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Project Summary

Pilot-Scale Incineration of Contaminated Sludges from the Bofors-Nobel Superfund Site

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A detailed test program was performed at the U.S. Environmental Protection Agency's (EPA's) Incineration Research Facility (IRF) to help determine the effectiveness of incineration in treating two contaminated lagoon sludges from the Bofors-Nobel Superfund site in Muskegon, MI. The sludges tested were contaminated with various organic constituents and trace metals. Three incineration tests were conducted for each sludge, for a total of six tests, in the IRF's pilot-scale rotary kiln incineration system (RKS). Target incineration conditions were held constant for all six tests, with a kiln temperature of 982°C (1,800°F); kiln exit flue gas O_2 at 8% to 10%; afterburner temperature of 1,204°C (2,200°F); and afterburner exit flue gas O_2 at 6%.

The test results suggest that incineration under the conditions tested represents an effective treatment option for the lagoon 8 sludge. Substantial decontamination of organics from the sludge was achieved; the principal organic hazardous constituent (POHC) was not detected in the flue gas; particulate and HCl emissions were low and in compliance with the incinerator performance standards; and incineration residuals (kiln ash and scrubber liquor) would not be toxicity characteristic (TC) hazardous wastes based on leachable trace metal content.

Incineration also appears to be an effective treatment option for the lagoon 3 sludge: substantial organic decontamination was achieved; the performance standard of 99.99% destruction and removal efficiency (DRE) for POHCs was met; and the resulting kiln ash toxicity characteristic leaching procedure (TCLP) leachate had trace metal concentrations below regulatory limits. A wet scrubber air pollution control system (APCS) of the type tested may not, however, be an appropriate choice for air pollution control. While HCl emissions were acceptable, particulate emissions at the primary APCS exit were greater than those allowed by the incinerator performance standards. Low cadmium and lead collection efficiencies resulted in cadmium emission levels in the 153 to 206 μg/dscm range and lead emission levels in the 4,420 to 6,180 μg/dscm range. In addition, the unfiltered scrubber liquor discharge exceeded the TCLP limits for lead and approached the limit for cadmium (scrubber liquor filtrate concentrations may be below these limits). If a wet scrubber APCS is used, incineration at a kiln temperature lower than the 982°C (1,800°F) temperature tested might be warranted. A lower kiln temperature would likely reduce the amount of cadmium and lead volatilized and carried out of the kiln in the combustion gas.

This Project Summary was developed by EPA's Risk Reduction Engineering Laboratory, Cincinnati, OH, to announce key findings of the research project that is fully documented in a separate report of the same title (see Project Report ordering information at back).

Introduction

One of the primary missions of the IRF, located in Jefferson, AR, is to support EPA's Regional Offices in evaluating incineration as a treatment option for contaminated soils and sludges at Superfund sites. One priority site

in Region V is the Bofors-Nobel site in Muskegon. The U.S. Army Corps of Engineers requested that the IRF conduct test burns to support evaluations of incineration as a treatment technology for the contaminated sludges at the site.

The Bofors site was included as a Superfund site on the National Priority List in March 1989. Several former lagoons at the site contain sludges contaminated with several volatile and semivolatile organic contaminants, chiefly methylene chloride, chloroform, benzene, toluene, azobenzene, benzidine, and 3,3'-dichlorobenzidine. The sludges are also contaminated with several trace metal contaminants, chiefly barium, cadmium, chromium, and lead. The purpose of the test program was to evaluate the incinerability of selected site sludges in terms of the destruction of organic contaminants and the fate of contaminant trace metals. The specific test objectives addressed the following questions:

- Can incineration effectively destroy the sludges' POHCs to the required DRE of 99.99%?
- Are treated sludges (kiln ash) free of organic contamination?
- What are the nature and concentrations of any organic contaminants in the discharge from a wet scrubber APCS?
- What is the distribution of the contaminant trace metals among the incineration system discharge streams?
- What is the effectiveness of the IRF APCS in collecting particulate and trace metals?

This test program investigated the treatability of sludges from two of the five lagoons. Three incineration tests, under similar incinerator operating conditions, were performed for each of the two sludges. All of the tests were conducted in the IRF's pilot-scale RKS, which was equipped with a venturi scrubber/packed-column scrubber APCS.

Results of the test program are discussed in the subsections that follow.

