Capture Efficiency

Run #	Waste Type	Kiln Gas Particulate Concentration (gr/dscf @7%O ₂)	Stack Gas Particulate Concentration (gr/dscf @7%O ₂)	Scrubber Particulate Capture Efficiency (%)
Blank	N/A	0.0079	0.022	N/A
1	E	0.077	0.044	20
2	E	0.056	0.022	30
3	E	0.11	0.017	79
4	F	0.033	0.011	53
5	E	0.10	0.052	27
6	F	0.090	0.024	62
7	G	0.16	0.058	54
8	G	0.14	0.035	63
9	E	0.13	0.054	36

The blank run was taken while no waste was being burned and the quench and scrubber were operating with water containing 2 wt% sodium chloride. The increase in particulate concentration from the kiln exit to the stack, during the blank run, is due to salt particulate generation in the

quench and scrubber and/or mist entrainment. Since stack gas particulate concentrations for runs 3 and 4 are lower than observed during the blank indicates that salt generation in the quench was a significant contributor to particulate in the stack gas. This is evident because runs 3 and 4 were the only runs that contained no sodium chloride in the scrubber and quench solutions. Previous testing of a Hydrosonic scrubber showed particulate concentrations of approximately 0.025 gr/dscf in the stack gas when scrubber and quench solutions contained 2 wt% sodium chloride and no waste was being burned.¹⁰

The degree of variability in the kiln offgas particulate concentration is quite high. Runs 1-3 were burned the same waste at identical kiln operating conditions, yet the particulate concentration ranged from 0.077 - 0.11 gr/dscf. Although the data has a significant degree of variability, a few general observations can be made. Kiln offgas particulate concentrations increased as the kiln temperature decreased while burning solid wastes. In Figure 11, kiln offgas particulate concentration is plotted as a function of kiln temperature for each waste type.

Figure 11
Total Kiln Offgas Particulate as Function of Kiln Temperature

Figure 11 indicates for both Waste Types E and F, the kiln offgas particulate concentration increases as incineration temperature decreased. This increase is probably due to a decrease in incineration efficiency at the lower temperatures. At lower kiln temperatures, soot could be seen exiting the kiln more frequently immediately after waste feeding.

The offgas velocity varied from 20 ft/sec to 55 ft/sec, in the offgas duct, over the temperature range tested. Figure 12 shows the relationship between particulate concentration in the kiln offgas and offgas velocity at the sampling point. This figure reveals no clear relationship between offgas particulate concentration and gas velocity.

Figure 12
Total Kiln Offgas Particulate as Function of Offgas Velocity

In addition to measuring kiln offgas total particle concentration, the offgas particulate size distribution was also measured for each run. Particle size distribution data is useful for determining particulate formation mechanisms. A single physical mechanism generally forms particles in a single, limited size range called a mode. Multiple modes in a given size distribution indicate the presence of multiple mechanisms for particle formation. Identifying modes and defining the effects of process variables on modes size and location can aid in reducing kiln particulate emissions.

Particulate size distributions are presented as both differential and cumulative distributions. The differential particle size distributions are plotted with $dM/d\log D$ as the ordinate and $\log D$ as the abscissa. The mass of particulates with diameters between D_1 and D_2 is designated by dM . The difference in the log of the diameters associated with dM is $\log D_1 - \log D_2$, designated $d\log D$. For these distributions, the area under the curve in a given size range is equal to the mass of particulate in that interval. Cumulative distributions are obtained by summing the percentages of the total concentration from the smallest diameter particles measured to the largest.

Analysis of the kiln offgas differential mass size distributions show all runs contain two distinct modes. One mode with particulates averaging 0.5 microns, and one with particle diameters averaging 10 microns. Typical differential mass distributions are shown in Figure 13. The smaller mode is most likely formed by semi-volatile compound condensation and fines released during waste combustion. The larger particles are likely entrained kiln bottom ash. None of the tested process variables showed a significant effect on the bimodal differential mass size distributions.

Figure 13
Differential Mass Size Distribution
High Kiln Temperature

Differential Mass Size Distribution
Low Kiln Temperature

A typical cumulative mass distribution plot is shown in Figure 14. Table 9 summarizes the cumulative particulate size distribution data. This table presents the cumulative wt% of collected offgas particulates both less than one micron diameter and less than 10 microns for each run.

Figure 14
Cumulative Mass Size Distribution

Table 9
Kiln Offgas Particulate Size Distribution

Run Number	Waste Type	Kiln Temp. (°F)	Cum % < 1 micron diameter	Cum % < 10 microns diameter
1	E	1832	66	95
2	E	1832	76	90
3	E	1832	64	96
4	F	1832	48	92
5	E	1600	60	90
6	F	1600	26	60
7	G	1832	70	98
8	G	1600	54	92
9	E	1400	44	84

Several general observations can be made from the data in Table 9. First, there was a large submicron particulate fraction in the kiln offgas for all conditions tested. The low gas velocities in the kiln (0.8-2.1 ft/s) is the primary reason kiln offgas particulates are so small. At these low gas velocities, entrainment of large particles is minimized. These kiln offgas velocities are considerably less than kiln exit velocities expected for the CIF (7-10 ft/s). Therefore, both the total particulate concentration and the fraction of larger particles is expected to be greater for the CIF. Limitations in the test facility equipment prevented operation at higher kiln exit velocities.

The data in Table 9 clearly shows that an increase in chloride concentration in the solid waste caused a decrease in submicron particulate concentration. At 1832°F, 69 wt% of the kiln offgas

particulate were less than one micron when the solid waste contained PVC. The submicron particulate percentage decreased to 48 wt% when the solid waste did not contain PVC. At 1600°F the percentage dropped from 60 wt% to 26 wt% submicron particulate when PVC was eliminated from the waste.

Another clear trend in the particulate size distribution data is the reduction in submicron particulate concentration as the kiln operating temperature is reduced. For all waste types, the submicron particulate fraction decreased as combustion temperatures were decreased. This phenomena is probably due to less efficient combustion at the lower operating temperatures. The increase in visible soot at lower operating temperatures would be expected to increase the average offgas particle size.

Scrubber particulate capture efficiencies (Table 8) were all below 80%, which is significantly below the >99% particulate capture efficiency expected. There are several reasons the capture efficiencies were lower than expected.

- The scrubber inlet particulate concentrations were very low.
- There was a large fraction of submicron particles in the offgas.
- Salt formation/entrainment in the scrubber offgas.
- Scrubber performance not optimized.

Scrubber capture efficiency is shown as a function of kiln offgas particulate concentration in Figure 15. The two runs (3 and 4) that had no sodium chloride in the scrubber water have been removed because the absence of salt particulate in the scrubber offgas greatly effects the particulate concentration in the stack gas. From this plot, there does not appear to be any significant relationship between scrubber capture efficiency and offgas particulate concentration.

Figure 15
Scrubber Capture Efficiency as a Function of Kiln Offgas Particulate Concentration

Figure 16 shows the relationship between scrubber particulate efficiency and kiln offgas submicron particulate concentration. Runs 3 and 4 were not included since sodium chloride was not present in the scrubber and quench solutions. This plot does not indicate a significant relationship between scrubber capture efficiency and offgas submicron particulate concentration.

Figure 16
Scrubber Capture Efficiency as a Function of Kiln Offgas Submicron Particulate Concentration

Although the scrubber capture efficiencies were low for these tests, the stack gas particulate concentration was very low, ranging from 0.011 to 0.058 gr/dscf. The scrubber used in these tests was atomized with air instead of steam. Earlier tests showed that steam atomization resulted in higher particulate capture efficiencies than air atomization.¹¹ Thus, since the CIF scrubber will use steam atomization, the particulate concentrations in the stack gas should be less than observed during these tests. Further Hydrosonic scrubber testing is planned to accurately determine the relationship between scrubber particulate capture efficiency and scrubber water salt concentration and offgas particulate concentration and size distribution.

Kiln Offgas HCl Concentration

HCl concentrations in the kiln offgas are summarized in Table 10. Also included are theoretical HCl emissions based on 100% chlorine conversion in the feed to HCl. There were two chlorine sources in the waste, PVC and the spiked POHCs (hexachlorobenzene and hexachloroethane).

The measured offgas HCl concentrations ranged from 63% to 1% of the theoretical HCl emissions. The difference is most likely due to the chlorinated metal compound formation in the kiln. The HCl sampling method is not isokinetic, thus particles with condensed metal chloride compounds would not have been collected. Also, chlorine from volatilized chlorinated metal compounds in the sample would not be detected unless the chlorine disassociated from the metal.

Figure 17 shows the actual/theoretical HCl emissions ratio as a function of kiln temperature for each waste type. For the solid wastes, the ratio decreases (actual HCl emissions decrease) as the kiln temperature decreases. Yet, the opposite behavior was observed for liquid waste. There is no apparent explanation for this behavior.

Table 10
Kiln HCl Emissions

Run #	Waste Type	Kiln Offgas HCl Concentration		Theoretical Emissions (g/kg feed)	Actual/Theoretical
		(ppmv @7%O ₂)	(g/kg feed)		
1	E	330	21	68	0.31
2	E	360	24	68	0.35
3	E	560	38	68	0.56
4	F	57	3.8	12	0.31
5	E	220	12	68	0.18
6	F	1.7	0.1	12	0.01
7	G	110	3.3	16	0.21
8	G	280	10	16	0.63
9	E	170	7.8	68	0.11

Figure 17
Actual/Theoretical HCl Emission Ratio as a Function of Kiln Temperature

Kiln Offgas Organics Concentration

The kiln offgas organics are divided into three categories, volatile, semi-volatile, and dioxins (PCDD/PCDF). The kiln offgas sampling results for these organics are discussed below. Also, two POHCs were spiked in the waste feed for all test runs. The destruction and removal efficiency (DRE) for the POHCs is also discussed.

Volatile Organics

The kiln offgas volatile organic sample results are summarized in Table 11. This table includes the actual volatile organic compound (VOC) concentrations measured in the kiln offgas, corrected to 7% O₂, and the maximum possible VOC concentration based on the detection limits. The predominant VOCs detected include: chloromethane, trichlorofluoromethane, methylene chloride, chloroform, carbon tetrachloride, benzene, toluene, and xylene. Appendix C contains a complete listing of VOC sample results.

