WSRC-TR-95-0016

SAVANNAH RIVER SITE
SAVANNAH RIVER TECHNOLOGY CENTER

KEYWORDS: CIF
Off-gas System
Particulate

RETENTION: Permanent

FINAL REPORT:
CONSOLIDATED INCINERATION FACILITY WASTE
BURN TEST (U)
Rev 0

by

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January 11, 1995

SRTC SAVANNAH RIVER TECHNOLOGY CENTER
AIKEN SC 29802
Westinghouse Savannah River Corporation
Prepared for the U. S. Department of Energy under
Contract DE-AC09-89SR18035

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DOCUMENT: WSRC-TR-95-0016
TITLE: Final Report: Consolidated Incineration Facility
Waste Burn Test (U)
REVISION NUMBER: 0

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SUMMARY

The Savannah River Technology Center (SRTC) is providing technical support for start-up and operation of the Consolidated Incineration Facility. This support program includes a series of pilot-scale incineration tests performed at the Environmental Protection Agency's (EPA's) Incineration Research Facility (IRF) using surrogate CIF mixed wastes. The objectives for this test program included measuring incinerator offgas particulate loading and size distribution as a function of several operating variables, characterizing kiln bottom ash and offgas particulates, determining heavy metal partition between the kiln bottom ash and incinerator stack gas, and measuring kiln organics emissions (particularly polychlorinated dioxins and furans).

These tests were designed to investigate the effect of the following operating parameters:

- Incineration Temperature
- Waste Feed Rate
- Waste Density
- Kiln Solids Residence Time
- Waste Composition

Tests were conducted at three kiln operating temperatures. Three solid waste simulants were burned, two waste mixtures (paper, plastic, latex, and PVC) with one containing spiked toxic organic and metal compounds, and one waste type containing only paper. Secondary Combustion Chamber (SCC) offgases were sampled for particulate loading and size distribution, organic compounds, polychlorinated dibenzo[p]dioxins and polychlorinated dibenzofurans (PCDD/PCDF), metals, and combustion products. Kiln bottom ash and offgas particulates were characterized to determine the principal elements and compounds comprising these secondary wastes.

Significant test results are summarized below.

Offgas Particulate Carryover

The percent ash in the waste feed carried into the system Air Pollution Control System (APCS) varied between 9 and 53%.

A statistical evaluation of the test results showed that incineration temperature was the most significant variable determining the percent ash carryover with ash carryover increasing with increasing kiln temperatures. Percent ash carryover also increased as waste feedrate increased.

Incinerator Offgas Particulate Characterization

Kiln offgas particulate concentrations ranged from 175 mg/dscm - 743 mg/dscm

Particulate loading in the SCC offgas increased with increasing waste feed rates

Test conditions did not appear to have a significant effect on the offgas particle size distributions

Approximately 40% of the SCC offgas particulates had diameters < 1 micron for both Waste Types A and E (solid waste mixtures of paper, latex, plastic, and PVC).

Approximately 10% of the SCC offgas particulates had diameters > 10 microns for Waste Type B (100% paper).

Kiln Bottom Ash Characterization

Compounds identified in the ash from Waste Types A and B include sodium zinc chloride hydrate, aluminum silicate, aluminum oxide, silicon oxide, sodium chloride, calcium hydroxide, and calcium carbonate.

The carbon content of the bottom ash was quite low, ranging from 0.022 to 0.867 wt% total carbon. As kiln temperature increased, the percent carbon in the bottom ash was found to decrease.

Organics Destruction

The target Principal Organic Hazardous Constituents (POHCs) were not found above method detection limits in any run. The Destruction and Removal Efficiency (DRE) for hexachlorobenzene was at least 99.999 percent. Hexachloroethane DRE was at least 99.998 percent.

The levels of total polychlorinated dibenzo[p]dioxins (PCDD) and polychlorinated dibenzofurans (PCDF) in the scrubber offgas ranged from 2.29 ng/dscm to 0.52 ng/dscm at 7 percent oxygen, and were significantly lower than the recent EPA guidance of 30 ng/dscm at 7 percent oxygen.

Metals Partition

The trace metals results indicate that Pb and Hg were very volatile and almost completely vaporized from the kiln bottom ash.

Two of the metals, Cr and Ba, were very nonvolatile and remained completely in the bottom ash.

Two metals, Sb and Tl, exhibited semi-volatile behavior and split between the kiln bottom ash and offgas stream.

The metal partitioning behavior observed during these tests is consistent with the data obtained in the previous study (the Metals Partitioning Test).

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 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.

In this series of tests, simulated low-level mixed wastes were burned in a pilot scale rotary kiln incinerator equipped with a wet offgas scrubber. The test objectives are listed below.

- Measure the incineration system offgas particulate loading and size distribution upstream of the air pollution control system (APCS) as a function of test variables
- Collect kiln bottom ash and offgas particulate upstream of the APCS for complete characterization.
- In a limited set of runs (three) using simulated wastes spiked with organic hazardous constituents and trace metals:
 - Characterize metals partition between kiln bottom ash and stack gas
 - Measure Destruction and Removal Efficiency (DRE) for CIF Principal Organic Hazardous Constituents (POHCs).
 - Compare test results to the Metals Partitioning Test results, a series of simulated waste burn tests conducted in a much smaller scale incinerator, approximately 1/10 the scale of these tests.¹

Three simulated waste mixtures were used in this 22 run test program. The following process variables were investigated: waste density, waste feed rate, solids residence time in the kiln, and incineration temperature. 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 in three of the runs to determine their fate under the various test conditions.

EXPERIMENTAL TEST FACILITY

Equipment

All testing was conducted at the Environmental Protection Agency's (EPA) Incineration Research Facility (IRF) in Jefferson, Arkansas. Acurex Environmental Corporation operates the IRF under contract to the EPA Risk Reduction Engineering Laboratory. All simulated wastes were

incinerated in the rotary kiln incineration system (RKS) at the IRF. A process schematic of the RKS is shown in Figure 1, and the system design characteristics are listed in Table 1.

TABLE 1
IRF RKS Design Characteristics

<u>Primary Combustion Chamber (Kiln) Characteristics</u>	
Length	7 ft 5 in (2.26 m)
Diameter, outside	4 ft 6 in (1.37 m)
Diameter, inside	3 ft 4.75 in (1.04 m)
Chamber Volume	67. cubic ft (1.9 cubic m)
Rotation	0.2 - 1.5 rpm
Burner	2.0 MMBtu/hr (590 kW)
Primary Fuel	Natural Gas
Feed System	Fiberpack ram feeder
Temperature (max)	1875°F (1010°C)
<u>Secondary Combustion Chamber Characteristics</u>	
Length	10 ft (3.05 m)
Diameter, outside	4 ft (1.22 m)
Diameter, inside	3 ft (0.91 m)
Chamber Volume	63.6 cubic ft (1.80 cubic m)
Gas Residence Time	1.2 - 2.5 s
Burner	2.0 MMBtu/hr (590 kW)
Primary Fuel	Natural Gas
Temperature (max)	2200°F (1200°C)

The primary combustion chamber (PCC), or kiln, has a 39" ID by 8' 2" long rotary section for solids treatment. The kiln is lined with refractory with an average thickness of 7.375". The total volume of the kiln chamber, including the transition section, is 67.2 cubic feet. Kiln offgas passes through a secondary combustion chamber (SCC) before entering the APCS. The SCC has a 3' ID and is approximately 10' long. The SCC is lined with refractory with an average thickness of 6". The volume of the SCC is approximately 63.6 cubic feet. A 14.5' long, 2' ID refractory-lined duct follows the SCC and allows isokinetic sampling of hot incinerator offgas prior to quenching. The RKS uses natural gas burners in both the PCC and SCC. The PCC and SCC both are equipped with 2,000,000 Btu/hr capacity burners.

FIGURE 1
IRF Rotary Kiln Incineration System (RKS)

After exiting the SCC, offgas flows through a quench where it is cooled to the saturation temperature (180°F) by direct injection of aqueous caustic scrubber liquid. After the quench, the cooled gases pass through a venturi scrubber equipped with an automatically adjustable area throat. The scrubber operates at 25 "WC differential pressure with a liquid flow of approximately 20 gpm. Downstream of the venturi scrubber, offgases enter a packed-column scrubber, where additional acid gas and particulate removal occurs. The scrubber column is packed with 2" diameter polypropylene ballast saddles to a depth of 82". The quench, venturi scrubber, and packed-column scrubber receive their scrubbing liquid from the same recirculation system containing a dilute NaOH aqueous solution. Downstream of the scrubbers is a secondary APCS, containing a demister, an activated-carbon adsorber, and a high-efficiency particulate air (HEPA) filter. The secondary APCS is in place to ensure emissions from the RKS are acceptable at all test conditions. Following the secondary APCS, an induced draft fan draws and vents the treated process gases to the atmosphere.

Instrumentation

The RKS is equipped with numerous temperature, pressure, and flow instruments. Table 2 contains a list of all facility operating parameters monitored and recorded during facility testing. Flowmeters and rotameters were used to measure the flow of natural gas and air to kiln and SCC burners. Kiln 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 kiln and SCC exit and scrubber inlet. Four thermocouples were also placed in the kiln ash bed to monitor ash bed temperature along the kiln axis.

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

Sampling and Analysis

For every run, SCC offgas was sampled (in triplicate) upstream of the quench to measure uncontrolled emissions of particulate, including particulate loading and size distribution. For the three runs that both hazardous metals and organics were added to the waste, the following samples were taken in addition to the particulate samples:

- hydrogen chloride
- heavy metals (triplicate)
- Principal Organic Hazardous Constituents (POHCs)
- Polychlorinated dibenzo[p]dioxins (PCDD) and polychlorinated dibenzofurans (PCDF)

TABLE 2
IRF RKS Measured Operating Parameters

<u>Temperature</u>	
Rotary kiln exit gas	
Rotary kiln ash bed at 4 axial locations	
SCC exit gas	
Quench inlet gas	
Quench exit gas	
Scrubber exit gas	
Stack gas	
Recirculating quench/scrubber liquor	
Scrubber blowdown liquor	
<u>Flowrates</u>	
Rotary kiln natural gas feed	
SCC natural gas feed	
Rotary kiln combustion air	
SCC combustion air	
Stack combustion gas	
Venturi scrubber liquor	
Packed tower scrubber liquor	
Scrubber blowdown liquor	
Scrubber makeup liquor	
<u>Pressures</u>	
Rotary kiln chamber	
SCC	
Venturi scrubber dP	
Packed tower scrubber dP	
<u>Other</u>	
Scrubber liquor pH	
Cumulative simulated waste weight fed	
Cumulative kiln ash weight discharged	
Rotary kiln rotation speed	

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 offgas 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 3.

TABLE 3
Summary of Analytical Procedures

Sample Train	Analyte	Analytical Technique	Reference Procedure
MM5 Organic	PCDD/PCDF	HRGC/MS	EPA Method 23 M8290
MM5 Organic	POHCs	GC/MS	EPA SW3540 M8270
HCl	HCl	Ion Chromatography	EPA Method 26 M9057
Metals/Particulates	Particulates	Gravimetric	EPA Method 5 and 17
Metals/Particulates	Sb Ba Cr Pb Tl (front)	ICAP	EPA SW846 M3010
Metals/Particulates	Sb Ba Cr Pb Tl (back)	ICAP	EPA SW846 M6010
Metals/Particulates	Hg	CVAAS	EPA SW846 M7470
Cascade Impactor	Particle Size	Gravimetric/PADRE	CARB 501

In addition to the offgas sampling, kiln ash was continuously collected in 20-gallon drums. After all the ash was collected, at the conclusion of a run, a grab-sample was collected in a pint-sized jar and stored under refrigeration for subsequent trace metal and organics analysis

EXPERIMENTAL PLAN

Simulated Waste Composition

All tests were conducted with simulated waste mixes. Three simulated waste feed mixtures were burned in this test program. The waste mixes were:

Waste Mix A: The design CIF solid waste mix with no hazardous constituents

Waste Mix E: The design CIF solid waste mix spiked with hazardous metals and organics

Waste Mix B The CIF high ash solid waste with no hazardous constituents

The composition of each waste is presented in Table 4.