Test Program

Test Facility

A process schematic of the RKS is shown in Figure 1. The IRF RKS consists of a primary combustion chamber, a transition section, and a fired afterburner chamber. After exiting the afterburner, flue gas flows through a quench section followed by a primary APCS. The primary APCS for these tests consisted of a venturi scrubber followed by a packed-column scrubber. Downstream of the primary APCS, a backup secondary APCS, consisting of a demister, an activated-carbon adsorber, and a high-efficiency particulate air (HEPA) filter, is in place.

Test Waste Description

The record of decision (ROD) document for the Bofors site identifies five lagoon sludges as candidates for incineration treatment. The sludges in these five lagoons are contaminated to varying degrees by several volatile and semivolatile organic compounds. From the baseline risk assessment, the ROD identified six principal organic contaminants of concern: methylene chloride, benzene, 3,3'-dichlorobenzidine, aniline, azobenzene, and benzidine. Hazardous metal contaminants were also present. Among these, cadmium and lead were present at maximum concentrations of 22 and 887 mg/kg, respectively, in some lagoon sludge samples.

Two of the five incineration candidate sludges, the lagoon 3 and lagoon 8 sludges, were selected for testing at the IRF based on the results of the bench-scale thermal treatability studies and on other considerations.

Test Conditions

Three tests were performed at similar incinerator operating conditions for each lagoon sludge selected (six tests total). For each test, sludges were fed to the kiln via the fiberpack-drum ram feeder system. This system batch feeds 1.5-gal fiberpack drums to the kiln. Each fiberpack drum was packaged to contain nominally 4.6 kg (10 lb) of sludge. During each test, one fiberpack was charged into the kiln every 5 min, resulting in target sludge feedrates of nominally 55 kg/hr (120 lb/hr). The kiln rotation rate was set to result in solids residences times in the kiln of 45 to 60 min.

Table 1 compares the target and actual test operating conditions for each test. As shown, average kiln temperatures were within 25°C (44°F) of target temperatures for all tests. Kiln exit flue gas O_2 levels were within 2% of target levels. Afterburner temperature was within 4°C (7°F) of target for all tests.

Sampling and Analysis

In addition to obtaining sludge feed, kiln ash, and scrubber liquor samples, the sampling protocol for all tests included sampling the flue gas at the afterburner exit and at the scrubber system exit: EPA Method 0010 for semivolatile organic constituents; EPA Method 0030 for volatile organic constituents; and an Anderson cascade impactor train for particulate size distribution. In addition, the EPA multiple metals sampling train sampled the flue gas downstream of the scrubber system for trace metals. Finally, EPA Method 5 was used to sample the flue gas at the afterburner exit, the scrubber system exit, and the stack downstream of the secondary APCS for particulate and HCl.

In addition to analyzing flue gas sampling trains for their sampled analyte set, the sludge feed sample for each test and each of the kiln ash and scrubber liquor samples were analyzed for semivolatile and volatile organic hazardous constituents and trace metals. Also, the sludge feed and the kiln ash for each test were subjected to TCLP extraction, and the resulting leachates were analyzed for trace metals.

Test Results

Volatile Organic Constituents

Table 2 summarizes the volatile organic constituent concentrations measured in each lagoon 3 test sample. A compound is noted in Table 2 if it was found in any test program sample in Tests 1 through 3. The major volatile organic contaminants in the lagoon 3 sludge samples were benzene, toluene, methylene chloride, and chloroform. These compounds were generally not found in the incineration residuals streams (kiln ash and scrubber liquor) or in the incinerator flue gas at the two locations sampled.

Incineration effectively decontaminated the lagoon 3 sludge of its major volatile organic constituents. Using the sludge feed and ash collected weights from each test, and the composition data in Table 2, the following decontamination efficiencies were calculated: at least 99.995% for methylene chloride; greater than 99.9991% for chloroform; and at least 99.99994% for benzene and toluene.

Table 3 summarizes the volatile organic constituent concentrations measured in each lagoon 8 sludge incineration test sample. Again, a compound is noted in Table 3 if it was found in any test sample from Tests 4 through 6. As shown in Table 3, toluene was the only volatile organic contaminant found in the lagoon 8 sludge; it was present at only 3 mg/kg. Toluene was found in all three kiln ash samples at levels of 36 to 38 µg/kg. The amount of toluene discharged in the kiln ash was about 0.5% of the amount fed. Thus, incineration achieved a decontamination efficiency for toluene of about 99.5%.