Table 11
Kiln Volatile Organic Emissions

Run Number	Waste Type	Kiln Temp. (°F)	Measured VOC Emissions		Maximum VOC Emissions	
			µg/dscm	ppbv	µg/dscm	ppbv
1	E	1832	51	11	<66	<15
2	E	1832	190	42	<200	<44
3	E	1832	28	6.2	<42	<9.2
4	F	1832	7.0	1.5	<57	<13
5	E	1600	290	64	<300	<66
6	F	1600	20	4.4	<34	<7.5
7	G	1832	0.9	0.2	<19	<4.2
8	G	1600	4.0	0.9	<21	<4.6
9	E	1400	160	35	<190	<42

Several general observations can be made from the data in Table 11. There appears to be a relationship between VOC emissions and feed chloride concentration. At similar kiln temperatures, Waste E consistently had higher VOC emissions than Waste F, which had no PVC. The liquid waste (Type G) had the lowest chlorine and the lowest VOC emissions. Therefore, for both solid and liquid wastes, increased waste chloride concentrations causes higher VOC emissions.

The VOC emissions in Run 2 are considerably higher than Runs 1 and 3, although all three were conducted under identical conditions. During Run 2, the kiln was experiencing pressure control problems that resulted in lower kiln oxygen concentrations and numerous carbon monoxide (CO) spikes were observed. This run was considered a "process upset" run. As expected, the destruction of organics was not as complete when high CO levels are present in the kiln.

The data in Table 11 also shows a general trend of higher VOC concentrations at lower kiln temperatures. This is expected, since greater organic destruction efficiencies would be expected at higher combustion temperatures.

Semi-volatile Organics

The kiln offgas semi-volatile organic sample results are summarized in Table 12. This table includes the actual semivolatile organic compound (SVOC) concentrations measured in the kiln offgas, corrected to 7% O₂, and the maximum possible SVOC concentration based on the detection limits for all compounds. The predominant SVOCs detected include: benzyl alcohol, benzoic acid, and a variety of polyaromatic hydrocarbons (PAH) including naphthalene, fluorine, phenanthrene, and pyrene. Appendix D contains a complete listing of SVOC sample results.

Table 12
Kiln Semivolatile Organic Emissions

Run Number	Waste Type	Kiln Temp. (°F)	Measured SVOC Emissions		Maximum SVOC Emission	
			µg/dscm	ppbv	µg/dscm	ppbv
1	E	1832	210	0.03	<860	<0.1
2	E	1832	700	0.10	<2100	<0.3
3	E	1832	490	0.07	<1400	<0.2
4	F	1832	300	0.04	<1000	<0.1
5	E	1600	300	0.04	<990	<0.1
6	F	1600	270	0.04	<1000	<0.1
7	G	1832	1.5	0.00	<84000	<12
8	G	1600	1.2	0.00	<78000	<11
9	E	1400	950	0.13	<1500	<0.2

The most significant effect on SVOC emissions was the waste form. Incinerating liquid wastes produced considerably less SVOC than burning solid wastes. This is not surprising because products of incomplete combustion (PIC) from solid wastes that contain plastics, PVC, and latex could be either VOC or SVOC. SVOC production from benzene and chlorobenzene combustion would require formation reactions between volatile PICs to form the larger SVOCs. Formation reactions creating more complex organic compounds are not very likely in an incinerator, therefore, SVOC emissions are very low when burning benzene and chlorobenzene.

Waste chloride concentration did not show a significant effect on SVOC formation since there is no difference in emissions between Waste Types E and F. SVOC emissions were not changed by lowering incineration temperature from 1832°F to 1600°F. But, at 1400°F incineration temperature, SVOC emissions increased by approximately three-fold. As discussed above, the SVOC emissions for Run 2 was high because of operation under "process upset" conditions.

Dioxins and Furans

The kiln offgas dioxin and furan sample results are summarized in Table 13. This table includes the measured concentrations of polychlorinated dibenzo[p]dioxins (PCDD) and polychlorinated dibenzofurans (PCDF). Total levels based on the toxic equivalency (TE) of 2,3,7,8 TCDD, the most hazardous isomer, are also given. Equivalency factors used for the individual congeners were recommended by the U.S. EPA (Boiler and Industrial Furnaces Methods Manual, 1991). These compounds result from incomplete combustion of wastes containing chlorinated organic compounds. Appendix E contains a complete listing of all PCDD/PCDF sample results.

Table 13
Kiln PCDD/PCDF Emissions

Run Number	Waste Type	Kiln Temp. (°F)	Kiln Offgas PCDD/PCDF Concentration					
			ng/dscm			ng/kg feed		
			PCDD	PCDF	TE	PCDD	PCDF	TE
1	E	1832	14	120	1.5	630	5200	68
2	E	1832	58	470	6.5	3900	32000	430
3	E	1832	4	31	0.5	190	1500	25
4	F	1832	2	8	0.3	73	400	13
5	E	1600	2	8	0.4	84	690	15
6	F	1600	1	5	0.2	43	200	5.9
7	G	1832	2	7	1.6	33	130	2.8
8	G	1600	1	6	1.3	48	200	4.4
9	E	1400	57	390	10	1900	29000	310

The data in Table 13 shows the most significant variable influencing PCDD/PCDF emissions is waste chloride concentration. Waste Type E produced the highest PCDD/PCDF emissions, while Waste Type F and G were significantly less. No correlations were observed between total PCDD/PCDF emissions and kiln temperature, offgas HCl concentration, or total particulate or submicron particulate in the offgas.

The PCDD/PCDF standard for municipal waste incinerators is 30 ng/dscm in the stack. All of the data in Table 13 was taken before the air pollution control equipment. No data on PCDD/PCDF was taken in the stack gas. Future testing is planned to quantify stack PCDD/PCDF emissions at a larger scale test facility.

POHC Destruction

The POHC DREs are summarized in Table 14. The solid waste (Type E and F) POHCs were hexachloroethane and hexachlorobenzene. The liquid waste (Type G) POHCs were benzene and chlorobenzene. These are the POHCs currently planned for use in the CIF trial burn. Table 14 includes kiln offgas POHC concentration and the calculated DRE.

Table 14
Destruction and Removal Efficiency of POHC

Run Number	Waste Type	Kiln Temp. (°F)	POHC	Kiln Gas Concentration (µg/dscm)	DRE (%)
1	E	1832	Hexachloroethane	<6.7	100.00000
			Hexachlorobenzene	<6.7	100.00000
2	E	1832	Hexachloroethane	<15	>99.99998
			Hexachlorobenzene	<15	>99.99998
3	E	1832	Hexachloroethane	<8.9	>99.99999
			Hexachlorobenzene	<8.9	>99.99999
4	F	1832	Hexachloroethane	<7.4	>99.99999
			Hexachlorobenzene	<7.4	>99.99999
5	E	1600	Hexachloroethane	<7.4	100.00000
			Hexachlorobenzene	<7.4	100.00000
6	F	1600	Hexachloroethane	<7.0	100.00000
			Hexachlorobenzene	<7.0	100.00000
7	G	1832	Benzene	<0.22	100.00000
			Chlorobenzene	<0.22	100.00000
8	G	1600	Benzene	0.59	100.00000
			Chlorobenzene	<0.21	100.00000
9	E	1400	Hexachloroethane	<5.6	100.00000
			Hexachlorobenzene	<5.6	100.00000

The CIF will be required to demonstrate 99.99% DRE for all POHCs during the trial burn. All observed DREs were greater than 99.99998%, far exceeding the required DRE. Based on these results, acceptable POHC DREs can be obtained at incineration temperatures as low as 1400°F.

Kiln Bottom Ash Characterization

Bottom ash was collected from the kiln at the conclusion of each test run. The ash hazardous metals concentration is summarized in Table 15.

Table 15
Metals Concentration in Kiln Bottom Ash (mg/kg)

Metal	Run Number						
	1	2	3	4	5	6	9
Lead	3900	1860	3515	5820	7665	7940	16040..
Mercury	0.12	0.29	0.15	0.07	0.18	0.14	0.09
Cadmium	15	15	15	15	20	10	15
Chromium	9365	9560	8535	6400	5615	7730	5735
Nickel	54160	49865	49865	33585	49345	44440	44170
Silver	6925	1220	6235	6360	15325	13830	18055
Antimony	3720	3710	3865	2695	3760	3115	3400
Arsenic	290	345	270	250	290	235	230
Barium	524825	466305	501450	351545	512895	468590	502625
Thallium	405	410	790	570	485	360	795

No kiln bottom ash was recovered for Runs 7 and 8 because only liquid waste was burned. The recovered ash was fairly uniform in appearance from run to run and resembled coarse beach sand. Some metals, in particular barium, were present in very high concentrations. This was due to the high metals concentration in the spiked waste feed. Expected CIF ash compositions, based on this tests and anticipated waste feeds, are discussed later in the CIF Emissions and Secondary Waste Characterization section of this report. The effects of process variables on metals partition to the bottom ash are discussed in detail in the Metals Partitioning section of this report.

In addition to the total metals concentration, the ash was analyzed with x-ray diffraction to identify specific compounds. The following compounds were present in the kiln ash: barium carbonate, barium calcium silicate, barium aluminum oxide, barium silicate, lead antimony sulfide, silicon oxide, sodium calcium aluminum silicate, aluminum oxide, and aluminum silicate. This analytical technique can detect only crystalline compounds, amorphous structures (e.g. glass) cannot be detected.

No organics analysis was conducted on this ash since the test facility did not allow for prototypic waste/ash residence time in the rotary kiln. Although the non-prototypic residence time prevents meaningful ash organics data, it should not have a significant effect on the kiln bottom ash metals composition. Future testing is planned at a test facility that allows for prototypic waste residence times. Kiln ash organic data and verification of ash metals composition will be obtained from these tests.

Efforts to stabilize this ash in cement to meet regulatory disposal requirements are currently in progress and will be reported in a separate report after all tests are complete.

Scrubber Blowdown Characterization

Quench and scrubber solutions were recirculated from a single 55 gallon polyethylene drum during these tests. At the conclusion of each run, the drum was replaced. This minimized contamination of scrubber solutions between test runs. The liquid blowdown collected from each run was characterized by the following analyses:

- Metals Concentration (soluble and insoluble)
- Solution pH
- Particulate Concentration
- Particulate Size Distribution
- Identification of Insoluble Compounds
- Concentration of Organics
- Total Carbon (organic and inorganic)

Analytical results for each of the above analyses is discussed below. Expected CIF blowdown compositions, based on this tests and anticipated waste feeds is discussed later in the CIF Emissions and Secondary Waste Characterization section of this report.

Metals Concentration

The metals concentration in the recovered scrubber blowdown solution is presented in Table 16. These values are the sum of both soluble and insoluble metals in the blowdown solution. These analyses were conducted using Inductively Coupled Plasma/Mass Spectroscopy (ICP/MS) on blowdown treated to bring all suspended solids into solution (soluble plus insoluble metals). The values in Table 16 are the blowdown metals concentrations generated during the test runs. These values are not equal to the anticipated metals concentrations in the CIF blowdown because the ratio of waste to blowdown is significantly less. A discussion of the predicted CIF blowdown is presented later in this report.