An industrial shredder was used to shred the paper and PVC waste components. The waste was packaged into 1.5 gallon (7" x 7" x 7") cardboard boxes. Each box was packed by lining the cardboard box with a polyethylene bag (except Waste Type B) and sequentially adding each item, and sealing the box with paper tape backed with water soluble glue

TABLE 4
Simulated Waste Compositions (Wt %)

Component	Solid Waste Mix Waste Type A	Spiked Solid Waste Waste Type E	High Ash Solid Waste Waste Type B
Copy Paper [C ₆ H ₁₀ O ₂]	30	29	100
Yellow Paper [C ₆ H ₁₀ O ₂]	15	15	0
Polyethylene [C ₂ H ₂]	25	25	0
Latex [(C ₅ H ₈) ₂ S]	20	20	0
PVC [C ₂ H ₃ Cl]	10	10	0
Antimony, C ₄ H ₄ KO ₇ Sb	0	730 mg/kg	0
Barium, Ba(CH ₃ OO) ₂	0	10,000 mg/kg	0
Chromium, Cr(NO ₃) ₃ ·9H ₂ O	0	550 mg/kg	0
Lead, Pb(NO ₃) ₂	0	9000 mg/kg	0
Mercury, Hg(NO ₃) ₂ ·H ₂ O	0	590 mg/kg	0
Thallium, TIC ₂ H ₃ O ₂	0	730 mg/kg	0
Hexachloroethane	0	0.6	0
Hexachlorobenzene	0	0.6	0
Waste Higher Heating Value	11,010 Btu/lb	11,010 Btu/lb	4,115 Btu/lb

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. Each POHC was preweighed into amounts required for one box into plastic test tubes which were emptied into the box. Metals spiking solutions were prepared by mixing water soluble, nonchlorinated metal compounds with deionized water. After addition of the POHCs and metals, the polyethylene bag lining the box was sealed with a plastic tie and the box was then sealed.

Test Conditions

The test program variables included waste type, operating temperature, waste density, waste feed rate, and kiln solids residence time. A statistical experimental design was used to develop the test matrix which is shown in Table 5.

Three temperature conditions were included in the test plan. The predominant temperature condition was the design flowsheet CIF operating temperatures (PCC = 1830°F; SCC = 2010°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 both particulate carry-over out of the kiln and waste metal volatility is a function of process temperature.

TABLE 5
Test Plan

Run	Waste Type	Offgas temp. (°F)		Waste feed rate		Kiln solids residence time, min.	Waste density lb/ft ³
		Kiln exit	SCC exit	kBtu/hr/ft ³	kBtu/hr		
1	A	1400	1600	5	335	30	3
2	A	1400	1600	9	605	60	3
3	A	1830	2010	9	605	30	3
4	A	1830	2010	5	335	60	3
5	A	1400	1600	5	335	30	9
6	A	1400	1600	9	605	60	9
7	E	1830	2010	9	605	30	9
8	A	1830	2010	5	335	60	9
9	A	1830	2010	9	605	60	6
10	E	1400	1600	9	605	30	6
11	A	1400	1600	5	335	60	6
12	A	1830	2010	5	335	30	6
13	A	1830	2010	7	470	45	9
14	E	1600	2000	9	605	45	9
15	A	1600	2000	7	470	60	9
16	A	1400	1600	7	470	30	9
17	A	1400	1600	7	470	60	3
18	A	1600	2000	9	605	30	3
19	A	1830	2010	5	335	45	3
20	A	1400	1600	5	335	45	9
21	B	1830	2010	4	270	30	9
22	B	1830	2010	4	270	60	9

The remaining test variables, waste density, waste feed rate, and kiln solids residence time are the other operating parameters suspected to impact kiln offgas particulate concentration and size distribution. For each of these variables, an upper and lower limit (based on the CIF design flow cases), along with the centerpoint was selected to complete the statistical experimental design. This design permits estimating the effects of each process variable on incinerator offgas particulate emissions.

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 RKS at each nominal test condition to establish these limits. In addition, waste feeding was subject to the following constraints: an integral number of boxes could be fed per hour, only one box could be fed per charge event, the feed rate was uniform, and the time interval between charges was achievable. The waste feeding technique involved placing the entire feedstock for a test on the weighing scale and manually placing each box into the kiln ramfeeder. The ramfeeder was remotely controlled to deliver each box into the kiln at the required feed rate. The setting of kiln solids residence time was estimated visually by measuring the time taken by the solids from the first few charges to travel the length of the kiln.

The oxygen concentration in the offgas from the kiln and SCC were targeted to be nominally held at 10 and 8 percent, respectively. Yet, achieving the target kiln temperature was given priority over maintaining the target offgas oxygen concentrations. For all tests, the scrubber system operating conditions are listed in Table 6. The scrubber recirculation system was operated as close to complete recirculation as possible. This was achieved by using the same scrubber liquid from test to test for a given waste type.

Table 6
Scrubber Operating Conditions

Venturi liquor flow rate	20 gpm
Venturi pressure drop	25 "WC
Packed tower liquor flow rate	30 gpm
Scrubber liquor temperature	120°F
Scrubber blowdown rate	0 gpm

The RKS was brought to the target operating temperature overnight, firing natural gas only. After initiation of waste feed, offgas sampling was not started before target conditions were established at steady-state, and in no case less than one hour after beginning solid waste feed. All system operating parameters were recorded at intervals less than every 15 minutes. Appendix A summarizes the actual system operating parameters for each test.

RESULTS AND DISCUSSION

Test results fall into five areas of interest, the carryover of particulate from the rotary kiln to the APCS, offgas particulate characterization, kiln bottom ash characterization, organics emissions, and metals partitioning between the kiln bottom ash and the APCS. Experimental results for each area is discussed in detail below.

Offgas Particulate Carryover

The primary test objective was determining the carryover of particulate from the rotary kiln into the APCS as a function of facility operating variables. The variables of interest included waste type, kiln operating temperature, waste density, waste feed rate, and kiln solids residence time. To determine the division of ash between the kiln and the APCS, first, the percent ash in the waste feed must be determined.

Waste Feed Ash Analysis

To determine the fraction of ash entrained into the APCS, laboratory analyses were conducted to measure the ash composition of each waste component as a function of incineration temperature. The results of these analyses are presented in Table 7.

Table 7
Feed Components Ash Content

Component	Chemical constituent	Percent Ash Content		
		@ 1022°F	@ 1742°F	@ 2012°F
Copy paper	$(C_6H_{10}O_5)_n$	18.81	15.16	9.66
Yellow paper	$(C_6H_{10}O_2)_n$	0.43	0.23	0
PE bags	$(C_2H_2)_n$	0.74	0.34	0.34
PVC	$(C_2H_3Cl)_n$	16.18	7.61	6.78
Latex gloves	$(C_5H_8)_n$	3.92	3.71	3.27
Cardboard box	$(C_6H_{10}O_2)_n$	1.66	0.71	0.71

Table 8 shows the actual average waste feed rate for each test. Using this data, and the laboratory analysis of each waste constituent, the percent ash (i.e. noncombustibles) in the waste feed was calculated, along with the quantity of ash fed to the kiln. For the Type E waste, the POHCs were assumed to contribute no mass to the ash, and the metals were assumed to contribute one hundred percent of their mass to the ash.

Ash Recovery

Ash was collected from two locations in the system. After every run, ash from the kiln bottom-ash was collected and weighed. In addition to the bottom-ash, fly ash was deposited in the horizontal secondary combustion chamber (SCC), and in the entry and observation hatches to the kiln. Ash from the SCC and the hatches was recovered when the kiln was shutdown and cooled sufficiently for manual entry. Consequently, the SCC ash was not collected at the end of every test. The ash collection history is presented in Table 9.

Table 8
Actual Waste Feed Rates and Ash Concentrations

Run	Feed Rate (lb/hr)		Estimated Ash in Feed	
	Target	Actual	wt%	lb/hr
1	42.2	40.0	5.27	2.11
2	79.2	81.2	5.14	4.17
3	79.2	81.3	4.10	3.33
4	42.2	43.4	4.10	1.78
5	33.3	34.7	6.28	2.18
6	62.4	60.5	6.15	3.72
7	87.2	86.1	6.86	5.91
8	33.3	35.0	4.94	1.73
9	66.6	67.5	4.73	3.19
10	94.5	92.2	7.84	7.23
11	35.5	36.7	6.01	2.21
12	35.5	36.1	4.73	1.71
13	49.9	51.6	4.94	2.55
14	87.2	85.7	7.82	6.70
15	49.9	50.9	5.92	3.01
16	49.9	49.5	6.28	3.11
17	63.4	59.7	5.29	3.16
18	79.2	81.5	5.27	4.30
19	42.2	43.7	4.10	1.79
20	33.3	35.9	6.30	2.26
21	74.9	75.2	12.3	9.23
22	74.9	76.6	12.3	9.40

Table 9
Ash Collection History

Run	Total waste feed (lbs)	Collected		Measured Offgas ash (lbs)	Total ash (lbs)	Theoretical ash (lbs)	Percent theoretical
		Bottom ash (lbs)	SCC ash (lbs)				
21	374	11.0		4.0	15.0	46.2	
22	334	18.0		5.0	23.0	41.4	
			25.0		25.0		
TOTAL					63.0	87.5	72
6	285	6.5		6.7	13.2	17.5	
5	157	2.5		2.7	5.2	10.5	
8	164	3.0		2.9	5.9	8.1	
			12.0		12.0		
TOTAL					36.3	36.1	101
20	186	2.0		2.9	4.9	11.8	
17	310	7.0		3.6	10.6	16.4	
			5.5		5.5		
TOTAL					21.0	28.2	75
3	401	5.5		8.6	14.1	16.3	
2	345	5.5		4.2	9.7	17.9	
13	221	2.5		3.9	6.4	11.0	
19	190	3.0		3.7	6.7	7.9	
			10.5		10.5		
TOTAL					47.4	53.1	89
16	229	4.0		4.1	8.1	14.3	
1	197	3.5		2.3	5.8	10.3	
			7.5		7.5		
TOTAL					21.4	24.6	87
11	154	2.0		1.8	3.8	9.3	
9	316	5.0		6.4	11.4	15.0	
			6.0		6.0		
TOTAL					21.2	24.3	87
12	162	2.0		3.2	5.2	7.7	
4	183	2.5		2.7	5.2	7.5	
			6.0		6.0		
TOTAL					16.4	15.2	108
18	366	6.0		5.3	11.3	19.4	
15	225	3.0		3.9	6.9	13.2	
			7.0		7.0		
TOTAL					25.2	32.6	77
10	547	11.0		8.7	19.7	42.7	
			3.5		3.5		
TOTAL					23.2	42.7	54
7	430	4.0		10.8	14.8	29.6	
14	471	4.5		9.3	13.8	37.5	
			19.5		19.5		
TOTAL					48.1	67.1	72

From the data in Table 9, it can be seen the average ash balance closure was 85% of the calculated ash fraction in the waste feed. This percent mass balance closure for waste ash is very good for this type of test facility. The unaccounted for ash most likely remained in the transition duct between the kiln and SCC, the horizontal SCC, and horizontal duct (15') between the SCC and the quench.

Ash Carryover

The CIF facility design does not contain horizontal duct runs between the incinerator and the APCS, thus all ash collected in the SCC and accumulated in the transition ducts in these tests would end up as kiln bottom ash at the CIF. Thus, the ash carryover to the APCS is only the ash measured in the offgas in the duct between the SCC and the quench. Since ash was not collected from the SCC and transition duct for every run, and 100% of the ash was not possible to retrieve, ash carryover fractions are calculated based on calculated ash fractions in the waste feed. The percent of ash carried from the kiln and SCC to the APCS is given in Table 10 for all test runs.