Benzene, ethyl benzene, and xylenes were found in all kiln ash samples at about 40, 10, and 10 µg/kg, respectively. No toluene, benzene, ethyl benzene, or xylenes were found in the scrubber liquor or the flue gas at either location sampled.

Semivolatile Organic Constituents

Of the list of analytes sought in the semivolatile organic analyses, only azobenzene and 3,3'-dichlorobenzidine were found in the lagoon 3 sludge and only 3,3'-dichlorobenzidine was found in the lagoon 8 sludge. The lagoon 3 sludge contained an average of 5,110 mg/kg of azobenzene and 4,390 mg/kg of 3,3'-dichlorobenzidine. The lagoon 8 sludge

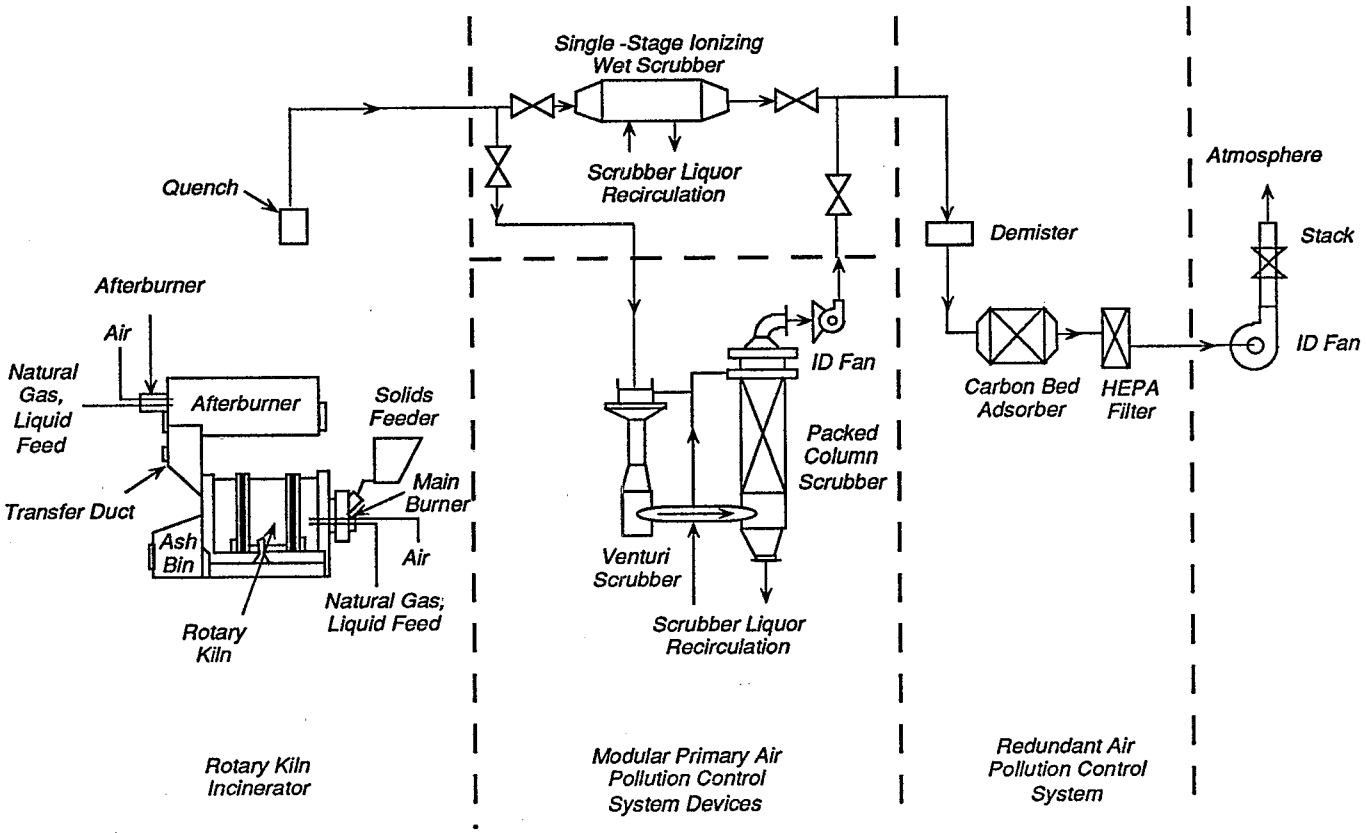

Figure 1. *Schematic of the IRF rotary kiln incineration system.*

contained 710 mg/kg of 3,3'-dichlorobenzidine.