The most abundant metal in the blowdown solution was iron. The source of iron in the blowdown was the carbon steel offgas duct. The CIF will not have carbon steel duct in contact with the scrubber or quench solutions, thus the iron concentration should be significantly less. Other contaminants resulting from non-prototypic facility equipment are zinc and copper.

The blowdown soluble metal percentage is particularly important for determining required treatment processes. Soluble metals are more difficult to treat than insoluble metals. To determine soluble metal concentration, samples were filtered prior to analysis. The percent soluble metal in solution for each run is shown in Table 17.

Table 16
Metals Concentration in Test Scrubber Blowdown (ppm)

Metal	Blank	Run Number								
		1	2	3	4	5	6	7	8	9
Antimony	0.19	1.06	0.43	0.26	0.33	0.37	0.24	0.32	0.27	0.21
Arsenic	0.20	0.31	0.20	0.20	0.23	0.32	0.20	0.23	0.31	0.24
Barium	0.48	59.19	24.45	31.99	37.72	35.68	50.79	5.58	6.43	42.20
Cadmium	0.04	0.86	0.36	0.55	0.15	0.60	0.15	0.42	0.27	0.61
Chromium	0.35	2.90	1.60	0.89	1.22	1.19	1.87	10.27	8.71	0.92
Copper	6.39	59.28	55.43	70.49	17.22	34.53	13.14	48.41	25.55	16.09
Iron	189.55	1080.25	485.72	434.59	451.08	544.95	374.37	587.46	607.16	292.02
Lead	9.71	80.46	38.43	51.73	27.03	55.20	26.36	148.70	100.11	41.38
Mercury	0.01	7.17	3.80	3.73	2.20	4.27	2.83	6.62	8.52	2.39
Nickel	0.68	6.37	3.78	3.34	3.66	4.10	5.46	65.20	88.10	4.91
Silver	0.02	18.61	13.42	17.26	7.56	18.18	10.12	65.81	38.94	6.15
Thallium	0.10	13.60	5.48	7.47	9.75	9.83	9.88	25.16	23.70	6.86
Zinc	4.77	23.62	21.69	28.24	15.81	21.98	11.37	19.45	18.61	15.08

Table 17
% Soluble Metals in the Blowdown Solution

Metal	Run Number								
	1	2	3	4	5	6	7	8	9
Antimony	70	100	100	100	100	100	100	100	100
Arsenic	63	100	100	100	100	100	100	100	100
Barium	2	6	15	1	7	2	38	47	8
Cadmium	94	100	100	100	100	100	100	100	100
Chromium	32	60	84	25	62	30	47	33	46
Lead	90	96	85	37	89	79	100	100	94
Mercury	72	100	78	82	94	88	100	100	87
Nickel	40	60	59	29	47	32	5	2	35
Silver	12	9	0	0	8	19	3	5	18
Thallium	100	100	100	100	100	100	100	100	100

The percentage of soluble metal in the blowdown solution is quite high for most metals. Antimony, arsenic, cadmium, lead, mercury, and thallium were essentially 100% soluble. One reason several metals are completely in solution is their relatively low concentration in the

blowdown. Antimony, arsenic, and cadmium are present in concentrations below 1 ppm. At higher concentrations, it is unlikely they would be 100% soluble. Lead, mercury, and thallium concentrations averaged 63, 5, and 12 ppm respectively. Therefore, significant quantities of these metals could be present as soluble species. Another reason for the high metal solubility observed is the low blowdown pH (discussed in next section).

Only a few metals appeared to exhibit a change in solubility when salt concentration in the water was varied. All runs contained 2 wt% sodium chloride in the scrubber waster except Runs 3 and 4. The concentration of Cl^- was the lowest in Run 4, where no PVC was in the waste, unlike Run 3. Lead and nickel solubility was reduced when no sodium chloride was in the scrubber solution. No other metal solubility was impacted by the presence or absence of sodium chloride.

Blowdown pH

The scrubber blowdown solution pH at the conclusion of each run is shown in Table 18. No pH adjustment was made during the course of the runs.

Table 18
Scrubber Blowdown pH

	Run Number									
	Blank	1	2	3	4	5	6	7	8	9
pH	3.2	2.4	2.1	2.7	2.8	4.9	2.4	2.1	2.2	2.9

No process variables or waste feed characteristics appeared to impact blowdown pH. The iron oxide from the carbon steel duct was the predominate species in the blowdown solution and probably controlled the pH of the solution. The chlorides in the waste or from added sodium chloride appeared to have no effect, since the pH of Run 4 was not significantly higher than the other runs. There is no apparent reason for the pH of Run 5 to be higher than the other runs.

Metal solubility is a function of solution pH. Another reason for the high metal solubility observed is the blowdown pH. Metals are generally more soluble at lower pH values. Raising the pH should drive some of the metals out of solution. Since the CIF quench and scrubber solutions will be maintained at a neutral pH, the percent of soluble metals could be less than observed during these tests.

Blowdown Solids Concentration

The solids concentration in the scrubber blowdown solution for each run is shown in Table 19. This table includes total dissolved solids (TDS), total suspended solids (TSS), and total solids (TS), the sum of both dissolved and suspended solids.

Table 19
Scrubber Blowdown Solids Concentration (wt %)

		Run Number								
	Blank	1	2	3	4	5	6	7	8	9
TDS	3.63	3.16	2.16	0.15	0.13	2.47	2.58	2.36	2.78	1.87
TSS	0.07	0.07	0.08	0.01	0.08	0.09	0.11	0.45	0.09	0.12
TS	3.70	3.23	2.24	0.16	0.21	2.56	2.69	2.81	2.88	1.99

The presence of large quantities of iron oxide in the blowdown did not permit correlation between the offgas particulate measurements and the blowdown particulate measurements. The quantity of material from the duct far exceeded the quantity of particulate from the kiln offgas.

Blowdown Solids Size Distribution

The blowdown solids size distribution was determined by Microtrac analysis. The size distributions are presented as both percent in channel and cumulative distributions. The percent in channel plots show the particle volume percent with a diameter less than the channel width and greater than the preceding channel. Cumulative distributions are obtained by summing the percentages of the total concentration from the smallest diameter particles to the largest.

The test data was categorized into two particle size distributions types. The first distribution contained a single limited size range, or mode. This distribution contained particles with diameters ranging from less than one micron (measurement limit = 0.82μ) to approximately four microns. Typical percent in channel and cumulative size distribution plots are shown in Figure 18.

Figure 18
Blowdown Solids Size Distribution (Single Mode)

The second type of size distribution contained two distinct modes. One mode for particles with diameters less than four microns, and one with particle diameters greater than ten microns. The small particle mode often accounted for greater than 70 vol% of the total particles in the blowdown. Typical percent in channel and cumulative size distribution plots for bimodal distributions are shown in Figure 19.

Figure 19
Blowdown Solids Size Distribution (Dual Mode)

There was no apparent correlation between test variables and the presence of either single or bimodal blowdown particle distributions. The presence of duct corrosion products is the most probable explanation for the data. These duct corrosion products most likely comprise the larger diameter particle mode. Yet, these corrosion products must also have a significant contribution to the smaller particle diameter mode because corrosion solids comprised the largest fraction of suspended solids for all runs, not just the runs with bimodal distributions.

Insoluble Compounds Identification

Two analytical techniques were used to identify insoluble solids in the blowdown solution, X-ray Fluorescence (XRF) and X-ray Powder Diffraction (XRD). Solids were filtered from blowdown samples for analysis. Table 20 summarizes the elements found in the filtered blowdown solids by XRF analysis. The element had to comprise 0.5 - 1.0 wt% of the sample to be detected.

The XRF results in Table 20 can be compared with the percent soluble blowdown metals analysis in Table 17. The quantitative technique showed antimony to be 100% in solution, yet filtered solids analysis identified antimony as a component. This discrepancy indicates the blowdown solids dissolution technique used to prepare samples for ICP/MS analysis did not bring 100% of the metal into solution. The other metals in Table 16 that were 100% soluble, arsenic, cadmium, and thallium, were not detected in the XRF solids analysis, as expected. Chromium was expected to be detected in the solids, yet the concentration was apparently too low to be detected in most of the samples. Overall, the quantitative ICP/MS results agree with the XRF solids analysis.

Table 20
Elements Composing the Scrubber Blowdown Solids

Metal	Run Number								
	1	2	3	4	5	6	7	8	9
Antimony	X	X	X	X	X	X	X		X
Arsenic									
Barium	X	X	X	X	X	X	X		X
Cadmium									
Chromium							X	X	
Lead	X	X	X	X	X	X	X	X	X
Mercury	X	X	X	X	X		X	X	X
Nickel	X	X	X	X	X	X	X	X	X
Silver	X	X	X	X	X	X	X	X	X
Thallium									
Iron	X	X	X	X	X	X	X	X	X
Zinc	X	X	X	X	X	X	X	X	X
Copper	X	X	X	X	X	X	X	X	X

XRD analysis of the filtered blowdown solids identifies crystalline compounds at concentrations greater than 5 wt%. The followings compounds were identified.

Barium Potassium Sulfate, BaKSO₄
 Barium Sulfate, BaSO₄
 Copper Nickel Oxide, Cu₂Ni₅O₁₀
 Iron Oxide, Fe₂O₃
 Iron Oxide Hydroxide, FeOOH
 Nickel Iron, Ni₃Fe
 Nickel Oxide, NiO
 Silver Chloride, AgCl

Barium, nickel, and silver were the only spiked metals that formed detectable crystalline solids in the blowdown. The other metals, copper and iron, were corrosion products from the process equipment in the test facility.

Blowdown Organics Analysis

Blowdown solution samples were analyzed for organics contaminants per EPA Method 8270. Blowdown from all nine runs contained no detectable organics. Detection levels were >330 ppb for most organics (e.g. hexachloroethane and hexachlorobenzene) and >4950 ppb for PCBs.

Total Carbon Analysis

Blowdown solution samples were analyzed for total carbon. The analysis results are shown in Table 21. Included in this table is total inorganic carbon, total organic carbon, and total carbon (inorganic plus organic). All blowdown carbon concentrations were very low (< 5 ppm). There was no apparent correlation between carbon concentration (organic or inorganic) and test variables.