TABLE 10
Percent Ash Carryover to the APCS

Run	Waste Type	Offgas temp. (°F)		Waste feed rate kBtu/hr	Kiln solids residence time, min.	Waste density lb/ft ³	Percent Ash Carryover
		Kiln exit	SCC exit				
1	A	1400	1600	335	30	3	22
2	A	1400	1600	605	60	3	23
3	A	1830	2010	605	30	3	53
4	A	1830	2010	335	60	3	36
5	A	1400	1600	335	30	9	26
6	A	1400	1600	605	60	9	38
7	E	1830	2010	605	30	9	36
8	A	1830	2010	335	60	9	36
9	A	1830	2010	605	60	6	43
10	E	1400	1600	605	30	6	20
11	A	1400	1600	335	60	6	19
12	A	1830	2010	335	30	6	42
13	A	1830	2010	470	45	9	35
14	E	1600	2000	605	45	9	25
15	A	1600	2000	470	60	9	30
16	A	1400	1600	470	30	9	29

TABLE 10 cont.
Percent Ash Carryover to the APCS

Run	Waste Type	Offgas temp. (°F)		Waste feed rate kBtu/hr	Kiln solids residence time, min.	Waste density lb/ft ³	Percent Ash Carryover
		Kiln exit	SCC exit				
17	A	1400	1600	470	60	3	22
18	A	1600	2000	605	30	3	27
19	A	1830	2010	335	45	3	47
20	A	1400	1600	335	45	9	25
21	B	1830	2010	270	30	9	9
22	B	1830	2010	270	60	9	12

Ash Carryover Statistical Model

Runs 1-20 of this test program comprise a statistically designed experimental program. A four variable (temperature, waste density, waste feed rate, waste residence time) quadratic mathematical model was used. Statistical analysis of the data (all independent variable values are scaled and centered to values between -1 and 1) is summarized in Table 11. The variables that are statistically significant in predicting the percent ash carryover to the APCS are: kiln temperature (Temp), waste feed rate (Rate), waste density (Den), and waste residence time (Time).

Table 11
Regression Summary for Dependent Variable: Percent Ash Carryover

R= 0.96701283 R²= 0.93511382 Adjusted R²= 0.90516636
F(6,13)=31.225 p<.000001 Std. Error of estimate: 2.9505

	BETA	St. Err. of BETA	B	St. Err. of B	t(13)	p-level
Intercept			24.8905	1.9357	12.859	.0000
Temperature	.8470	.0744	8.5941	.7545	11.390	.0000
Feed Rate	.2395	.0757	2.4959	.7888	3.1642	.0075
Density*Temp	-.4058	.0717	-4.7077	.8318	-5.6599	.0001
Density*Res. Time	.2416	.0767	2.9124	.9246	3.1498	.0077
Rate*Res. Time	.2065	.0741	2.3962	.8597	2.7873	.0154
(Temp) ²	.3210	.0807	8.4535	2.1254	3.9773	.0016

The mathematical equation expressing percent ash carryover in terms of the significant variables in engineering units is shown below. Converting the model in Table 11 to engineering units brought the density and residence time linear variables into the model

$$\begin{aligned} \% \text{ Ash Carryover} = & 396.2885 - (0.5012)(\text{Temp}) - (2.2660)(\text{Rate}) + (8.8278)(\text{Den}) - \\ & (0.9170)(\text{Time}) - (0.007267)(\text{Den})(\text{Temp}) + (0.06472)(\text{Den})(\text{Time}) + \\ & (0.07721)(\text{Rate})(\text{Time}) + (0.0001812)(\text{Temp})^2 \end{aligned}$$

Units: Temp = °F

Rate = kBtu/hr/ft³

Density = lbs/ft³

Time = minutes

A plot of the values predicted by the above model vs. the observed percent ash carryover values is included in Figure 2. As can be seen in the plot below, the value of ash carryover can be predicted within approximately 6% using the model above.

Figure 2
Predicted Vs. Observed Values for Percent Ash Carryover

Offgas Particulate Characterization

The kiln offgas particulate concentration and size distribution was measured as a function of kiln operating conditions. During each run, three offgas particulate concentration and size distribution samples were obtained using EPA Method 5 and Anderson cascade impactor trains. In addition to these samples, a gram sized particulate sample was obtained using Modified Method 17 for subsequent laboratory analysis.

Offgas Particulate Loading

Table 12 contains the SCC offgas total particulate emission for each test. Figure 3 is a graphical representation of the particulate loading data.

TABLE 12
SCC Offgas Particulate Loading

Run	Waste Type	Offgas temp. (°F)		Waste feed rate kBtu/hr	Particulate Loading, mg/dscm @ 7% O ₂			
		Kiln exit	SCC exit		Train 1	Train 2	Train 3	Average
1	A	1400	1600	335	224	203	255	227
2	A	1400	1600	605	700	708	598	669
3	A	1830	2010	605	735	715	779	743
4	A	1830	2010	335	186	175	205	189
5	A	1400	1600	335	359	264	477	367
6	A	1400	1600	605	652	706	697	685
7	E	1830	2010	605	597	438	632	556
8	A	1830	2010	335	161	191	172	175
9	A	1830	2010	605	418	382	419	406
10	E	1400	1600	605	803	719	670	731
11	A	1400	1600	335	202	199	244	215
12	A	1830	2010	335	186	181	252	206
13	A	1830	2010	470	259	245	259	254
14	E	1600	2000	605	520	469	505	498
15	A	1600	2000	470	244	239	300	261
16	A	1400	1600	470	448	440	712	533
17	A	1400	1600	470	496	509	216	407
18	A	1600	2000	605	418	315	287	340
19	A	1830	2010	335	387	340	350	359
20	A	1400	1600	335	256	298	402	319
21	B	1830	2010	270	268	107	207	193
22	B	1830	2010	270	308	85	245	213

FIGURE 3
SCC Offgas Particulate Loading

The particulate loading ranged from 175 mg/dscm to 743 mg/dscm. In general, the overall trend is the particulate loading increased with increasing feed rate. This trend in the data can be seen in Figure 4.

FIGURE 4
SCC Offgas Particulate Loading as a Function of Waste Feed Rate

The relationship between particulate loading and incineration temperature showed no clear trend as can be seen in Figures 5 and 6. This behavior differs from the earlier CIF waste burn tests conducted in a much smaller scale test facility.¹ In the previous test, the incinerator offgas particulate loading was found to decrease as incineration temperature increased. Waste feed density and residence time also did not appear to have a significant impact on SCC offgas particulate loading.

FIGURE 5
SCC Offgas Particulate Loading as a Function of Kiln Temperature

FIGURE 6
SCC Offgas Particulate Loading as a Function of SCC Temperature

Offgas Particulate Size Distribution

In addition to measuring SCC offgas total particle concentration, the offgas particulate size distribution was also measured for each run. Size distribution samples were taken in triplicate for each run with Anderson cascade impactors. Particulate size distributions are presented as cumulative distributions which are obtained by summing the percentages of the total concentration from the smallest diameter particles measured to the largest. Appendix B contains all valid size distributions plots for each run. During the course of the test program, it was observed that the cascade impactor trains were susceptible to transient events (such as "puffs") in the SCC. A common phenomena was plugging of individual stages in the impactor train resulting in loss of isokineticity and eventual stoppage of the train before target loadings were achieved. Appendix B only contains trains successfully completed within Method isokinetic guidelines.

Representative cumulative mass distribution plots are shown in Figure 7. The five tests in the plot were chosen to represent the three waste types, and the three different temperature conditions under similar waste feed rates. From this plot, it can be seen that a significant difference in particulate size distribution was observed only when burning Waste Type B. Waste Types A and E showed similar particulate size distributions at all test conditions. Statistical analysis of the data also confirmed that temperature, waste feed rate, waste residence time, and waste density did not have a statistically significant effect on SCC offgas particulate size distribution.

Figure 7
Cumulative Mass Size Distribution

Table 13 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.

Table 13
Kiln Offgas Particulate Size Distribution

Run	Waste Type	Offgas temp. (°F)		Waste feed rate kBtu/hr	Cum % < 1 micron diameter	Cum % < 10 microns diameter
		Kiln exit	SCC exit			
1	A	1400	1600	335	58	60
2	A	1400	1600	605	77	90
3	A	1830	2010	605	54	68
4	A	1830	2010	335	30	57
5	A	1400	1600	335	23	47
6	A	1400	1600	605	17	52
7	E	1830	2010	605	39	53
8	A	1830	2010	335	40	66
9	A	1830	2010	605	39	65
10	E	1400	1600	605	29	64
11	A	1400	1600	335	18	25
12	A	1830	2010	335	39	56
13	A	1830	2010	470	42	71
14	E	1600	2000	605	39	56
15	A	1600	2000	470	28	54
16	A	1400	1600	470	39	47
17	A	1400	1600	470	62	82
18	A	1600	2000	605	27	43
19	A	1830	2010	335	40	98
20	A	1400	1600	335	20	33
21	B	1830	2010	270	5	8
22	B	1830	2010	270	5	7

Offgas Particulate Characterization

A modified Method 17 was used to collect gram-sized SCC offgas particulate in oversized alundum thimbles (> 5 micron retention capacity) placed within the sampling probe. Samples from selected runs were analyzed by ICP mass spectroscopy. The results from this analysis is shown in Table 14.

Table 14
SCC Offgas Particulate Elemental Analysis (wt%)

Element	Run #						
	10 (Waste E)	7 (Waste E)	14 (Waste E)	6 (Waste A)	11 (Waste A)	2 (Waste A)	21 (Waste B)
Ca	0.563	0.777	0.86	2.499	0.254	0.367	45.774
Cd	0.008	0.01	0.004	0.125	0.013	0.012	0.003
Cu	0.013	0.009	0.013	0.135	0.004	0.008	0.014
Mg	0.033	0.028	0.012	0.026	0.054	0.041	0.405
Mn	0.049	0.013	0.011	0.02	0.017	0.019	0.013
Pb	2.196	2.201	0.927	0.025	0	0	0
Zn	1.631	1.766	0.788	>16.495	1.008	1.83	0.122
Al	31.467	27.578	0.15	2.665	>31.785	>27.155	0.462
Ba	0.103	0.255	0.112	0.074	0	0	0.091
Fe	0.824	0.617	0.65	0.108	0.931	1.009	0.116
Na	0.79	2.323	0.653	8.754	0.598	1.352	3.048
Ni	0.09	0.083	0.08	0.136	0.127	0.129	0.017
Ti	0.018	0.036	0.002	0.001	0.026	0.007	0.02
Cr	0.18	0.151	0.156	0.01	0.199	0.233	0.013
P	0.43	0.404	0.239	3.315	0	0.451	0.107
Si	2.488	2.902	0.076	0.093	4.224	2.272	0.23

Cascade impactors were used to determine the size distribution of SCC offgas particulates. These impactors consists of eight stages where offgas particulates are collected for gravimetric measurement. The impactor is designed to catch the largest diameter particles in the first stages and the smallest particles in the last stages. At the end of the train, a total filter captures all remaining particulate. For a selected number of runs, each stage of the impactor was analyzed by a scanning electron microscope equipped with an energy dispersive system detector which qualitatively detects elements with an atomic number greater than or equal to eleven. Thus, the tendency of certain metals to concentrate in certain size particulates can be seen. For these tests, the average cut sizes for each stage is given in Table 15.

Table 16 summarizes the cascade impactor stage elemental analysis data. Three runs, 7, 10, and 14, used simulated waste spiked with heavy metals (Waste Type E). One run, 18, used simulated waste with no added metals (Waste Type A). While the last run was 100% paper (Waste Type B). The blank is an analysis of unused impactor substrate fibers. All elements detected on each stage is indicated by an "X" in Table 19. In conducting the analysis, elemental profiles of the particles on the stage (as opposed to the fibers of the substrate) were taken. In most cases discrete particles could be seen on the substrates. The first few stages often contained very large

and irregular particles (often containing Fe). While the last stages contained more uniformly shaped particulates (often containing Pb and Cl).

Table 15
Cascade Impactor Stage Average Particle Diameter

Stage Number	Particle Diameter (microns)
1	10
2	8.5
3	6.0
4	4.0
5	2.5
6	1.0
7	0.75
8	0.50
Filter	0.30

Table 16
Cascade Impactor Stage Elemental Analysis

Run 7 (Waste E)																		
Stage	C	O	Al	Si	P	Cl	Ca	Cr	Fe	Ni	Zn	Ba	S	Pb	K	Na	Mg	Ti
1	X	X	X	X	X	X	X	X	X	X	X	X	X					
2	X	X	X	X	X	X	X	X	X	X	X	X		X	X			
3	X	X	X	X	X	X	X	X	X		X	X		X	X			
4	X	X	X	X	X	X	X				X	X		X	X			
5	X	X	X	X	X	X	X				X	X		X	X			
6	X	X	X	X	X	X	X	X	X	X	X	X		X		X		
7	X	X			X	X	X				X	X		X	X	X		
8	X	X	X	X	X	X	X				X	X		X	X			
Filter	X	X			X	X	X				X			X				

Table 16 cont.
Cascade Impactor Stage Elemental Analysis

Run 10 (Waste E)																		
Stage	C	O	Al	Si	P	Cl	Ca	Cr	Fe	Ni	Zn	Ba	S	Pb	K	Na	Mg	Ti
1	X	X	X	X	X	X	X	X	X	X			X	X			X	
2	X	X	X	X	X	X	X	X	X	X	X			X		X	X	
3	X	X	X	X	X	X	X	X	X	X	X		X	X	X	X		
4	X	X	X	X	X	X	X	X	X	X	X	X		X	X	X	X	
5	X	X	X	X	X	X	X				X	X	X	X	X	X		
6	X	X			X	X					X			X				
7	X	X			X	X					X			X				
8	X	X			X	X					X			X	X			
Filter	X	X	X	X	X	X	X				X			X	X			
Run 14 (Waste E)																		
Stage	C	O	Al	Si	P	Cl	Ca	Cr	Fe	Ni	Zn	Ba	S	Pb	K	Na	Mg	Ti
1	X	X	X	X		X	X	X	X	X				X	X	X		
2	X	X	X	X		X	X	X	X	X				X	X			
3	X	X	X	X	X	X	X	X	X	X	X	X		X	X			
4	X	X	X	X	X	X	X	X	X	X	X	X		X				
5	X	X	X	X	X	X	X	X	X	X	X	X		X	X	X		
6	X	X	X	X	X	X	X				X	X		X	X	X		
7	X	X				X					X			X	X	X		
8	X	X			X	X					X			X	X			
Filter	X	X			X	X					X			X		X		
Run 18 (Waste A)																		
Stage	C	O	Al	Si	P	Cl	Ca	Cr	Fe	Ni	Zn	Ba	S	Pb	K	Na	Mg	Ti
1	X	X	X	X	X	X	X	X	X	X	X		X			X		
2	X	X	X	X	X	X	X	X	X	X	X					X		
3	X	X	X	X	X	X	X	X	X	X	X					X		
4	X	X	X	X		X	X	X	X	X	X					X		
5	X	X	X	X	X	X	X	X	X	X	X					X		
6	X	X	X	X	X	X	X				X			X		X		
7	X	X	X	X	X	X	X				X			X		X		
8	X	X	X	X	X	X	X				X			X	X	X		
Filter	X	X	X	X		X	X	X	X		X					X		

Table 16 cont.
Cascade Impactor Stage Elemental Analysis

Run 21 (Waste B)																		
Stage	C	O	Al	Si	P	Cl	Ca	Cr	Fe	Ni	Zn	Ba	S	Pb	K	Na	Mg	Ti
1	X	X	X	X		X	X	X	X	X			X					
2	X	X	X	X			X		X						X		X	X
3	X	X	X	X			X		X									X
4	X	X	X	X		X	X		X									
5	X	X	X	X		X	X	X	X							X		
6	X	X	X	X		X	X		X				X		X	X		
7	X	X	X	X		X	X	X	X									
8	X	X	X	X		X	X		X	X								
Filter	X	X	X	X		X	X		X						X	X		
Blank Substrate Fibers																		
	C	O	Al	Si	P	Cl	Ca	Cr	Fe	Ni	Zn	Ba	S	Pb	K	Na	Mg	Ti
Stage	X	X	X	X			X											
Filter	X	X	X	X			X											

Kiln Bottom Ash Characterization

The ash collected at the kiln exit was analyzed for total carbon, chlorine, and selected samples were sampled by X-ray Diffraction for the presence of crystalline compounds. The variables expected to impact the composition of the bottom ash are waste type, ash bed temperature, and residence time of the ash in the kiln

Ash collected after burning Type B Waste was very light (bulk density of approximately 0.2 g/cc), flaky, and white in color. Ash from the Type A and E runs ranged from granular to a fine dust (bulk density between 0.5-0.6 g/cc) within the same run. These ashes varied in color from brownish-green to bright-green

Kiln Ash Bed Temperature Profile

The ash bed temperature was continuously measured at four locations in the kiln: T4 is 2 ft from the feed end, T3 is 3.5 ft from the feed end, T2 is 5 ft from the feed end, and T1 is 6.5 ft from the feed end (1 ft from the ashout end). Table 17 summarizes the kiln solids bed temperatures observed during each run

TABLE 17
Kiln Solids Bed Temperature Profile

Run	Waste Type	Measured Avg. Kiln Temp, °F	Solids Bed Temperature, °F			
			T1 (ash end)	T2	T3	T4 (feed end)
1	A	1410	1275	1323	1434	1625
2	A	1497	1375	1431	1596	1628
3	A	1829	1787	1837	2001	1807
4	A	1837	1718	1886	1987	1996
5	A	1423	1293	1368	1474	1564
6	A	1517	1400	1487	1687	1530
7	E	1832	1791	1832	2072	1547
8	A	1823	1736	1773	1838	1775
9	A	1844	1780	1915	2067	2009
10	E	1413	1285	1322	1614	1255
11	A	1417	1232	1317	1409	1588
12	A	1843	1703	1849	1916	1927
13	A	1838	1782	1826	1988	1813
14	E	1606	1522	1585	1898	1339
15	A	1612	1496	1573	1822	1462
16	A	1441	1322	1387	1525	1607
17	A	1376	1288	1345	1524	1681
18	A	1616	1590	1634	1886	1596
19	A	1840	1779	1819	1919	1961
20	A	1398	1281	1300	1434	1573
21	B	1826	1688	1691	1796	1617
22	B	1827	1726	1716	1844	1574

The maximum average bed temperature occurred at either location T3 or T4. These locations corresponded with the most vigorous burning area, typically immediately after ignition of the waste feed box. For either high feed rate conditions and/or densely packed waste, the most vigorous burning occurred at T3. While at lower feed rates and lower waste densities, the most vigorous burning occurred closest to the waste feed inlet. For Type A simulated waste, this data is plotted in Figures 8 and 9. In these graphs, the kiln bed temperature profile is shown for target kiln temperatures of 1400°F (Figure 8) and 1830°F (Figure 9). Also included is the average kiln offgas temperature during the run.

FIGURE 8
Kiln Bed Temperature Profile @ 1400°F Target Kiln Offgas Temperature
Type A Waste

FIGURE 9
Kiln Bed Temperature Profile @ 1830°F Target Kiln Offgas Temperature
Type A Waste

In Figures 10 and 11 the kiln bed temperature profiles are plotted for Types B and E waste respectively.

FIGURE 10
Kiln Bed Temperature Profile Type B Waste

FIGURE 11
Kiln Bed Temperature Profile Type E Waste

Kiln Bottom Ash Carbon Content

Kiln bottom ash from every run was collected and analyzed for total carbon using method ASTM D-3178. The results from these analyses are presented below in Table 18.

TABLE 18
Kiln Bottom Ash Carbon Content

Run	Waste Type	Offgas temp. (°F)		Waste feed rate kBtu/hr	Kiln solids residence time, min.	Waste density lb/ft ³	Ash Carbon Content wt%
		Kiln exit	SCC exit				
1	A	1400	1600	335	30	3	0.397
2	A	1400	1600	605	60	3	0.134
3	A	1830	2010	605	30	3	0.093
4	A	1830	2010	335	60	3	0.022
5	A	1400	1600	335	30	9	0.430
6	A	1400	1600	605	60	9	0.225
7	E	1830	2010	605	30	9	0.090
8	A	1830	2010	335	60	9	0.105
9	A	1830	2010	605	60	6	0.152
10	E	1400	1600	605	30	6	0.576
11	A	1400	1600	335	60	6	0.867
12	A	1830	2010	335	30	6	0.091
13	A	1830	2010	470	45	9	0.057
14	E	1600	2000	605	45	9	0.108
15	A	1600	2000	470	60	9	0.164
16	A	1400	1600	470	30	9	0.421
17	A	1400	1600	470	60	3	0.204
18	A	1600	2000	605	30	3	0.138
19	A	1830	2010	335	45	3	0.080
20	A	1400	1600	335	45	9	0.240
21	B	1830	2010	270	30	9	0.273
22	B	1830	2010	270	60	9	0.204

A statistical analysis was conducted on the data in Table 18 to determine if a mathematical model could be derived to predict the weight percent carbon in the kiln bottom ash as a function of kiln temperature, waste feed rate, waste density, and waste residence. Although the data did not reveal a reliable model for predicting carbon content of the ash, average kiln offgas temperature

and waste density were found to be the most significant variables for determining ash carbon content. The relationship between percent carbon in the ash and kiln temperature is shown in Figure 12. As expected, as kiln temperature is increased, the carbon remaining in the bottom ash decreases.

FIGURE 12
Ash Weight Percent Carbon As A Function of Kiln Offgas Temperature

Kiln Bottom Ash Chloride Content

The bottom ash from five runs was analyzed to measure the concentration of chloride remaining in the ash. The results from this analysis is shown in Table 19.

TABLE 19
Kiln Bottom Ash Chloride Content

Run	Waste Type	Offgas temp. (°F)		Waste feed rate kBtu/hr	Kiln solids residence time, min.	Waste density lb/ft ³	Ash Chloride Content wt%
		Kiln exit	SCC exit				
7	E	1830	2010	605	30	9	0.000578
10	E	1400	1600	605	30	6	3.73
14	E	1600	2000	605	45	9	0.190
15	A	1600	2000	470	60	9	0.000940
18	A	1600	2000	605	30	3	0.160

There does not appear to be any strong correlation between ash chloride concentration and the test variables. A weak relationship between kiln temperature and ash chloride concentration might exist, yet the data set is too limited for statistical determination.

Ash X-Ray Diffraction Analysis

Bottom ash from four runs was analyzed by X-Ray Diffraction to identify any crystalline phases in the ash. This method will detect crystalline phases with concentrations greater than 5-10 wt%. Three runs burning Type A waste and one run using Type B waste were analyzed. Table 20 lists the compounds detected in each of these samples.