Table 21
Blowdown Carbon Analysis (ppm)

	Run Number								
	1	2	3	4	5	6	7	8	9
Inorganic C	0.47	0.62	0.21	0.44	0.60	0.67	0.76	0.62	0.54
Organic C	0.86	1.23	1.53	4.29	0.24	1.66	1.85	0.55	0.99
Total C	1.32	1.85	1.74	4.73	0.84	2.33	2.61	1.17	1.53

PROJECTED CIF EMISSIONS AND SECONDARY WASTE CHARACTERIZATION

CIF metals emissions will be in either the kiln bottom ash, scrubber blowdown, or the stack gas. A review of all hazardous and mixed wastes currently in storage for treatment in the CIF quantified the waste volumes contaminated with toxic metals. These results are summarized in Table 22. Only limited waste metals concentration data was available. The waste metals concentration is based on available waste characterization data.¹² Although no waste in storage contained either thallium or antimony, the waste quantities contaminated with these metals is assumed to be equal with the smallest identified waste stream (arsenic contaminated waste). Table 22 includes the percentage of waste containing each metal, the annual pounds of each waste planned for treatment, the assumed waste metals concentration, and the total pounds per year of metal that will be in the CIF feed.

The "worst case" partitions of each metal to either the kiln bottom ash, scrubber blowdown, or stack gas are shown in Table 23. The "worst case" values are the highest observed partition of each metal under any of the tested conditions. The highest blowdown and stack partition values were usually observed will burning liquid wastes. For the metals not used in the liquid waste runs, antimony, arsenic, and barium, only partitions observed during the solid waste runs were considered.

TABLE 22
ASSUMED CIF WASTE FEED

Quantity of Hazardous Waste with composition of stored waste = 1,119,000 lbs/yr
Quantity of DWPF Waste = 367,000 lbs/yr (Mercury contaminated)

	% of Inventoried Haz. Waste	lbs/yr of waste feed	conc. of metal in waste feed (ppm)	lbs/yr of metal in kiln feed
Arsenic	0.25	2798	50	0.1
Barium	0.94	10519	100000	1052
Cadmium	14.91	166843	20	3.3
Chromium	15.23	170424	2500	426
Lead	29.88	334357	5000	1672
Mercury	4.59	418362	260	57
Silver	14.59	163262	730	119
Nickel	13.34	149275	3200	478
Thallium	0	2798	730	2.0
Antimony	0	2798	730	2.0

TABLE 23
Maximum Metals Partition Percentages

	Maximum Ash Partition, %	Maximum Blowdown Partition, %	Maximum Stack Gas Partition, %
Arsenic	100	10	50
Barium	100	5	2
Cadmium	35	90	40
Chromium	100	95	30
Lead	65	85	50
Mercury	0	100	95
Silver	95	100	10
Nickel	100	95	15
Thallium	30	90	45
Antimony	100	5	1

Using the assumptions listed in Tables 22 and 23, CIF secondary wastes were calculated (both quantity and composition) for two cases. The first case assumed solid waste feeds contained 10 wt% PVC (Waste Type E). The second case assumed that PVC in the waste feed was reduced to only 2 wt%. Results for these cases are shown in Tables 24 and 25.

Table 24
CIF Secondary Waste For 10% PVC Solid Waste

PVC in solid waste = 10 wt%

Chloride in liquid waste = 0.5 wt%

Scrubber chloride removal efficiency = 99%

NaCl in the blowdown = 10 wt%

Suspended solids in the blowdown = 2.7 wt%

Blowdown Specific Gravity = 1

Waste Type	Waste Generation (lbs/yr)	Waste Inventory (lbs/yr)	Wt% Ash	Ash Carryover, %	Kiln Ash (lbs/yr)	Fly Ash (lbs/yr)
Liquids	763600	1419400	0.5	50	3092	3092
Solids	191700	649600	5	50	10206	10206
Job Control	1125000	0	5	50	28125	28125
Total	2080300	2069000			41423	41423

Blowdown Generation = 185,136 gal/yr = 1,544,036 lbs/yr

Metal	lbs/yr of metal in kiln feed	max metal in ash (ppm)	max metal in blowdown (ppm)	max metal out the stack (lbs/yr)
Arsenic	0.1	3	0	0.1
Barium	1052	25393	34	21.0
Cadmium	3.3	28	2	1.3
Chromium	426	10286	262	127.8
Lead	1672	26233	920	835.9
Mercury	57	0	37	54.5
Silver	119	2733	77	11.9
Nickel	478	11532	294	71.7
Thallium	2.0	15	1	0.9
Antimony	2.0	49	0	0.0

Table 25
CIF Secondary Waste For 2% PVC Solid Waste

PVC in solid waste = 2 wt%

Chloride in liquid waste = 0.5 wt%

Scrubber chloride removal efficiency = 99%

NaCl in the blowdown = 9.5 wt%

Suspended solids in the blowdown = 10 wt%

Blowdown Specific Gravity = 1

Waste Type	Waste Generation (lbs/yr)	Waste Inventory (lbs/yr)	Wt% Ash	Ash Carryover, %	Kiln Ash (lbs/yr)	Fly Ash (lbs/yr)
Liquids	763600	1419400	0.5	50	3092	3092
Solids	191700	649600	5	50	10206	10206
Job Control	1125000	0	5	50	28125	28125
Total	2080300	2069000			41423	41423

Blowdown Generation = 49,667 gal/yr = 414,227 lbs/yr

Metal	lbs/yr of metal in kiln feed	max metal in ash (ppm)	max metal in blowdown (ppm)	max metal out the stack (lbs/yr)
Arsenic	0.1	3	0	0.1
Barium	1052	25393	127	21.0
Cadmium	3.3	28	7	1.3
Chromium	426	10286	977	127.8
Lead	1672	26233	3431	835.9
Mercury	57	0	139	54.5
Silver	119	2733	288	11.9
Nickel	478	11532	1096	71.7
Thallium	2.0	15	4	0.9
Antimony	2.0	49	0	0.0

CONCLUSIONS

The test program objectives included determining metals partition, measuring organics DRE, and characterizing secondary wastes for further treatment studies. Three simulated waste mixes spiked with metals and organics were burned at three incineration temperatures. Both solid waste types (E and F) exhibited very rapid burn rates as evidenced by the swift consumption of oxygen after each charging cycle. Both kiln bottom ash and scrubber blowdown solution were collected after each run for detailed characterization. Metals partition was determined from ash and blowdown sample analysis and stack gas metals sampling. The waste feed was spiked with known organic POHC concentrations. Organics sampling in the incinerator offgas stream was used to determine POHC DRE. Particulate loading was measured both before and after the offgas scrubber to determine scrubber particulate capture efficiencies. Significant test conclusions for each area of interest are discussed below.

Metals Partition

The metals were categorized into three groups based on partition behavior; volatile, semi-volatile, and nonvolatile. Only mercury showed volatile behavior with all the mercury escaping the kiln ash in every run. The mercury split between the blowdown and stack gas was dependent upon incineration conditions. Lead, cadmium, thallium, and silver exhibited semi-volatile behavior. These metals partitioned between the kiln ash, blowdown, and stack gas with ratios dependent upon incineration conditions. Chromium, nickel, barium, antimony, and arsenic exhibited nonvolatile behavior at incineration temperatures. The vapor phase metal concentration at incineration temperatures is negligible, resulting in greater than 90 wt% of the metal remaining in the kiln bottom ash.

The effect of several incineration operating parameters on metals partition was evaluated. As expected, incineration temperature had a significant effect on volatile and semi-volatile metals partition, and minimal effect on nonvolatile metals partition. As incineration temperatures were increased, the metal fraction leaving the kiln ash increased. For mercury, the stack gas metal fraction increased with increasing incineration temperature. Three metals tested, lead, cadmium, and mercury showed a relationship between waste chloride concentration and metals partition. Increasing the waste chloride concentration resulted in a larger metal fraction exiting the kiln and stack. Feeding the metals to the kiln in liquid waste versus solid waste resulted in an increase of metals partition to both the blowdown and stack gas for all metals. One reason for this behavior is that no kiln bottom ash was recovered for the liquid waste runs. Other test variables, such as scrubber water chloride concentration, offgas particulate concentration, and offgas chloride concentration did not show a significant effect on metals partition.

Offgas Particulate Concentration and Scrubber Removal Efficiencies

Kiln offgas particulate concentrations were very low, ranging from 0.056 - 0.16 gr/dscf. Also, the fraction of particles less than one micron was quite high, averaging greater than 50%. The low particulate concentrations and large submicron particle fraction resulted in low scrubber particulate removal efficiencies. Limitations in the test facility equipment caused gas velocities in

the kiln exit duct to be approximately 75% less than expected CIF kiln exit gas velocities. Therefore, particulate carryover data and scrubber particulate removal efficiencies observed during these tests are not considered representative of the CIF. Future testing on a prototypic test facilities will allow proper simulation of these test variables and permit investigation of particulate carryover and scrubber removal efficiencies.

Organics Destruction

To measure the organics destruction at varying kiln operating temperatures, hexachloroethane, hexachlorobenzene, benzene, and chlorobenzene were burned and sampled in the kiln offgas. The CIF permit requires organic destruction of greater than 99.99%. Measured organic destruction efficiencies exceeded 99.99998% for all tested conditions (Kiln temperatures from 1400°F - 1832°F).

Kiln Bottom Ash Characterization

Kiln bottom ash from each run was collected and analyzed for metals concentration and identification of specific compounds. All metals spiked in the waste, except mercury, were present in the ash. Compounds identified in the ash include barium carbonate, barium calcium silicate, barium aluminum oxide, barium silicate, lead antimony sulfide, silicon oxide, sodium calcium aluminum silicate, aluminum oxide, and aluminum silicate. Barium was the predominant metal in the ash, present at a concentration of approximately 50 wt% (due to a very high barium waste feed concentration).

Scrubber Blowdown Characterization

Scrubber blowdown solution from each run was collected and analyzed for metals concentration, organics concentration, solution pH, total carbon, and particulate concentration and size distribution. All metals spiked in the waste were detected in the blowdown. The most abundant metal in the blowdown was iron from the carbon steel offgas duct. Only minimal amounts of iron will be present in the CIF blowdown since no carbon steel duct or pipe will contact the quench or scrubber solutions. The percentage of soluble metals in the blowdown was quite high, with antimony, arsenic, cadmium, lead, mercury, and thallium nearly 100% soluble in the blowdown. The high solubility is due to both the low absolute concentrations of these metals and the low solution pH (approximately 2.5). The CIF quench and scrubber solution pH will be maintained at approximately 7, thus reducing the solubility of heavy metals. The presence of large quantities of duct corrosion products prevented correlation of blowdown particulate concentration and size distribution with kiln offgas particulate concentration and size distribution. Compounds identified in the blowdown solids include barium potassium sulfate, barium sulfate, copper nickel oxide, iron oxide, iron oxide hydroxide, nickel iron, nickel oxide, and silver chloride. No organics were detected in any of the blowdown solutions.