TABLE 20
Kiln Bottom Ash Chloride Content

Run	Waste Type	Detected Crystalline Species
2	A	Sodium Zinc Chloride Hydrate Aluminum Silicate Aluminum Oxide Sodium Chloride
11	A	Aluminum Silicate Aluminum Oxide Sodium Chloride
16	A	Sodium Zinc Chloride Hydrate Aluminum Oxide Sodium Chloride Silicon Oxide
21	B	Calcium Hydroxide Calcium Carbonate Sodium Chloride Aluminum Oxide

Ash Elemental Analysis

Bottom ash samples from selected runs were analyzed by ICP mass spectroscopy. The results from this analysis are shown in Table 21

Table 21
Bottom Ash Elemental Analysis (wt%)

Element	RUN #								
	21	6	8	10	16	9	10	7	14
Ca	30.71	36.97	37.03	44.31	40.89	34.09	31.78	37.95	38.09
Cd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Cu	nd	0.009	0.01	0.005	0.005	0.003	0.007	nd	nd
Mg	0.553	0.546	0.531	0.654	0.889	0.446	0.562	0.464	0.464
Mn	0.022	0.038	0.158	0.075	0.049	0.073	0.052	0.048	0.037
Pb	nd	nd	nd	nd	nd	nd	0.281	nd	nd
Sb	0.061	0.044	0.051	0.061	nd	0.054	0.76	0.262	0.403
Tl	0.42	0.305	0.254	0.355	0.276	0.421	0.435	0.486	0.409
Zn	0.098	0.549	0.461	0.236	0.586	0.266	0.794	0.184	0.352
Al	0.416	1.124	2.031	1.122	1.145	2.593	1.687	1.81	0.867
Ba	0.002	0.114	0.047	0.065	0.121	0.058	3.889	6.745	6.354
Fe	0.396	0.768	4.988	3.024	1.007	1.717	1.442	1.461	0.463
Na	0.308	0.21	nd	nd	0.06	0.107	0.352	nd	nd
Ni	nd	0.057	0.353	0.208	0.136	0.146	0.218	0.172	0.224
Ti	0.039	0.064	0.053	0.072	2.11	0.231	0.085	0.079	0.051
Cr	0.048	0.075	0.228	0.303	0.097	0.086	0.704	0.789	0.723
P	0.142	2.802	1.463	2.191	0.456	1.669	2.311	1.907	1.99
Si	0.276	0.578	0.488	0.99	1.101	0.602	1.054	0.897	0.927

Note: nd=non-detect

SCC Offgas Organics Emissions

The incinerator SCC offgas was sampled for organics during runs 7, 10, and 14. During each of these runs, two Principal Organic Hazardous Constituents (POHCs), hexachlorobenzene and hexachloroethane were added to the waste feed. These are the POHCs currently planned for use in the CIF trial burn.

POHC Destruction

The SCC offgas was sampled using Method 0010 and then analyzed for the test POHCs according to Method 8270. The test POHCs were not detected in the afterburner offgas above the Method detection limit of 2.02 µg/train for hexachlorobenzene and 4.32 µg/train for hexachloroethane. The offgas samples were also analyzed for the target POHCs using a selected

ion monitoring (SIM) technique, which gave the ability to detect lower concentrations of the target compounds. A Method 0010 sampling train was also run for Run 18 with Waste Type A for background information purpose. The Method 8270 full-scan analysis, and the SIM analyses results are summarized in Table 22.

Table 22
POHCs Analysis Results

Run	Method 8270, $\mu\text{g}/\text{train}$		Method 8270, $\mu\text{g}/\text{train}$	
	Hexachlorobenzene	Hexachloroethane	Hexachlorobenzene	Hexachloroethane
18	< 2.02	< 4.32	0.486	<0.02
10	< 2.02	< 4.32	0.072	0.975
7	< 2.02	< 4.32	0.129	1.53
14	< 2.02	< 4.32	0.061	1.64

The POHCs feed rates for the three Waste E runs (7, 10, and 14) were 146.8 g/hr of hexachlorobenzene and hexachloroethane each. The POHCs emission rates in the SCC offgas for the three runs and the DREs are calculated and listed in Table 23. DREs for hexachlorobenzene and hexachloroethane were calculated based on the Method 8270 analysis data. DRE of hexachlorobenzene was at least 99.999 percent, and DRE of hexachloroethane was at least 99.990 percent. The SIM analysis results were not used to estimate the DREs, since it is not an EPA standard method. However, the levels detected using the SIM technique were much lower than the method detection limit of Method 8270 for hexachlorobenzene and hexachloroethane. Therefore, the DRE using the SIM data would be greater than those reported using Method 8270 data.

Table 23
POHCs Analysis Results

Run	Hexachlorobenzene		Hexachloroethane	
	$\mu\text{g}/\text{hr}$	DRE	$\mu\text{g}/\text{hr}$	DRE
10	< 761	> 99.9995	< 1627	> 99.999
7	< 1096	> 99.9993	< 2344	> 99.998
14	< 1094	> 99.9993	< 2341	> 99.998

The CIF will be required to demonstrate at least 99.99% DRE for all POHCs during the trial burn. All observed DREs were greater than 99.998%, exceeding the required DRE. Based on these results, acceptable POHC DREs can be obtained at incineration temperatures as low as 1400°F.

Chlorinated Dioxin and Furan Results

The scrubber offgas was sampled and analyzed for polychlorinated dibenzo[p]dioxins (PCDD) and polychlorinated dibenzofurans (PCDF). The toxicity equivalent factor (TEF) is the 2,3,7,8 TCDD (the most hazardous isomer) toxicity equivalent of the various mono through octachlorinated dibenzodioxins and dibenzofurans. TEFs used (Table 24, column 2) for the individual congeners were recommended by the U.S. EPA (Boiler and Industrial Furnaces Methods Manual, 1991). The total 2,3,7,8 TCDD toxicity equivalent is calculated by multiplying the TEF of each compound with its concentration and summing the result of all compounds. Results are summarized in Table 24. The levels of total PCDDs/PCDFs range from 2.30 ng/dscm to 0.50 ng/dscm @ 7% O₂. These values are considerably lower than the current EPA guidance of 30 ng/dscm @ 7% O₂. As shown in Table 24, most isomer and total PCDD/PCDF levels in Run 18 are greater than Runs 10, 7, and 14. The concentration levels in Run 18 imply that most of the chlorinated PCDDs/PCDFs that were formed were likely due to the PVC in the feed, and the contribution from added POHCs (in Runs 10, 7, and 14) was not significant.

Table 24
Scrubber PCDD/PCDF Emissions

Compound	TEF	Scrubber offgas, ng/dscm			
		Run 18	Run 10	Run 7	Run 14
2,3,7,8-TCDD	1.0	<0.0009	<0.003	<0.0039	<0.006
1,2,3,7,8-PeCDD	0.5	<0.015	<0.009	<0.025	<0.013
1,2,3,4,7,8-HxCDD	0.1	0.012*	<0.006	<0.019	<0.009
1,2,3,6,7,8-HxCDD	0.1	0.009*	0.0003	<0.013	0.006
1,2,3,7,8,9-HxCDD	0.1	0.015	0.006*	0.013*	<0.006
1,2,3,4,6,7,8-HpCDD	0.01	0.078	0.031	0.047*	0.051
OCDD	0.001	0.33	0.097*	0.138	0.102
2,3,7,8-TCDF	0.1	0.126*	0.034	0.119	0.074
1,2,3,7,8-PeCDF	0.005	0.033	0.014*	<0.019	0.0013
2,3,4,7,8-PeCDF	0.5	0.099	0.023*	0.075	0.058*
1,2,3,4,7,8-HxCDF	0.1	0.121	0.031	0.103	0.074
1,2,3,6,7,8-HxCDF	0.1	0.048	0.011	0.038	0.023
2,3,4,4,7,8-HxCDF	0.1	0.108	0.028	0.081	0.07
1,2,3,7,8,9-HxCDF	0.1	<0.009	0.003	<0.015	<0.009
1,2,3,4,6,7,8-HpCDF	0.01	0.0142	0.037	0.084*	0.08
1,2,3,4,7,8,9-HpCDF	0.01	0.048	0.020	0.028	0.023
OCDF	0.001	0.332	0.094	0.144*	0.141

* - detected at estimated maximum possible concentration (EMPC)

Table 24 cont.
Scrubber PCDD/PCDF Emissions

Total TCDD	-	0.015*	0.006*	0.03	0.013
Total PeCDD	-	0.069	0.02	0.081	0.022
Total HxCDD	-	0.045	0.02	0.041	0.04
Total HpCDD	-	0.145	0.031	0.059	0.096
Total TCDF	-	0.393	0.123	0.21	0.289
Total PeCDF	-	0.785	0.088	0.312	0.282
Total HxCDF	-	0.513	0.120	0.344	0.273
Total HpCDF	-	0.332	0.094	0.097	0.180
Total PCDD/PCDF		2.297	0.502	1.174	1.195
TEQ	-	0.116	0.033	0.0097	0.064

* - detected at estimated maximum possible concentration (EMPC)

Metals Partitioning

Another test objective was determining waste feed heavy metals partition between the kiln bottom ash and incinerator offgas and comparing to the previous waste burn test conducted on a much smaller scale incinerator.¹ 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 25 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

Six metals were spiked into the waste feed (Waste Type E) for these tests: mercury, lead, chromium, thallium, barium, and antimony. The average metal composition in Waste E is presented in Table 4. Partition factors were determined by measuring the metal concentration in the kiln bottom ash and SCC offgas generated during each test run. 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.⁴ 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 normalized distributions to best quantify metal partitioning, given the variable and less than perfect metals mass balance closure

TABLE 25
Metal Volatility Temperature⁴

Metal	Volatility Temp (°F)	Volatility Temp (°F) with chlorides present
Chromium	2935	2930
Barium	1560	1660
Thallium	1330	280
Antimony	1220	1220
Lead	1160	5
Mercury	57	57

Table 26 summarizes the trace metal test results. The trace metal worksheets used to calculate normalized metal distributions are included in Appendix C. The average kiln ash solids bed temperature ranged from 1369 to 1810°F. Lead and mercury have the lowest volatility temperatures in the presence of chlorides. The test data showed that practically 100% of these metals volatilized out of the kiln and entered the APCS. The volatility temperature of thallium is significantly below the observed average kiln bed temperature and, as expected, approximately 70% of the metal volatilized into the APCS. The volatility temperature of antimony was in the same range as the observed kiln bed temperatures and the fraction of antimony remaining in the kiln bottom ash averaged approximately 70%. The volatility temperature of barium is greater than the volatility temperature of antimony, and the fraction of barium remaining in the kiln bottom ash averaged approximately 90%. Chromium, having the highest volatility temperature, was found to exhibit the least volatile behavior of all the metals with approximately 95% of the chromium remaining in the kiln bottom ash. These results are very similar to the metals partition observed in the small-scale metals partitioning study.¹ The only significant difference is the volatility of antimony was consistently higher in these tests. The fraction of antimony remaining in the kiln bottom ash during the previous study averaged approximately 95%, while only 70% of the antimony remained in the kiln ash during these tests.

The normalized metals distributions for Runs 7, 10, and 14 are presented graphically in Figures 13, 14, and 15 respectively.

Table 26
Metals Partitioning Percent Distribution

Metal	Run 7		Run 10		Run 14	
	Ash	Offgas	Ash	Offgas	Ash	Offgas
Chromium	91	9	97	3	95	5
Barium	86	14	97	3	93	7
Thallium	32	68	40	60	27	73
Antimony	53	47	85	15	68	32
Lead	0	100	7	93	3	97
Mercury	0	100	0	100	0	100
Kiln temp. (°F)	1413		1832		1606	
SCC temp. (°F)	1606		2017		2008	
Avg. kiln bed temp. (°F)	1369		1810		1586	
% Cl in feed	3.7		3.9		3.9	

Figure 13
Run 7 Normalized Metal Distribution

Figure 14
Run 10 Normalized Metal Distribution

Figure 15
Run 14 Normalized Metal Distribution

Metals Mass Balance

System mass balances for each spiked metal were calculated for each test run. These results are summarized in Table 27. The percent recovered is defined as the total mass of metal measured in the bottom ash and stack gas, divided by the total metal spiked in the waste feed. Calculation of total metal in the stack gas was conducted by multiplying the metal concentration by the total volume of 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 ash after each test run. This number was calculated using the ash analysis of the simulated waste feed material. Using the percent ash in 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 28 to 97%. These percent recoveries are typical of other metals mass balance closure for this type of test.⁴

Table 27
Metals Percent Recovery

METAL	Run Number			Average
	7	10	14	
Lead	24	25	36	28
Mercury	53	54	66	58
Chromium	69	74	77	73
Antimony	47	68	79	65
Barium	31	27	38	32
Thallium	92	84	115	97

CONCLUSIONS

A series of tests were conducted to study the incineration characteristics of simulated waste feeds representing Savannah River Site solid low-level radioactive mixed wastes. Three simulated waste types were burned in a test program which evaluated the following system variables: waste type, waste density, waste feed rate, solids residence time, and incineration temperature. A statistical experimental design was utilized to model kiln emissions with a quadratic mathematical model. The following conclusions are drawn from the test program results:

Offgas Particulate Carryover

The percent of ash in the waste feed carried into the system APCS varied between 9% and 53%. A statistical evaluation of the test results showed that incineration temperature was the most

significant variable determining percent ash carryover. Ash carryover increased with increasing kiln temperature. Percent ash carryover also increased as the waste feedrate was increased.