Projected CIF Secondary Waste

Test results were utilized to determine CIF secondary waste quantities and "worst case" metals concentrations. CIF waste feed characterization was based on a review of all hazardous and mixed wastes currently being stored for eventual thermal treatment. The "worst case" partition of metals to each waste stream, kiln bottom ash, scrubber blowdown, and stack gas, was used for this analysis. Waste characterizations were predicted for the cases of burning waste with both 10 and 2 wt% PVC. Annual blowdown generations rates for these two design cases range from 185,000 gallons to 45,000 gallons.

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APPENDIX

A

Appendix A

Waste Type: E

Test Number: 1

Component	Weight Per Charge (grams)	Total Weight Per Test (grams)	Total Dry Composition (%)	Dry Composition W/O Box, (%)
Simulated Waste	125	3875	63.4	73.9
Hexachloroethane	1.25	38.75	0.6	0.7
Hexachlorobenzene	1.25	38.75	0.6	0.7
Paperboard Box	28	868	14.2	
Metals Solution Water	125	3875		
Metals Spike	grams of compound	grams of compound	mg of metal per kg waste	mg of metal per kg waste
Lead	1.9986	61.9551	6384	7441
Mercury	0.1295	4.0155	388	452
Cadmium	0.0038	0.1187	7	8
Chromium	2.4071	74.6201	1587	1849
Nickel	6.2179	192.7542	6306	7349
Silver	1.4406	44.6590	4675	5449
Antimony	0.2524	7.8257	461	537
Arsenic	0.0280	0.8689	34	40
Barium	29.1161	902.5998	73819	86034
Thallium	0.1179	3.6560	466	544
TOTAL	322.21	9988.6		
DRY TOTAL	197.21	6113.6		
DRY TOTAL W/O BOX	169.21	5245.6		

Appendix A

Waste Type: E

Test Number: 2

Component	Weight Per Charge (grams)	Total Weight Per Test (grams)	Total Dry Composition (%)	Dry Composition W/O Box, (%)
Simulated Waste	125	2500	63.4	73.9
Hexachloroethane	1.25	25.00	0.6	0.7
Hexachlorobenzene	1.25	25.00	0.6	0.7
Paperboard Box	28	560	14.2	
Metals Solution Water	125	2500		
Metals Spike	grams of compound	grams of compound	mg of metal per kg waste	mg of metal per kg waste
Lead	2.0055	40.1100	6407	7467
Mercury	0.1318	2.6360	394	459
Cadmium	0.0041	0.0820	7	9
Chromium	2.4139	48.2780	1591	1855
Nickel	6.1881	123.7620	6276	7315
Silver	1.4446	28.8920	4688	5464
Antimony	0.2520	5.0400	460	536
Arsenic	0.0263	0.5260	32	37
Barium	29.1158	582.3160	73823	86039
Thallium	0.1182	2.3640	468	545
TOTAL	322.20	6444.0		
DRY TOTAL	197.20	3944.0		
DRY TOTAL W/O BOX	169.20	3384.0		

Appendix A

Waste Type: E

Test Number: 3

Component	Weight Per Charge (grams)	Total Weight Per Test (grams)	Total Dry Composition (%)	Dry Composition W/O Box, (%)
Simulated Waste	125	3875	63.4	73.9
Hexachloroethane	1.25	38.75	0.6	0.7
Hexachlorobenzene	1.25	38.75	0.6	0.7
Paperboard Box	28	868	14.2	
Metals Solution Water	125	3875		
Metals Spike	grams of compound	grams of compound	mg of metal per kg waste	mg of metal per kg waste
Lead	2.0038	62.1163	6403	7462
Mercury	0.1296	4.0167	388	452
Cadmium	0.0046	0.1411	8	10
Chromium	2.3985	74.3526	1581	1843
Nickel	6.1799	191.5763	6269	7306
Silver	1.4391	44.6109	4671	5444
Antimony	0.2543	7.8843	464	541
Arsenic	0.0267	0.8264	32	38
Barium	29.1104	902.4221	73822	86040
Thallium	0.1202	3.7275	476	554
TOTAL	322.17	9987.2		
DRY TOTAL	197.17	6112.2		
DRY TOTAL W/O BOX	169.17	5244.2		

Appendix A

Waste Type: F
Test Number: 4

Component	Weight Per Charge (grams)	Total Weight Per Test (grams)	Total Dry Composition (%)	Dry Composition W/O Box, (%)
Simulated Waste	125	3875	63.4	73.9
Hexachloroethane	1.25	38.75	0.6	0.7
Hexachlorobenzene	1.25	38.75	0.6	0.7
Paperboard Box	28	868	14.2	
Metals Solution Water	125	3875		
Metals Spike	grams of compound	grams of compound	mg of metal per kg waste	mg of metal per kg waste
Lead	1.9976	61.9242	6377	7432
Mercury	0.1269	3.9349	380	442
Cadmium	0.0044	0.1361	8	9
Chromium	2.5422	78.8068	1675	1952
Nickel	6.1924	191.9629	6276	7314
Silver	1.4466	44.8439	4691	5467
Antimony	0.2595	8.0454	473	552
Arsenic	0.277	0.8577	34	39
Barium	29.1232	902.8198	73790	85991
Thallium	0.1179	3.6540	466	543
TOTAL	322.34	9992.5		
DRY TOTAL	197.34	6117.5		
DRY TOTAL W/O BOX	169.34	5249.5		

Appendix A

Waste Type: E

Test Number: 5

Component	Weight Per Charge (grams)	Total Weight Per Test (grams)	Total Dry Composition (%)	Dry Composition W/O Box, (%)
Simulated Waste	125	3875	63.4	73.9
Hexachloroethane	1.25	38.75	0.6	0.7
Hexachlorobenzene	1.25	38.75	0.6	0.7
Paperboard Box	28	868	14.2	
Metals Solution Water	125	3875		
Metals Spike	grams of compound	grams of compound	mg of metal per kg waste	mg of metal per kg waste
Lead	1.9997	61.9913	6389	7446
Mercury	0.1274	3.9500	381	444
Cadmium	0.0038	0.1184	7	8
Chromium	2.4149	74.8612	1592	1856
Nickel	6.1932	191.9907	6282	7321
Silver	1.4382	44.5829	4668	540
Antimony	0.2544	7.8869	464	541
Arsenic	0.0262	0.8129	32	37
Barium	29.1125	902.4875	73818	86035
Thallium	0.1196	3.7091	473	552
TOTAL	322.19	9987.9		
DRY TOTAL	197.19	6112.9		
DRY TOTAL W/O BOX	169.19	5244.9		

Appendix A

Waste Type: F

Test Number: 6

Component	Weight Per Charge (grams)	Total Weight Per Test (grams)	Total Dry Composition (%)	Dry Composition W/O Box, (%)
Simulated Waste	125	3875	63.4	73.9
Hexachloroethane	1.25	38.75	0.6	0.7
Hexachlorobenzene	1.25	38.75	0.6	0.7
Paperboard Box	28	868	14.2	
Metals Solution Water	125	3875		
Metals Spike	grams of compound	grams of compound	mg of metal per kg waste	mg of metal per kg waste
Lead	1.9368	60.0409	6229	7268
Mercury	0.1254	3.8865	378	441
Cadmium	0.0037	0.1155	7	8
Chromium	2.3229	72.0093	1542	1799
Nickel	6.0090	186.2780	6135	7158
Silver	1.3959	43.2718	4561	5321
Antimony	0.2433	7.5416	447	522
Arsenic	0.0269	0.8333	33	38
Barium	28.2081	874.4503	72001	84009
Thallium	0.1147	3.5547	457	533
TOTAL	320.89	9947.5		
DRY TOTAL	195.89	6072.5		
DRY TOTAL W/O BOX	167.89	5204.5		

Appendix A

Waste Type: G

Test Number: 7

Component	Total Weight Per Test (kg)	Dry Composition (%)
Total High Btu Liquids	10.31	91.0
Benzene	9.79	86.5
Chlorobenzene	0.52	4.6
Metals Solution	11.37	9.0
Total Spiked Waste	21.68	

Metals Spike	Metals Solution (mg of metal per kg solution)	Dry Waste Feed (mg of compound per kg waste)	Dry Waste Feed (mg of metal per kg waste)
Lead	9171	14613	9053
Mercury	541	921	534
Cadmium	10	27	10
Chromium	2278	17589	2249
Nickel	9020	45271	8903
Silver	6704	10514	6617
Antimony	0	0	0
Arsenic	0	0	0
Barium	0	0	0
Thallium	668	859	659
Water	91.05%		

Appendix A

Waste Type: G

Test Number: 8

Component	Total Weight Per Test (kg)	Dry Composition (%)
Total High Btu Liquids	7.99	91.0
Benzene	7.59	86.5
Chlorobenzene	0.40	4.6
Metals Solution	8.78	9.0
Total Spiked Waste	16.77	

Metals Spike	Metals Solution (mg of metal per kg solution)	Dry Waste Feed (mg of compound per kg waste)	Dry Waste Feed (mg of metal per kg waste)
Lead	9169	14561	9174
Mercury	550	932	550
Cadmium	10	28	10
Chromium	2284	17579	2285
Nickel	9018	45110	9022
Silver	6705	10482	6709
Antimony	0	0	0
Arsenic	0	0	0
Barium	0	0	0
Thallium	667	856	667
Water	91.05%		

Appendix A

Waste Type: E

Test Number: 9

Component	Weight Per Charge (grams)	Total Weight Per Test (grams)	Total Dry Composition (%)	Dry Composition W/O Box, (%)
Simulated Waste	125	3875	63.4	73.9
Hexachloroethane	1.25	38.75	0.6	0.7
Hexachlorobenzene	1.25	38.75	0.6	0.7
Paperboard Box	28	868	14.2	
Metals Solution Water	125	3875		
Metals Spike	grams of compound	grams of compound	mg of metal per kg waste	mg of metal per kg waste
Lead	2.0060	62.1851	6408	7468
Mercury	0.1245	3.8584	372	434
Cadmium	0.0043	0.1328	8	9
Chromium	2.4331	75.4260	1604	1869
Nickel	6.1898	191.8850	6277	7316
Silver	1.4445	44.7807	4688	5463
Antimony	0.2527	7.8346	461	538
Arsenic	0.0264	0.8197	32	38
Barium	29.1188	902.6813	73824	86039
Thallium	0.1183	3.6683	468	545
TOTAL	322.22	9988.8		
DRY TOTAL	197.22	6113.8		
DRY TOTAL W/O BOX	169.22	5245.8		