Incinerator Offgas Particulate Characterization

Kiln offgas particulate concentrations ranged from 175 mg/dscm - 743 mg/dscm. In general, the particulate in the SCC offgas increased with increasing waste feed rates. Yet, no general trend was observed between particulate loading and incineration temperature. The size distributions of offgas particulates were also measured. Test conditions did not appear to have a significant effect on the particle size distributions. Yet, the distributions between Waste Type B and Waste Types A and E had a very significant difference. Waste Type B offgas particulate had a much larger average particle diameter than offgas particulate from Waste Types A or E.

Kiln Bottom Ash Characterization

Kiln bottom ash from each run was collected and analyzed for metals concentration and identification of specific compounds. Compounds identified in the ash from Waste Types A and B include sodium zinc chloride hydrate, aluminum silicate, aluminum oxide, silicon oxide, sodium chloride, calcium hydroxide, and calcium carbonate. Compounds previously identified in the Waste Type E ash included barium carbonate, barium calcium silicate, barium aluminum oxide, barium silicate, lead antimony sulfide, silicon oxide, sodium calcium aluminum silicate, aluminum oxide, and aluminum silicate. The carbon content of the bottom ash was quite low, ranging from 0.022 to 0.867 wt% total carbon. A correlation between kiln temperature and ash carbon content was observed. As kiln temperature increased, the percent carbon in the bottom ash was found to decrease.

Organics Destruction

To measure the organics destruction at varying kiln operating temperatures, hexachloroethane and hexachlorobenzene were burned and sampled in the kiln offgas. The CIF permit requires organic destruction of greater than 99.99%. The target POHCs were not found above the method detection limits in any of the tests. The DRE for hexachlorobenzene was at least 99.999 percent. Hexachloroethane DRE was at least 99.998 percent (Kiln temperatures from 1400°F - 1832°F).

Offgas from the scrubber was sampled and analyzed for PCDDs/PCDFs during Runs 18, 10, 7, and 14. The levels of total PCDDs/PCDFs ranged from 2.30 ng/dscm to 0.50 ng/dscm at 7 percent oxygen, and were significantly lower than the recent EPA guidance of 30 ng/dscm at 7 percent oxygen. PCDDs and PCDFs were found at somewhat higher levels during Run 18 which did not contain the two added chlorinated POHCs. This suggests the PCDD/PCDF generation was more likely due to the PVC in the feed than from the two added POHCs.

Metals Partition

The trace metals results indicate that Pb and Hg were very volatile and almost completely vaporized from the kiln bottom ash. Two of the metals, Cr and Ba were very nonvolatile and remained completely in the bottom ash (a small fraction was entrained in the flyash). Two metals, Sb and Tl exhibited semi-volatile behavior and split between the bottom ash and the offgas. The metal partitioning behavior observed during these tests is consistent with the data obtained in the previous study.

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APPENDIX A

Kiln Operating Conditions

	Test 1 (5/06/93)	Test 2 (4/27/93)	Test 3 (4/13/93)	Test 4 (5/19/93)	Test 5 (3/31/93)	Test 6 (3/30/93)	Test 7 (6/08/93)	Test 8 (4/01/93)	Test 9 (5/13/93)	Test 10 (6/03/93)	Test 11 (5/11/93)
Kiln											
Natural gas feed											
Average, scfm/hr	12	4	11	32	13	5	18	23	18	4	15
(scfh)	(429)	(131)	(371)	(1129)	(451)	(160)	(648)	(808)	(623)	(150)	(525)
kW	126	38	109	331	132	47	190	237	163	44	154
(kBtu/hr)	(429)	(131)	(371)	(1129)	(451)	(160)	(648)	(808)	(623)	(150)	(525)
Combustion air flow rate,											
Average, scfm/hr	57	180	285	270	127	63	271	272	281	139	155
(scfh)	(2010)	(6346)	(10066)	(9533)	(4471)	(3271)	(9590)	(9611)	(9940)	(4893)	(5467)
Total air input flow rate											
average, dscfm/hr	57	180	285	270	127	93	271	272	281	139	155
(dscfh)	(2010)	(6346)	(10066)	(9533)	(4471)	(3271)	(9590)	(9611)	(9940)	(4893)	(5467)
Draft											
Average, Pa	6	7	8	8	6	10	2	6	3	6	6
(in WC)	(0.023)	(0.027)	(0.033)	(0.033)	(0.023)	(0.04)	(0.01)	(0.023)	(0.012)	(0.023)	(0.023)
Exit temperature											
Range, °C	717-823	598-883	943-1033	959-1034	733-821	706-907	917-1048	950-1042	959-1042	874-811	736-810
(°F)	(1323-1513)	(1108-1622)	(1730-1891)	(1758-1894)	(1352-1510)	(1302-1664)	(1683-1919)	(1742-1908)	(1759-1908)	(1245-1492)	(1357-1490)
Average, °C	766	814	998	1003	773	825	1000	995	1007	767	769
(°F)	(1410)	(1497)	(1829)	(1837)	(1423)	(1517)	(1832)	(1823)	(1844)	(1413)	(1417)

Kiln operating conditions (cont'd)

	Test 1 (5/06/93)	Test 2 (4/27/93)	Test 3 (4/13/93)	Test 4 (5/19/93)	Test 5 (3/5/93)	Test 6 (3/30/93)	Test 7 (6/08/93)	Test 8 (4/01/93)	Test 9 (5/13/93)	Test 10 (6/03/93)	Test 11 (5/11/93)
Kiln (cont'd)											
Exit O ₂											
Range, %	6.9-16.3	6.8-19.9	8.1-14.0	6.4-13.4	7.9-16.1	6.3-17.2	3.7-15.1	2.9-14.5	5.8-17.8	8.2-14.9	6.9-14.9
Average, %	12.5	12.4	10.5	9.8	13.4	11.1	9	9.9	10	12.2	12.6
Waste feed rate											
Average, kg/hr (lb/hr)	18 (40)	37 (81.2)	37 (81.3)	20 (43.4)	16 (34.7)	27 (60.5)	39 (86.1)	16 (35)	31 (67.5)	42 (92.2)	17 (36.7)
Solid Waste											
Waste heating											
kJ/kg	25609	25609	25609	25609	25609	25609	25609	25609	25609	25609	25609
(Btu/lb)	(11010)	(11010)	(11010)	(11010)	(11010)	(11010)	(11010)	(11010)	(11010)	(11010)	(11010)
Waste heat input											
kW	129	262	262	140	112	195	278	113	216	297	118
(Btu/hr)	(440400)	(894012)	(895113)	(477834)	(382047)	(666105)	(947961)	(385350)	(743175)	(1015122)	(404067)
Total heat input											
kW	255	300	371	471	244	242	468	350	400	341	272
(kBtu/hr)	(869)	(1025)	(1266)	(1807)	(833)	(826)	(1596)	(1193)	(1366)	(1165)	(929)
Residence time											
Solids, hr	0.5	1	0.5	1	0.5	1	0.5	1	1	0.5	1
rpm	0.5	0.17	0.5	0.17	0.5	0.17	0.5	0.17	0.17	0.5	0.17

Kiln Operating Conditions (cont'd)

	Test 12 (5/18/93)	Test 13 (4/28/93)	Test 14 (6/10/93)	Test 15 (5/27/93)	Test 16 (5/05/93)	Test 17 (4/07/93)	Test 18 (5/25/93)	Test 19 (4/29/93)	Test 20 (4/06/93)	Test 21 (3/24/93)	Test 22 (3/25/93)
Kiln											
Natural gas feed											
Average, scm/hr	29	18	11	16	8	6	10	25	13	21	22
(scfh)	(1011)	(626)	(397)	(576)	(267)	(215)	(373)	(883)	(446)	(768)	(791)
kW	296	183	118	168	78	63	109	259	130	225	232
(KBtu/hr)	(1024)	(636)	(388)	(565)	(282)	(282)	(388)	(883)	(459)	(777)	(777)
Combustion air flow rate,											
Average, scm/hr	269	284	273	261	104	116	230	280	125	277	275
(scfh)	(9484)	(10032)	(9651)	(9212)	(3668)	(4113)	(8137)	(9900)	(4413)	(9793)	(9715)
Total air input flow rate											
Average, dscm/hr	269	284	273	261	104	116	230	280	125	277	275
(dscfh)	(9484)	(10032)	(9651)	(9212)	(3668)	(4113)	(8137)	(9900)	(4413)	(9793)	(9715)
Draft											
Average, Pa	4	3	3	4	5	10	4	4	7	5	5
(in WC)	(0.016)	(0.014)	(0.014)	(0.016)	(0.021)	(0.039)	(0.016)	(0.016)	(0.029)	(0.021)	(0.021)
Exit temperature											
Range, °C	977-1037	954-1049	822-915	842-917	739-833	566-860	837-916	970-1032	656-829	987-1028	978-1021
(°F)	(1790-1898)	(1749-1921)	(1511-1679)	(1547-1682)	(1362-1532)	(1051-1580)	(1539-1681)	(1778-1890)	(1212-1524)	(1773-1883)	(1788-1869)
Average, °C	1006	1003	874	878	783	747	860	1004	759	997	997
(°F)	(1843)	(1838)	(1606)	(1612)	(1441)	(1376)	(1616)	(1840)	(1398)	(1826)	(1827)

Kiln operating conditions (cont'd)

	Test 12 (5/18/93)	Test 13 (4/28/93)	Test 14 (6/10/93)	Test 15 (5/27/93)	Test 16 (5/05/93)	Test 17 (4/07/93)	Test 18 (5/25/93)	Test 19 (4/29/93)	Test 20 (4/06/93)	Test 21 (3/24/93)	Test 22 (3/25/93)
Kiln (cont'd)											
Exit O ₂											
Range, %	6.8-14.5	6.8-13.9	6.6-14.8	6.6-14.2	4.0-16.0	8.6-19.0	8.9-13.9	7.9-12.7	6.3-17.0	6.7-11.5	7.3-13.7
Average, %	11	11.1	11	11.9	12.1	12.9	10	10.8	12.9	9.2	10.1
Waste feed rate											
Average, kg/hr	16	23	39	23	22	27	37	20	16	34	35
(lb/hr)	(36.1)	(51.6)	(85.7)	(50.9)	(49.5)	(59.7)	(81.5)	(43.7)	(35.9)	(75.2)	(76.6)
Solid Waste											
Waste heating											
kJ/kg	25609	25609	25609	25609	25609	25609	25609	25609	25609	25609	25609
(Btu/lb)	(11010)	(11010)	(11010)	(11010)	(11010)	(11010)	(11010)	(11010)	(11010)	(11010)	(11010)
Waste heat input											
kW	118	166	276	164	160	193	263	141	116	91	92
(Btu/hr)	(397461)	(568116)	(943557)	(560409)	(544995)	(657297)	(897315)	(481137)	(395259)	(309448)	(315209)
Total heat input											
kW	413	350	393	332	238	256	372	400	246	316	324
(KBtu/hr)	(1408)	(1194)	(1341)	(1134)	(812)	(872)	(1270)	(1364)	(839)	(1077)	(1106)
Residence time											
Solids, hr	0.5	0.75	0.75	1	0.5	1	0.5	0.75	0.75	0.5	1
rpm	0.5	0.25	0.25	0.17	0.5	0.17	0.5	0.25	0.25	0.5	0.17