**APPENDIX
B**

Appendix B

CALCULATION OF METALS PARTITIONS

METALS IN FEED (grams)

	1	2	3	4	5	6	7	8	9
LEAD	39.032	26.536	39.133	39.012	39.055	37.826	102.390	80.550	39.177
MERCURY	2.369	1.633	2.370	2.322	2.331	2.293	6.040	4.830	2.276
CADMIUM	0.043	0.031	0.051	0.049	0.043	0.042	0.110	0.090	0.048
CHROMIUM	9.701	6.590	9.666	10.245	9.732	9.361	25.440	20.060	9.805
NICKEL	38.551	26.000	38.315	38.393	38.398	37.256	100.690	79.210	38.377
SILVER	28.582	19.507	28.551	28.700	28.533	27.694	74.840	58.910	28.660
ANTIMONY	2.817	0.191	2.838	2.896	2.839	2.715	0.000	0.000	2.820
ARSENIC	0.209	1.270	0.198	0.206	0.195	0.200	0.000	0.000	0.197
BARIUM	451.300	305.700	451.211	451.410	451.244	437.225	0.000	0.000	451.341
THALLIUM	2.852	1.936	2.907	2.850	2.893	2.773	7.450	5.860	2.861

METALS IN ASH (grams)

	1	2	3	4	5	6	7	8	9
LEAD	2.797	0.773	2.255	2.997	5.355	5.149	0.000	0.000	11.031
MERCURY	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
CADMIUM	0.011	0.006	0.010	0.008	0.014	0.006	0.000	0.000	0.010
CHROMIUM	6.716	3.974	5.475	3.296	3.923	5.012	0.000	0.000	3.944
NICKEL	38.839	20.730	31.985	17.295	34.474	28.817	0.000	0.000	30.377
SILVER	4.966	0.507	3.999	3.275	10.706	8.968	0.000	0.000	12.417
ANTIMONY	2.668	1.542	2.479	1.388	2.627	2.020	0.000	0.000	2.338
ARSENIC	0.208	0.143	0.173	0.129	0.203	0.152	0.000	0.000	0.158
BARIUM	376.356	193.858	321.644	181.033	358.322	303.856	0.000	0.000	345.667
THALLIUM	0.290	0.170	0.507	0.294	0.339	0.233	0.000	0.000	0.547

METALS IN KILN OFF-GAS (grams)

	1	2	3	4	5	6	7	8	9
LEAD	10.896	5.336	12.249	3.000	9.803	5.892	13.790	16.095	6.790
MERCURY	0.878	0.670	0.472	0.063	0.171	0.615	1.665	3.293	1.582
CADMIUM	0.101	0.494	0.128	0.012	0.087	0.018	0.025	0.016	0.101
CHROMIUM	0.083	0.463	0.098	0.105	0.048	0.187	0.483	0.681	0.084
NICKEL	0.200	0.120	0.266	0.241	0.160	0.298	2.142	3.800	0.357
SILVER	0.009	0.008	0.012	0.004	0.005	0.005	0.006	0.004	0.005
ANTIMONY	0.033	0.019	0.041	0.033	0.020	0.054	0.006	0.008	0.032
ARSENIC	0.002	0.002	0.002	0.002	0.007	0.003	0.004	0.003	0.002
BARIUM	4.193	2.518	5.891	3.102	2.901	8.818	0.075	0.051	5.627
THALLIUM	1.660	1.072	1.713	0.986	1.362	1.577	2.594	3.045	1.154

Appendix B

METALS IN STACK (grams)

	1	2	3	4	5	6	7	8	9
LEAD	2.469	1.299	2.426	1.161	2.036	1.051	9.876	1.459	1.092
MERCURY	0.700	0.338	0.344	0.001	0.028	0.189	1.122	0.634	NA
CADMIUM	0.028	0.013	0.026	0.004	0.018	0.004	0.021	0.002	0.017
CHROMIUM	0.010	0.008	0.012	0.016	0.005	0.009	0.332	0.076	0.006
NICKEL	0.022	0.014	0.023	0.019	0.014	0.014	0.988	0.317	0.022
SILVER	0.007	0.019	0.008	0.412	0.004	0.009	0.002	0.006	0.001
ANTIMONY	0.006	0.004	0.006	0.007	0.003	0.006	0.006	0.004	0.004
ARSENIC	0.002	0.002	0.002	0.028	0.002	0.002	0.004	0.003	0.004
BARIUM	0.737	0.445	0.822	0.636	0.356	0.490	0.009	0.006	0.502
THALLIUM	0.369	0.226	0.391	0.352	0.242	0.291	1.840	0.308	0.159

METALS IN BLOWDOWN (grams)

	1	2	3	4	5	6	7	8	9
LEAD	7.961	3.830	4.973	1.752	6.066	2.105	11.300	12.055	5.563
MERCURY	0.805	0.488	0.376	0.291	0.539	0.229	0.882	1.518	0.350
CADMIUM	0.093	0.043	0.060	0.011	0.075	0.014	0.031	0.030	0.102
CHROMIUM	0.287	0.167	0.064	0.089	0.112	0.192	0.807	1.115	0.101
NICKEL	0.640	0.414	0.315	0.301	0.456	0.605	5.246	11.658	0.756
SILVER	2.092	1.586	1.744	1.005	2.296	0.821	8.773	6.947	0.903
ANTIMONY	0.098	0.032	0.007	0.014	0.024	0.005	0.011	0.010	0.003
ARSENIC	0.012	0.000	0.000	0.004	0.015	0.000	0.004	0.019	0.005
BARIUM	6.650	3.197	3.728	3.766	4.693	6.359	0.414	0.793	7.447
THALLIUM	1.520	0.718	0.872	0.976	1.298	1.236	2.038	3.148	1.207

TOTAL METALS RECOVERED (grams)

	1	2	3	4	5	6	7	8	9
LEAD	13.227	5.902	9.654	5.910	13.457	8.305	21.176	13.514	17.686
MERCURY	1.505	0.826	0.720	0.292	0.567	0.418	2.004	2.152	-
CADMIUM	0.132	0.062	0.096	0.023	0.107	0.024	0.052	0.032	0.129
CHROMIUM	7.013	4.149	5.551	3.401	4.040	5.213	1.139	1.191	4.051
NICKEL	39.501	21.158	32.323	17.615	34.944	29.436	6.234	11.975	31.155
SILVER	7.065	2.112	5.751	4.692	13.006	9.798	8.775	6.953	13.321
ANTIMONY	2.772	1.578	2.492	1.409	2.654	2.031	0.017	0.014	2.345
ARSENIC	0.222	0.145	0.175	0.161	0.220	0.154	0.008	0.022	0.167
BARIUM	383.743	197.500	326.194	185.435	363.371	310.705	0.423	0.799	353.616
THALLIUM	2.179	1.114	1.770	1.622	1.879	1.760	3.878	3.456	1.913

Appendix B

% METAL IN ASH

	1	2	3	4	5	6	7	8	9
LEAD	21	13	23	51	40	62	0	0	62
MERCURY	0	0	0	0	0	0	0	0	-
CADMIUM	8	10	10	34	13	26	0	0	8
CHROMIUM	96	96	99	97	97	96	0	0	97
NICKEL	98	98	99	98	99	98	0	0	98
SILVER	70	24	70	70	82	92	0	0	93
ANTIMONY	96	98	99	99	99	99	0	0	100
ARSENIC	94	99	99	80	92	99	0	0	95
BARIUM	98	98	99	98	99	98	0	0	98
THALLIUM	13	15	29	18	18	13	0	0	29

% METAL IN BLOWDOWN

	1	2	3	4	5	6	7	8	9
LEAD	60	65	52	30	45	25	53	89	31
MERCURY	53	59	52	100	95	55	44	71	-
CADMIUM	71	69	63	48	70	57	60	94	79
CHROMIUM	4	4	1	3	3	4	71	94	2
NICKEL	2	2	1	2	1	2	84	97	2
SILVER	30	75	30	21	18	8	100	100	7
ANTIMONY	4	2	0	1	1	0	65	71	0
ARSENIC	5	0	0	2	7	0	50	86	3
BARIUM	2	2	1	2	1	2	98	99	2
THALLIUM	70	64	49	60	69	70	53	91	63

% METAL IN STACK GAS

	1	2	3	4	5	6	7	8	9
LEAD	19	22	25	20	15	13	47	11	6
MERCURY	47	41	48	0	5	45	56	29	-
CADMIUM	21	21	27	18	17	16	40	6	13
CHROMIUM	0	0	0	0	0	0	29	6	0
NICKEL	0	0	0	0	0	0	16	3	0
SILVER	0	1	0	9	0	0	0	0	0
ANTIMONY	0	0	0	0	0	0	35	29	0
ARSENIC	1	1	1	17	1	1	50	14	2
BARIUM	0	0	0	0	0	0	2	1	0
THALLIUM	17	20	22	22	13	17	47	9	8

APPENDIX
C

EPA SW846 METHOD 0030 - VOLATILE ORGANICS SAMPLING TRAIN (VOST)

VOC FLUE GAS CONCENTRATION @7%O2

C7 = C*13.9/(20.9-CO2,m) RUN NUMBER	SYMBOL	UNITS	FIELD	TRIP	TRIP	DATA	DATA	DATA	DATA	DATA	DATA	DATA	DATA	DATA
SAMPLE	--	--	BLANK	BLANK 1	BLANK 2	1	2	3	4	5	6	7	8	9
CHLOROMETHANE	C7	ng/dscm				4444	8871	983	< 359	1415	559	N/A	< 449	19601
VINYL CHLORIDE	C7	ng/dscm				< 404	< 329	< 393	< 359	< 337	< 350	N/A	< 449	< 350
BROMOMETHANE	C7	ng/dscm				< 404	< 329	< 393	< 359	< 337	< 350	N/A	< 449	< 350
CHLOROETHANE	C7	ng/dscm				< 404	< 329	< 393	< 359	< 337	< 350	N/A	< 449	< 350
TRICHLOROFLUOROMETHANE	C7	ng/dscm				606	1117	< 393	< 359	E 107830	629	N/A	< 449	6650
1,1-DICHLOROETHENE	C7	ng/dscm				< 404	< 329	< 393	< 359	< 337	< 350	N/A	< 449	< 350
CARBON DISULFIDE	C7	ng/dscm				< 404	3023	< 393	< 359	1617	< 350	N/A	808	< 350
ACETONE	C7	ng/dscm				< 4040	3286	< 3932	< 3590	10109	< 3496	N/A	< 4489	5600
METHYLENE CHLORIDE	C7	ng/dscm				16969	29242	17299	< 359	E 336968	34958	N/A	494	E 59504
TRANS-1,2-DICHLOROETHENE	C7	ng/dscm				< 404	< 329	< 393	< 359	< 337	< 350	N/A	< 449	< 350
1,1-DICHLOROETHANE	C7	ng/dscm				< 404	< 329	< 393	< 359	< 337	< 350	N/A	< 449	< 350
VINYL ACETATE	C7	ng/dscm				< 4040	3286	< 3932	< 3590	< 3370	< 3496	N/A	< 4489	< 3500
CIS-1,2-DICHLOROETHENE	C7	ng/dscm				< 404	< 329	< 393	< 359	< 337	< 350	N/A	< 449	< 350
2-BUTANONE	C7	ng/dscm				< 4040	3286	< 3932	< 3590	< 3370	< 3496	N/A	< 4489	< 3500
CHLOROFORM	C7	ng/dscm				3677	329	629	< 359	2056	350	N/A	1122	1610
1,1,1-TRICHLOROETHANE	C7	ng/dscm				< 404	< 329	< 393	< 359	14490	1014	N/A	< 449	2310
CARBON TETRACHLORIDE	C7	ng/dscm				3959	2136	865	< 359	3707	< 350	N/A	1257	3500
BENZENE	C7	ng/dscm				6464	E 106138	865	< 359	1179	< 350	N/A	538	E 178513
1,2-DICHLOROETHANE	C7	ng/dscm				< 404	1446	< 393	< 359	< 337	< 350	N/A	< 449	10501
TRICHLOROETHANE	C7	ng/dscm				606	< 329	< 393	< 359	< 337	< 350	N/A	< 449	700
1,2-DICHLOROPROPANE	C7	ng/dscm				< 404	< 329	< 393	< 359	< 337	< 350	N/A	< 449	< 350
BROMODICHLOROMETHANE	C7	ng/dscm				< 404	< 329	< 393	< 359	1280	< 350	N/A	< 449	< 350
TRANS-1,3-DICHLOROPROPENE	C7	ng/dscm				< 404	< 329	< 393	< 359	< 337	< 350	N/A	< 449	< 350
4-METHYL-2-PENTANONE	C7	ng/dscm				< 4040	3286	< 3932	< 3590	< 3370	< 3496	N/A	< 4489	< 3500
TOLUENE	C7	ng/dscm				4848	1511	1769	431	E 101090	2132	N/A	< 449	E 49004
CIS-1,3-DICHLOROPROPENE	C7	ng/dscm				< 404	< 329	< 393	< 359	< 337	< 350	N/A	< 449	< 350
1,1,2-TRICHLOROETHANE	C7	ng/dscm				< 404	< 329	< 393	< 359	< 337	< 350	N/A	< 449	< 350
TETRACHLOROETHENE	C7	ng/dscm				3596	361	< 393	< 359	< 337	< 350	N/A	< 449	2905
2-HEXANONE	C7	ng/dscm				< 4040	3286	< 3932	< 3590	4381	< 3496	N/A	< 4489	< 3500
DIBROMOCHLOROMETHANE	C7	ng/dscm				< 404	< 329	< 393	< 359	< 337	< 350	N/A	< 449	< 350
CHLOROBENZENE	C7	ng/dscm				< 404	1380	< 393	< 359	< 337	< 350	N/A	< 449	5950
ETHYL BENZENE	C7	ng/dscm				< 404	493	511	< 359	< 337	< 350	N/A	< 449	455
M,P-XYLENE	C7	ng/dscm				2788	3614	3302	1759	944	< 350	N/A	< 449	595
O-XYLENE	C7	ng/dscm				< 404	690	708	< 359	< 337	< 350	N/A	< 449	455
STYRENE	C7	ng/dscm				< 404	< 329	< 393	< 359	< 337	< 350	N/A	< 449	17601
BROMOFORM	C7	ng/dscm				< 404	< 329	< 393	< 359	< 337	< 350	N/A	< 449	< 350
1,1,2,2-TETRACHLOROETHANE	C7	ng/dscm				< 404	< 329	< 393	< 359	< 337	< 350	N/A	< 449	< 350
1,3-DICHLOROBENZENE	C7	ng/dscm				< 404	< 329	< 393	< 359	< 337	< 350	N/A	< 449	< 350
1,4-DICHLOROBENZENE	C7	ng/dscm				< 404	< 329	< 393	< 359	< 337	< 350	N/A	< 449	< 350
1,2-DICHLOROBENZENE	C7	ng/dscm				< 404	< 329	< 393	< 359	< 337	< 350	N/A	< 449	560
TOTAL MAXIMUM POSSIBLE	C7	ng/dscm				78,258	182,678	56,811	31,986	605,262	67,259	N/A	40,131	386,218
TOTAL DETECTED	C7	ng/dscm				48,361	54,212	26,931	2,190	41,178	39,642	N/A	4,220	78,896

* : Note that numbers in italics signify compounds that were not detected in the other Tenax pair
 ND = Not detected E = Estimated N/A : Not available

APPENDIX D

PCDD/PCDF, SEMIVOLATILE AND POHC EMISSIONS FOR FEED TYPES E & F TESTS

CONCENTRATIONS OF SEMIVOLATILES, DRY STP @ 7% O ₂ Ct-402 64"W, d/VmSmp(20 95-Co2, m)	SYMBOL	UNITS	METHOD	FIELD	TRIP	SAMPLING LOCATION						
						UPSTREAM						
						DATA	DATA	DATA	DATA	DATA	DATA	DATA
			BLANK	BLANK	BLANK	1	2	3	4	5	6	9
PHENOL	Ctm.i	µg/dscm				< 7.63	< 16.3	< 10.3	< 8.15	< 8.17	< 8.51	< 8.48
BIS (2-CHLOROETHYL) ETHER	Ctm.i	µg/dscm				< 7.63	< 16.3	< 10.3	< 8.15	< 8.17	< 8.51	< 8.48
2-CHLOROPHENOL	Ctm.i	µg/dscm				< 7.63	< 16.3	< 10.3	< 8.15	< 8.17	< 8.51	< 8.48
1, 3-DICHLOROBENZENE	Ctm.i	µg/dscm				< 7.63	< 16.3	< 10.3	< 8.15	< 8.17	< 8.51	< 8.48
1, 4-DICHLOROBENZENE	Ctm.i	µg/dscm				< 7.63	< 16.3	< 10.3	< 8.15	< 8.17	< 8.51	< 8.48
BENZYL ALCOHOL	Ctm.i	µg/dscm				9.18	228.3	113.7	60.81	58.06	10.22	148.96
2-METHYLPHENOL	Ctm.i	µg/dscm				< 7.63	< 16.3	< 10.3	< 8.15	< 8.17	< 8.51	< 8.48
1, 3-DICHLOROBENZENE	Ctm.i	µg/dscm				< 7.63	< 16.3	< 10.3	< 8.15	< 8.17	< 8.51	< 8.48
BIS (2-CHLOROISOPROPYL) ETHER	Ctm.i	µg/dscm				< 7.63	< 16.3	< 10.3	< 8.15	< 8.17	< 8.51	< 8.48
4-METHYLPHENOL	Ctm.i	µg/dscm				< 7.63	< 16.3	< 10.3	< 8.15	< 8.17	< 8.51	< 8.48
N-NITROSO-DI-N-PROPYLAMINE	Ctm.i	µg/dscm				< 7.63	< 16.3	< 10.3	< 8.15	< 8.17	< 8.51	< 8.48
HEXACHLOROETHANE	Ctm.i	µg/dscm				< 7.63	< 16.3	< 10.3	< 8.15	< 8.17	< 8.51	< 8.48
NITROBENZENE	Ctm.i	µg/dscm				< 7.63	< 16.3	< 10.3	< 8.15	< 8.17	< 8.51	< 8.48
ISOPHORONE	Ctm.i	µg/dscm				< 7.63	< 16.3	< 10.3	< 8.15	< 8.17	< 8.51	< 8.48
2, 4-DIMETHYLPHENOL	Ctm.i	µg/dscm				< 7.63	< 16.3	< 10.3	< 8.15	< 8.17	< 8.51	< 8.48
1,2,4-TRICHLOROBENZENE	Ctm.i	µg/dscm				< 7.63	< 16.3	< 10.3	< 8.15	< 8.17	< 8.51	< 8.48
2-NITROPHENOL	Ctm.i	µg/dscm				< 7.63	< 16.3	< 10.3	< 8.15	< 8.17	< 8.51	< 8.48
BENZOIC ACID	Ctm.i	µg/dscm				198.37	456.6	372.2	211.80	156.11	263.82	123.06
BIS(2-CHLOROETHOXY) METHANE	Ctm.i	µg/dscm				< 7.63	< 16.3	< 10.3	< 8.15	< 8.17	< 8.51	< 8.48
2,4-DICHLOROPHENOL	Ctm.i	µg/dscm				< 7.63	< 16.3	< 10.3	< 8.15	< 8.17	< 8.51	< 8.48
4-CHLOROANILINE	Ctm.i	µg/dscm				< 7.63	< 16.3	< 10.3	< 8.15	< 8.17	< 8.51	< 8.48
HEXACHLOROBUTADIENE	Ctm.i	µg/dscm				< 7.63	< 16.3	< 10.3	< 8.15	< 8.17	< 8.51	< 8.48
4-CHLORO-3-METHYLPHENOL	Ctm.i	µg/dscm				< 7.63	< 16.3	< 10.3	< 8.15	< 8.17	< 8.51	< 8.48
2-METHYLNAPHTHALENE	Ctm.i	µg/dscm				< 7.63	< 16.3	< 10.3	< 8.15	< 8.17	< 8.51	< 8.48
HEXACHLOROCYCLOPENTADIENE	Ctm.i	µg/dscm				< 7.63	< 16.3	< 10.3	< 8.15	< 8.17	< 8.51	< 8.48
2, 4, 6-TRICHLOROPHENOL	Ctm.i	µg/dscm				< 7.63	< 16.3	< 10.3	< 8.15	< 8.17	< 8.51	< 8.48
2, 4, 5-TRICHLOROPHENOL	Ctm.i	µg/dscm				< 7.63	< 16.3	< 10.3	< 8.15	< 8.17	< 8.51	< 8.48
2-CHLORONAPHTHALENE	Ctm.i	µg/dscm				< 7.63	< 16.3	< 10.3	< 8.15	< 8.17	< 8.51	< 8.48
3-NITROANILINE	Ctm.i	µg/dscm				< 38.15	< 81.5	< 51.7	< 40.73	< 40.86	< 42.57	< 32.38
DIMETHYLPHTHALATE	Ctm.i	µg/dscm				< 7.63	< 16.3	< 10.3	< 8.15	< 8.17	< 8.51	< 8.48
2, 6-DINITROTOLUENE	Ctm.i	µg/dscm				< 7.63	< 16.3	< 10.3	< 8.15	< 8.17	< 8.51	< 8.48
2-NITROANILINE	Ctm.i	µg/dscm				< 38.15	< 81.5	< 51.7	< 40.73	< 40.86	< 42.57	< 32.38
2, 4-DINITROPHENOL	Ctm.i	µg/dscm				< 38.15	< 81.5	< 51.7	< 40.73	< 40.86	< 42.57	< 32.38
4-NITROPHENOL	Ctm.i	µg/dscm				< 7.63	< 16.3	< 10.3	< 8.15	< 8.17	< 8.51	< 8.48
2, 4-DINITROTOLUENE	Ctm.i	µg/dscm				< 7.63	< 16.3	< 10.3	< 8.15	< 8.17	< 8.51	< 8.48
DIBENZOFURAN	Ctm.i	µg/dscm				< 7.63	< 16.3	< 10.3	< 8.15	< 8.17	< 8.51	< 8.48
DIETHYLPHTHALATE	Ctm.i	µg/dscm				< 7.63	< 16.3	< 10.3	< 8.15	< 8.17	< 8.51	< 8.48
ALPHA-BHC	Ctm.i	µg/dscm				< 7.63	< 16.3	< 10.3	< 8.15	< 8.17	< 8.51	< 8.48
4-CHLOROPHENYL-PHENYLETHER	Ctm.i	µg/dscm				< 7.63	< 16.3	< 10.3	< 8.15	< 8.17	< 8.51	< 8.48
4-NITROANILINE	Ctm.i	µg/dscm				< 38.15	< 81.5	< 51.7	< 40.73	< 40.86	< 42.57	< 32.38