Afterburner operating conditions

	Test 1 (5/06/93)	Test 2 (4/27/93)	Test 3 (4/13/93)	Test 4 (5/19/93)	Test 5 (3/31/93)	Test 6 (3/30/93)	Test 7 (6/08/93)	Test 8 (4/01/93)	Test 9 (5/13/93)	Test 10 (6/03/93)	Test 11 (5/11/93)
Afterburner											
Natural gas feed rate											
Average, scm/hr	14	11	20	20	8	9	26	18	21	16	14
(scfh)	(505)	(392)	(700)	(704)	(296)	(326)	(915)	(637)	(715)	(553)	(492)
kW	148	115	115	206	87	96	268	187	209	162	138
(KBtu/hr)	(505)	(392)	(700)	(704)	(296)	(326)	(915)	(637)	(715)	(553)	(492)
Total air input flow rate											
Average, dscm/hr	72	80	136	224	70	73	272	224	221	134	150
(dscfh)	(2551)	(3175)	(4817)	(7906)	(2469)	(2574)	(9609)	(7919)	(7789)	(4721)	(5300)
Exit temperature											
Range, °C	868-882	867-892	1096-1109	1096-1107	664-882	864-886	1095-1110	1095-1107	1093-1108	860-883	887-881
(°F)	(1590-1619)	(1593-1638)	(2004-2029)	(2004-2024)	(1588-1619)	(1587-1627)	(2003-2030)	(2003-2024)	(1999-2027)	(1580-1621)	(1592-1618)
Average, °C	874	873	1102	1102	874	874	1103	1102	1101	874	873
(°F)	(1605)	(1603)	(2016)	(2015)	(1605)	(1605)	(2017)	(2015)	(2014)	(1605)	(1604)
Exit O ₂											
Range, %	7.6-13.5	9.3-19.7	10.2-15.5	6.8-11.3	8.1-16.1	7.1-16.5	4.4-14.4	2.8-11.4	6.1-11.3	8.9-14.2	8.2-13.3
Average, %	11.2	14	12.8	8.9	13.6	11.1	8.7	8.6	8.7	11.1	11.5
Gas phase											
Residence time AB, s	2.4	1.6	1.2	2.3	2.1	2.7	1.5	1.8	1.6	2.2	2.2
Residence time AB & duct, s	4.1	2.8	2.0	4.1	3.7	4.6	2.6	3.2	2.8	3.8	3.8

Afterburner operating conditions (cont'd)

	Test 12 (5/18/93)	Test 13 (4/28/93)	Test 14 (6/10/93)	Test 15 (5/27/93)	Test 16 (5/05/93)	Test 17 (4/07/93)	Test 18 (5/25/93)	Test 19 (4/29/93)	Test 20 (4/06/93)	Test 21 (3/24/93)	Test 22 (3/25/93)
Afterburner											
Natural gas feed rate											
Average, scm/hr	23	25	33	27	11	7	27	20	6	18	16
(scfh)	(813)	(900)	(1167)	(976)	(402)	(249)	(961)	(722)	(196)	(621)	(575)
kW	238	264	342	296	118	73	282	212	57	182	168
(KBtu/hr)	(813)	(900)	(1167)	(976)	(402)	(249)	(961)	(722)	(196)	(621)	(575)
Combustion air flow rate											
Average, scm/hr	230	255	273	251	71	73	230	229	83	227	225
(scfh)	(8120)	(9015)	(9656)	(8876)	(2490)	(2579)	(8102)	(8070)	(2922)	(8026)	(7933)
Total air input flow rate											
Average, dscm/hr	230	255	273	251	71	73	229	229	83	227	225
(dscfh)	(8120)	(9015)	(9656)	(8876)	(2490)	(2579)	(8102)	(8102)	(2922)	(8026)	(7933)
Exit temperature											
Range, °C	1094-1106	1096-1109	1087-1104	1089-1105	865-883	856-901	1090-1102	1096-1107	864-886	1094-1108	1095-1107
(°F)	(2001-2022)	(2005-2028)	(1988-2020)	(1992-2021)	(1589-1621)	(1572-1654)	(1994-2016)	(2001-2024)	(1587-1826)	(2002-2026)	(2003-2024)
Average, °C	1101	1103	1098	1097	874	874	1097	1102	873	1102	1102
(°F)	(2014)	(2017)	(2008)	(2006)	(1605)	(1605)	(2006)	(2015)	(1604)	(2015)	(2015)
Exit O₂											
Range, %	3.9-10.6	4.9-11.6	5.7-12.9	4.6-10.8	9.3-15.6	9.3-15.8	6.5-10.3	9.8-13.7	8.0-15.9	8.1-10.0	8.4-9.7
Average, %	8.3	8.7	9.1	8.8	13.1	13	8.4	12.3	12.6	8.3	8.5
Gas phase											
Residence time AB, s	1.6	1.6	1.5	1.6	2.1	2.3	1.6	1.2	2.5	1.9	1.8
Residence time AB & duct, s	2.8	2.8	2.6	2.7	3.6	4.1	2.8	2.0	4.3	3.2	3.2

Air pollution control system operating conditions

	Test 1 (5/06/93)	Test 2 (4/27/93)	Test 3 (4/13/93)	Test 4 (5/19/93)	Test 5 (3/31/93)	Test 6 (3/30/93)	Test 7 (6/08/93)	Test 8 (4/01/93)	Test 9 (5/13/93)	Test 10 (6/03/93)	Test 11 (5/11/93)
Quench chamber liquor flow rate											
Average, L/min	76	76	76	76	76	76	76	76	76	76	76
(gpm)	(20)	(20)	(20)	(20)	(20)	(20)	(20)	(20)	(20)	(20)	(20)
Venturi scrubber pressure drop											
Average, L/min	83	83	83	83	83	83	83	83	83	83	83
(gpm)	(22)	(22)	(22)	(22)	(22)	(22)	(22)	(22)	(22)	(22)	(22)
Venturi scrubber pressure drop											
Average, Pa	5718	5444	6041	5071	5718	6091	6240	5419	5693	8215	5842
(in WC)	(23)	(21.9)	(24.3)	(20.4)	(23)	(24.5)	(25.1)	(21.8)	(22.9)	(25)	(23.5)
Packed-column scrubber liquor flow											
Average, L/min	114	114	114	114	114	114	114	114	114	114	114
(in WC)	(30)	(30)	(30)	(30)	(30)	(30)	(30)	(30)	(30)	(30)	(30)
Packed-column scrubber pressure drop											
Average, Pa	348	396	124	945	99	124	920	124	671	497	497
(in WC)	(1.4)	(1.8)	(0.5)	(3.8)	(0.4)	(0.5)	(3.7)	(0.5)	(2.7)	(2)	(2)
Scrubber liquor pH											
Range	3.9-8.5	5.6-8.2	6.9-7.5	5.3-8.4	6.9-7.6	6.8-7.6	6.1-8.4	3.6-9.3	5.1-7.9	3.5-8.9	4.8-9.3
Average	7.8	7.8	7.3	7	7.3	7.3	7.7	7.2	7.2	7.8	7.5
Scrubber makeup total											
Average, L	352	151	1135	1389	901	1173	1344	1370	1177	636	594
(gal)	(93)	(40)	(300)	(367)	(238)	(310)	(355)	(362)	(311)	(168)	(157)
Scrubber blowdown total											
Average, L	0	0	0	0	68	397	0	0	0	0	0
(gal)	(0)	(0)	(0)	(0)	(18)	(105)	(0)	(0)	(0)	(0)	(0)
Scrubber liquor temperature											
Average, °C	70	70	73	74	69	69	74	73	74	70	69
(°F)	(158)	(158)	(164)	(185)	(156)	(156)	(166)	(164)	(165)	(158)	(157)
Scrubber liquor collected											
Total, L	852	852	757	946	1189	1117	1136	946	652	1514	948
(gal)	(225)	(225)	(200)	(250)	(314)	(295)	(300)	(250)	(225)	(400)	(250)
Scrubber inlet gas temperature											
Average, °C	74	74	80	78	74	74	80	78	78	74	75
(°F)	(165)	(166)	(178)	(173)	(168)	(165)	(178)	(173)	(173)	(166)	(167)
Scrubber exit gas temperature											
Average, °C	73	74	79	78	73	73	80	78	78	74	74
(°F)	(164)	(168)	(175)	(172)	(164)	(163)	(178)	(173)	(172)	(165)	(165)

Air pollution control system operating conditions (cont'd)

	Test 12 (5/18/93)	Test 13 (4/28/93)	Test 14 (6/10/93)	Test 15 (5/27/93)	Test 16 (5/05/93)	Test 17 (4/07/93)	Test 18 (5/25/93)	Test 19 (4/29/93)	Test 20 (4/08/93)	Test 21 (3/24/93)	Test 22 (3/25/93)
Quench chamber liquor flow rate											
Average, L/min	76	76	76	76	76	76	76	76	76	76	76
(gpm)	(20)	(20)	(20)	(20)	(20)	(20)	(20)	(20)	(20)	(20)	(20)
Venturi scrubber pressure drop											
Average, L/min	83	83	95	95	83	76	83	79	76	88	68
(gpm)	(22)	(22)	(25)	(25)	(22)	(20)	(22)	(21)	(20)	(18)	(18)
Venturi scrubber pressure drop											
Average, Pa	5370	5221	6116	5817	5345	5942	6066	4972	5792	5395	5345
(in WC)	(21.6)	(21)	(24.6)	(23.4)	(21.5)	(23.9)	(24.4)	(20)	(23.3)	(21.7)	(21.5)
Packed-column scrubber liquor flow											
Average, L/min	114	114	114	114	114	114	114	114	114	114	114
(in WC)	(30)	(30)	(30)	(30)	(30)	(30)	(30)	(30)	(30)	(30)	(30)
Packed-column scrubber pressure drop											
Average, Pa	746	696	895	845	273	124	845	671	124	124	124
(in WC)	(3)	(2.8)	(3.6)	(3.4)	(1.1)	(0.5)	(3.4)	(2.7)	(0.5)	(0.5)	(0.5)
Scrubber liquor pH											
Range	4.2-8.3	4.7-7.3	4.1-8.4	4.2-9.3	3.8-8.0	3.4-9.3	4.2-9.8	6.5-8.3	5.1-9.1	7.5-7.8	7.5-7.8
Average	7.4	6.8	7.7	7.6	6.8	7.8	6.9	7.1	7.3	7.7	7.8
Scrubber makeup total											
Average, L	1166	923	1514	1238	360	1234	1351	1196	17600	1605	1366
(gal)	(308)	(244)	(400)	(327)	(95)	(326)	(357)	(316)	(485)	(424)	(361)
Scrubber blowdown total											
Average, L	0	0	0	0	0	295	0	0	534	0	0
(gal)	(0)	(0)	(0)	(0)	(0)	(78)	(0)	(0)	(141)	(0)	(0)
Scrubber liquor collected											
Total, L	757	852	757	855	946	1234	852	757	1344	473	473
(gal)	(200)	(225)	(200)	(226)	(250)	(326)	(225)	(200)	(355)	(125)	(125)
Scrubber liquor temperature											
Average, °C	76	74	74	74	70	68	73	74	69	74	75
(°F)	(168)	(168)	(165)	(166)	(158)	(154)	(164)	(164)	(156)	(165)	(167)
Scrubber inlet gas temperature											
Average, °C	78	81	81	78	74	75	78	79	73	78	79
(°F)	(173)	(177)	(177)	(173)	(168)	(167)	(173)	(174)	(164)	(173)	(174)
Scrubber exit gas temperature											
Average, °C	78	80	80	78	74	74	78	78	72	78	78
(°F)	(173)	(176)	(176)	(172)	(165)	(165)	(172)	(173)	(162)	(173)	(173)

Continuous Emission Monitor data

Parameter	Test 1 (5/06/93)	Test 2 (4/27/93)	Test 3 (4/13/93)	Test 4 (5/19/93)	Test 5 (3/31/93)	Test 6 (3/30/93)	Test 7 (6/08/93)	Test 8 (4/01/93)	Test 9 (5/13/93)	Test 10 (6/03/93)	Test 11 (5/11/93)
Kiln exit											
O ₂ range, %	6.9-16.3	6.8-19.9	8.1-14.0	6.4-13.4	7.9-16.1	6.3-17.2	3.7-15.1	2.9-14.5	5.8-17.8	8.2-14.9	6.9-14.9
average, %	12.5	12.4	10.5	9.8	13.4	11.1	9	9.9	10.0	12.2	12.6
target, %	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
Afterburner exit											
O ₂ range, %	7.6-13.5	9.3-19.7	10.2-15.5	6.8-11.3	8.1-16.1	7.1-16.5	4.4-14.4	2.8-11.4	6.1-11.3	8.9-14.2	8.2-13.3
average, %	11.2	14.0	12.8	8.9	13.6	11.1	8.7	8.6	8.7	11.1	11.5
target, %	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0
CO range, ppm	1-23	2.0-461	----a-	26.0-32.5	9.5-127	8.5-407	2.5-15.0	8.5-60	21-27.5	39.0-58.5	16.0-30.0
average, ppm	2.5	6.5	---	28.1	17.8	29.7	6.5	10.2	24.3	47.0	19.5
CO ₂ range, %	4.4-9.9	1.0-8.2	3.3-7.8	5.8-9.8	9.4-0.1	3.0-10.9	4.0-11.8	5.9-11.0	5.9-10.5	4.3*-9.9	4.6-8.4
average, ppm	6.3	5.0	5.7	7.7	4.7	7.1	8.1	7.6	8.1	7.0	6.1
TUHC range, ppm (as propane)	7.8-12.6	27.3-369	----a-	10.5-21.6	9.3-14.1	-6.0-18	5.7-17.7	-1.2-2.7	7.5-11.7	-3.0-32.4	3.9-6.3
average, ppm (as propane)	9.6	61.0	---	12.4	11.8	6.6	9.3	0.3	9.4	1.6	5.0
NO _x range, ppm	23.3-52.8	4.2-60	13.9-54.5	----a-	32.5-66.1	12.3-65.2	35.4-103.1	41.5-66.4	42.9-68.9	12.9-29.9	30.7-62.8
average, ppm	37.0	32.6	31.3	---	41.8	36.5	60.7	51.3	52.6	20.2	43.0
Scrubber exit											
O ₂ range, %	9.9-14.2	7.1-19.4	7.1-12.5	7.8-11.8	6.1-14.1	6.1-15.0	6.0-12.7	3.7-11.7	6.3-11.9	10.0-14.9	9.9-14.1
average, %	12.1	12.1	9.4	9.9	11.3	11.5	9.3	9.1	9.1	12.2	12.6
CO ₂ range, %	3.6-8.0	0.1-8.3	5.3-10.2	4.9-9.0	3.5-10.3	3.7-10.9	4.6-10.3	5.3-10.9	5.0-10.3	3.6-8.1	3.9-7.8
average, %	5.4	5.9	7.8	6.6	5.9	6.3	7.4	7.1	7.4	5.8	5.2
NO _x range, ppm	---	2.5-68.5	37.8-58.2	47.8-73.7	25.5-64.1	15.9-58.4	40.5-81.2	24.4-70.5	42.0-65.6	30.8-66.5	29.6-53.4
average, ppm	---	32.7	46.8	58.4	44.5	36.7	62.3	57.4	51.5	47.3	38.4

-a- monitor not in operation

Continuous Emission Monitor data (cont'd)

Parameter	Test 12 (5/18/93)	Test 13 (4/28/93)	Test 14 (6/10/93)	Test 15 (5/27/93)	Test 16 (5/05/93)	Test 17 (4/07/93)	Test 18 (5/25/93)	Test 19 (4/29/93)	Test 20 (4/06/93)	Test 21 (3/24/93)	Test 22 (3/25/93)
Kiln exit											
O ₂ range, %	6.8-14.5	6.8-13.9	6.6-14.8	6.6-14.2	4.0-16.0	8.6-19.0	6.4-13.4	7.9-12.7	6.3-17.0	6.7-11.5	7.3-13.7
average, %	11.0	11.1	11.00	11.9	12.1	12.9	9.8	10.8	12.9	9.2	10.1
target, %	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.00	10.0
Afterburner exit											
O ₂ range, %	3.9-10.6	4.9-11.6	5.7-12.9	4.6-10.8	9.3-15.6	9.3-15.8	6.5-10.3	9.8-13.7	8.0-15.9	6.1-10.0	6.4-9.7
average, %	8.3	8.7	9.1	8.8	13.1	13.0	8.4	12.3	12.6	8.3	8.5
target, %	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0
CO range, ppm	23.5-31.0	4.5-10.5	12.5-19.0	5.5-13.0	10.0-30.0	5.5-39.5	5.0-9.0	3.0-19.5	4.5-12.1	5.5-9.5	6.5-11.5
average, ppm	26.7	4.7	15.6	7.2	12.7	10.1	7.2	6.6	9.2	7.5	8.2
CO ₂ range, %	5.8-11.9	5.8-11.8	5.0-10.8	6.1-10.4	3.3-8.9	3.2-9.3	6.6-10.9	1.6-7.3	3.0-9.5	6.7-10.6	7.1-11.3
average, ppm	7.9	8.0	7.8	7.8	5.4	5.6	8.5	5.4	5.5	8.7	8.6
TUHC range, ppm (as propane)	1.8-11.7	8.4-21.9	7.2-36.9	1.8-9.3	1.2-8.4	-----	-----	-----	0.3-5.7	6.0-18	6.0-18
average, ppm (as propane)	7.6	10.5	22.6	3.6	3.8	---	---	---	1.9	9.3	5.7
NO _x range, ppm	45.6-79.7	49.7-73.5	23.6-67.3	34.1-52.4	37.1-125.9	16.9-56.5	28.5-57.63	35.3-45.4	21.5-59.8	36.6-74.1	36.5-57.9
average, ppm	58.0	59.2	51.6	40.4	78.4	28.0	39.7	38.6	33.0	44.3	43.8
Scrubber exit											
O ₂ range, %	5.9-11.5	6.2-12.1	6.8-12.3	6.7-12.0	7.0-14.6	6.9-15.6	7.8-11.7	7.1-11.4	7.9-17.0	7.6-11.1	7.3-11.3
average, %	9.4	9.6	9.7	10.00	11.2	12.0	9.9	9.6	13.1	9.5	9.5
CO ₂ range, %	5.1-10.2	5.0-10.0	5.1-9.9	5.2-9.3	3.4-10.0	2.9-10.3	5.2-9.6	3.1-9.4	2.1-9.7	5.5-10.1	6.1-9.54
average, %	6.8	6.9	7.1	6.7	6.2	5.9	7.1	6.9	4.9	7.4	7.4
NO _x range, ppm	49.3-72.6	50.0-73.2	47.6-74.3	42.1-62.7	28.0-60.5	2.1-58.7	37.9-56.6	4.3-61.8	12.5-62.9	42.2-76.2	42.1-61.3
average, ppm	57.0	59.1	60.7	48.8	38.1	32.3	44.4	49.6	38.3	48.5	49.2

-a- monitor not in operation

APPENDIX
B

Run 1.2

Run 1.3

Run 2.1

Run 2.3

Run 3.3

Run 4.1

Run 4.2

Run 5.2

Run 5.3

Run 6.1

Run 6.2

Run 6.3

Run 7.2

Run 8.1

Run 8.3

Run 9.1

Run 10.1

Run 10.2

- Run 11.1

Run 12.2

Run 12.3

Run 13.1

Run 13.2

Run 13.3

Run 14.2

Run 15.2

Run 16.3

Run 18.1

Run 18.2

Run 18.3

Run 19.3

Run 20.3

Run 20.4

Run 21.1

Run 21.2

Run 21.3

Run 22.1

Run 22.2

Run 22.3

APPENDIX C

TTLBAL.XLS

UNACCOUNTED FOR METALS (grams)						
RUN	PB	HG	CR	SB	BA	TL
7	1,331.487	53.545	32.822	74.921	1,336.850	11.386
10	1,747.009	67.358	35.382	57.116	1,818.172	29.482
14	1,221.422	43.219	27.216	32.692	1,321.048	-22.667
NORMALIZED METALS PARTITION						
TOTAL RECOVERED METALS (grams)						
RUN	PB	HG	CR	SB	BA	TL
7	423.936	61.533	74.454	67.463	613.620	130.998
10	564.157	79.032	101.083	124.011	663.008	151.644
14	701.374	82.831	90.288	123.268	815.392	178.627
METALS PERCENT RECOVERY						
RUN	PB	HG	CR	SB	BA	TL
7	24	53	69	47	31	92
10	25	54	74	68	27	84
14	36	66	77	79	38	115
PERCENT METAL IN BOTTOM ASH						
RUN	PB	HG	CR	SB	BA	TL
7	0	0	91	53	86	32
10	7	0	97	85	97	40
14	3	0	95	68	93	27
PERCENT METAL IN OFFGAS						
RUN	PB	HG	CR	SB	BA	TL
7	100	100	9	47	14	68
10	93	100	3	15	3	60
14	97	100	5	32	7	73

TTLBAL.XLS

MATERIAL BALANCES FOR PARTICULATE CARRYOVER TEST						
		7	10	14		
WASTE FEED (grams)		195,047.0	248,118.0	213,644.0		
% ASH		6.86%	7.84%	7.80%		
OFFGAS FLOW (dscm/h)		1714.0	1288.0	1706.0		
PARTICULATE CONC. (mg/dscm)		556.0	731.0	498.0		
ASH FEED (grams)		13380.2	19452.5	16664.2		
ASH IN OFFGAS (grams)		4764.9	5555.0	4757.7		
CALC. BOTTOM ASH (grams)		8615.3	13897.4	11906.5		
METALS BALANCE AROUND KILN						
METALS FEED (mg/kg)						
RUN	PB	HG	CR	SB	BA	TL
7	9000	590	550	730	10000	730
10	9000	590	550	730	10000	730
14	9000	590	550	730	10000	730
METALS FEED (grams)						
RUN	PB	HG	CR	SB	BA	TL
7	1755.4	115.1	107.3	142.4	1950.5	142.4
10	2233.1	146.4	136.5	181.1	2481.2	181.1
14	1922.8	126.0	117.5	156.0	2136.4	156.0
OFFGAS METALS (mg/dscm)						
RUN	PB	HG	CR	SB	BA	TL
7	49.4	7.18	0.756	3.69	10.2	10.4
10	69.1	10.4	0.427	2.42	2.76	12
14	71.4	8.67	0.44	4.19	6.16	13.6
OFFGAS METALS (grams)						
RUN	PB	HG	CR	SB	BA	TL
7	423.36	61.53	6.48	31.62	87.41	89.13
10	525.10	79.03	3.24	18.39	20.97	91.19
14	682.13	82.83	4.20	40.03	58.85	129.93
BOTTOM ASH METALS (mg/kg)						
RUN	PB	HG	CR	SB	BA	TL
7	67.1	0	7890	4160	61078	4860
10	2810	0.04	7040	7600	46198	4350
14	1616.5	0.1	7230	6991	63540	4090
BOTTOM ASH METALS (grams)						
RUN	PB	HG	CR	SB	BA	TL
7	0.578	0.00E+00	67.975	35.840	526.206	41.870
10	39.052	5.56E-04	97.838	105.621	642.034	60.454
14	19.247	1.19E-03	86.084	83.239	756.542	48.698