PCDD/PCDF, SEMIVOLATILE AND POHC EMISSIONS FOR FEED TYPE G TESTS

SAMPLE LOCATION UPSTREAM					
CONCENTRATIONS OF SEMIVOLATILES DRY STP @ 7% O ₂	SYMBOL	UNITS	FIELD	DATA	DATA
Cl=492 64"W. (V _m Smp1)/(20 95-Co2 m)	--	--	BLANK	7	8
PHENOL	C1m.1	µg/dscm	<	928	863
BIS (2-CHLOROETHYL) ETHER	C1m.1	µg/dscm	<	928	863
2-CHLOROPHENOL	C1m.1	µg/dscm	<	928	863
1, 3-DICHLOROBENZENE	C1m.1	µg/dscm	<	928	863
1, 4-DICHLOROBENZENE	C1m.1	µg/dscm	<	928	863
BENZYL ALCOHOL	C1m.1	µg/dscm	<	928	863
2-METHYLPHENOL	C1m.1	µg/dscm	<	928	863
1, 2-DICHLOROBENZENE	C1m.1	µg/dscm	<	928	863
BIS (2-CHLOROISOPROPYL) ETHER	C1m.1	µg/dscm	<	928	863
4-METHYLPHENOL	C1m.1	µg/dscm	<	928	863
N-NITROSO-DI-N-PROPYLAMINE	C1m.1	µg/dscm	<	928	863
HEXACHLOROETHANE	C1m.1	µg/dscm	<	928	863
NITROBENZENE	C1m.1	µg/dscm	<	928	863
ISOPHORONE	C1m.1	µg/dscm	<	928	863
2, 4-DIMETHYLPHENOL	C1m.1	µg/dscm	<	928	863
1,2,4 TRICHLOROBENZENE	C1m.1	µg/dscm	<	928	863
2-NITROPHENOL	C1m.1	µg/dscm	<	928	863
BENZOIC ACID	C1m.1	µg/dscm	<	4641	4313
BIS(2-CHLOROETHOXY) METHANE	C1m.1	µg/dscm	<	928	863
2,4 DICHLOROPHENOL	C1m.1	µg/dscm	<	928	863
4-CHLOROANILINE	C1m.1	µg/dscm	<	928	863
HEXACHLOROBUTADIENE	C1m.1	µg/dscm	<	928	863
4-CHLORO-3-METHYLPHENOL	C1m.1	µg/dscm	<	928	863
2-METHYLNAPHTHALENE	C1m.1	µg/dscm	<	928	863
HEXACHLOROCYCLOPENTADIENE	C1m.1	µg/dscm	<	928	863
2, 4, 6-TRICHLOROPHENOL	C1m.1	µg/dscm	<	928	863
2, 4, 5-TRICHLOROPHENOL	C1m.1	µg/dscm	<	928	863
2-CHLORONAPHTHALENE	C1m.1	µg/dscm	<	928	863
3-NITROANILINE	C1m.1	µg/dscm	<	4641	4313
DIMETHYLPHTHALATE	C1m.1	µg/dscm	<	928	863
2, 6-DINITROTOLUENE	C1m.1	µg/dscm	<	928	863
2-NITROANILINE	C1m.1	µg/dscm	<	4641	4313
2, 4-DINITROPHENOL	C1m.1	µg/dscm	<	4641	4313
4-NITROPHENOL	C1m.1	µg/dscm	<	928	863
2, 4-DINITROTOLUENE	C1m.1	µg/dscm	<	928	863
DIBENZOFURAN	C1m.1	µg/dscm	<	928	863
DIETHYLPHTHALATE	C1m.1	µg/dscm	<	928	863
ALPHA- BHC	C1m.1	µg/dscm	<	928	863
4-CHLOROPHENYL-PHENYLETHER	C1m.1	µg/dscm	<	928	863
4-NITROANILINE	C1m.1	µg/dscm	<	4641	4313

**APPENDIX
E**

PCDD/PCDF, SEMIVOLATILE AND POHC EMISSIONS FOR FEED TYPES E & F TESTS

CORRECTED FOR FIELD BLANK

SAMPLING LOCATION: UPSTREAM

STACK GAS CONCENTRATION OF PCDD/PCDF @ 7% O ₂ Cm=0.4928*(W _i -W _b)/[Vm*Smpl]*(20.95-Co ₂ ,m)] If the field blank is "ND" then no correction is made		SYMBOL	UNITS	METHOD	FIELD	TRIP	DATA	DATA	DATA	DATA	DATA	DATA
				BLANK	BLANK	BLANK	1	2	3	4	5	6
2,3,7,8-TCDD		Cmb.i	ng/dscm				< 0.01 G	0.038 <	0.004 <	0.004 <	0.005	0.000 G
Total TCDD		Cmb.j	ng/dscm				0.27	1.223	0.135	0.281	0.081	0.110
1,2,3,7,8-PeCDD		Cmb.i	ng/dscm			G	0.05 G	0.328 <	0.024 <	0.020 <	0.015 MP	0.013 G
Total PeCDD		Cmb.j	ng/dscm				0.08	2.835	0.067	0.147 <	0.278	0.221
1,2,3,4,7,8-HxCDD		Cmb.i	ng/dscm			G	0.11 G	0.457 MP	0.080 MP	0.034 G	0.024 MP	0.028 G
1,2,3,6,7,8-HxCDD		Cmb.i	ng/dscm			G	0.18 G	0.783 G	0.052 G	0.038 G	0.045 G	0.030 G
1,2,3,7,8,9-HxCDD		Cmb.i	ng/dscm			G	0.14 G	0.638 MP	0.050 G	0.035 G	0.034 MP	0.025 G
Total HxCDD		Cmb.j	ng/dscm				2.14	8.182	0.734	0.603	0.618	0.282
1,2,3,4,6,7,8-HpCDD		Cmb.i	ng/dscm				1.05	8.084	0.588	0.178	0.284	0.108
Total HpCDD		Cmb.j	ng/dscm				3.78	14.878	1.088	0.282	0.543	0.288
OCDD		Cmb.i	ng/dscm			B	7.31 B	30.620 B	2.047 B	0.171 B	0.801 B	0.170 B
TOTAL PCDD's							14	80	6	2	2	1
2,3,7,8-TCDF		Cmb.i	ng/dscm			MP	0.12 MP	0.571 MP	0.051 MP	0.088 MP	0.080 MP	0.033 MP
Total TCDF		Cmb.j	ng/dscm				8.48	29.348	1.864	2.851	4.167	1.447
1,2,3,7,8-PeCDF		Cmb.i	ng/dscm			G	0.37 G	1.435 G	0.114 G	0.171 G	0.135 G	0.081 G
2,3,4,7,8-PeCDF		Cmb.i	ng/dscm			G	1.14 G	4.728 G	0.372 G	0.285 G	0.343 G	0.153 G
Total PeCDF		Cmb.j	ng/dscm				12.18	53.791	3.481	2.808	4.487	1.988
1,2,3,4,7,8-HxCDF		Cmb.i	ng/dscm			G	1.45 G	5.870 G	0.485 G	0.228 G	0.441 G	0.138 G
1,2,3,6,7,8-HxCDF		Cmb.i	ng/dscm			G	1.88 G	8.848 G	0.588 G	0.301 G	0.438 G	0.138 G
2,3,4,6,7,8-HxCDF		Cmb.i	ng/dscm			G	2.87 G	13.318 G	1.000 G	0.291 G	0.651 G	0.151 G
1,2,3,7,8,9-HxCDF		Cmb.i	ng/dscm			G	0.18 G	0.885 G	0.238 <	0.011 <	0.051 <	0.028 G
Total HxCDF		Cmb.j	ng/dscm			G	21.86	88.883	7.255	2.338	4.878	1.507
1,2,3,4,6,7,8-HpCDF		Cmb.i	ng/dscm				12.10	47.055	4.404	0.481	1.847	0.358
1,2,3,4,7,8,9-HpCDF		Cmb.i	ng/dscm				3.84	15.082	0.870	0.012	0.271	0.038
Total HpCDF		Cmb.j	ng/dscm				28.70	111.882	8.888	0.888	2.121	0.613
OCDF		Cmb.i	ng/dscm				48.88	178.882	8.787	-0.187	1.381	0.834
TOTAL PCDF's							118	473	31	6	18	5
TOTAL PCDD/PCDF's		Cmb.i	ng/dscm				130.43	530.58	34.82	10.04	20.23	6.30
TOTAL EQUIVALENT 2,3,7,8-TCDD TOXICITY*		Cmb.i	ng/dscm				1.5	6.5	0.5	0.3	0.4	0.2

G = Reported off SP-2331

B=Blank value column

I = Chemical Interference

MPC = maximum possible concentration

*: Equivalent toxicity from EPA BIF Methods Manual (1991)

END

DATE

FILMED

5/16/94