No semivolatile organic constituents were found at concentrations above the method practical quantitation limit (PQL) in any test program incineration residuals (kiln ash and scrubber liquor) or flue gas (measured at both the afterburner and scrubber exits) samples. Using the sludge feed and ash collected weights from each test, the sludge feed organic contaminant concentrations noted above, and the ash contaminant PQLs, the following decontamination efficiencies were calculated: greater than 99.990% to 99.993% for azobenzene from the lagoon 3 sludge; greater than 99.989% to 99.992% for 3,3'-dichlorobenzidine from the lagoon 3 sludge; and greater than 99.89% for 3,3'-dichlorobenzidine from the lagoon 8 sludge.

POHC DREs

Based on POHC selection criteria specified in the hazardous waste incinerator regulations, the POHCs in the lagoon 3 sludge would be benzene, toluene, and 3,3'-dichlorobenzidine; in lagoon 8 sludge the POHC would be 3,3'-dichlorobenzidine. Table 4 summarizes the DREs measured for these POHCs in the tests performed.

As discussed above, no POHCs were detected in any flue gas sample analyzed, with the exception of benzene in the lagoon 3 sludge Test 1 afterburner exit flue gas. Therefore, except for this one instance, only a minimum POHC DRE, based on the flue gas analysis method PQL, can be established.

Table 1. *Target Versus Actual Operating Conditions*

	Kiln						Afterburner					
	Exit temperature, °C (°F)				Flue gas O_2, %		Exit temperature, °C (°F)				Flue gas O_2, %	
Test	Target		Actual average		Target	Actual average	Target		Actual average		Target	Actual average
1	982	(1,800)	1,007	(1,844)	10	10.3	1,204	(2,200)	1,208	(2,207)	7	4.7
2	982	(1,800)	986	(1,806)	10	9.4	1,204	(2,200)	1,208	(2,207)	7	11.2[a]
3	982	(1,800)	996	(1,825)	10	8.1	1,204	(2,200)	1,208	(2,207)	7	5.7
4	982	(1,800)	988	(1,811)	10	8.1	1,204	(2,200)	1,208	(2,207)	7	5.9
5	982	(1,800)	976	(1,788)	10	9.5	1,204	(2,200)	1,208	(2,207)	7	6.0
6	982	(1,800)	979	(1,794)	10	9.3	1,204	(2,200)	1,208	(2,207)	7	6.1

[a] *Afterburner O_2 sampling probe clogged.*

Table 2. Concentrations of Volatile Organic Constituents for the Lagoon 3 Sludge Tests

Sample	Bromo methane	Trichloro-fluoro-methane	Acetone	Methylene chloride	Chloro-form	1,1,1-Tri chloro-ethane	Benzene	Toluene	Chloro-benzene	Ethyl benzene	Total xylenes	All others
Test 1												
Sludge feed, mg/kg	4.3	<0.625 [b]	<12.5	190	190	17	2,500	3,100	55	3.5	13	ND [a]
Kiln ash, mg/kg	<0.01	0.006	<0.1	0.005	<0.005	0.010	<0.005	0.010	0.10	<0.005	<0.005	ND
Afterburner exit flue gas, µg/dscm	180	<48	8.7	<7.7	<1.0	<1.0	29	<7.7	<1.2	<1.4	<4.8	ND
Scrubber liquor, µg/L	<10	<5	<100	110	<5	<5	<5	<5	<5	<5	<5	ND
Scrubber exit flue gas, µg/dscm	<1.0	<2.5	<1.0	<1.0	<1.0	<1.0	<20	<4.6	<1.0	<4.7	<20	ND
Test 2												
Sludge feed, mg/kg	<125	<62.5	<1,250	130	120	<62.5	2,400	2,500	<62.5	<62.5	<62.5	ND
Kiln ash, mg/kg	<0.01	0.006	<0.1	0.015	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	ND
Afterburner exit flue gas, µg/dscm	8.1	<16	<1.0	<1.0	<1.0	<1.2	<8.1	<5.3	<1.0	<1.0	<12	ND
Scrubber liquor, µg/L	<10	<5	<100	16	<5	<5	<5	<5	<5	<5	<5	ND
Scrubber exit flue gas, µg/dscm	760	<10	<1.0	<1.0	1.1	<1.0	<12	<6.9	<1.0	<3.5	<14	ND
Test 3												
Sludge feed, mg/kg	<125	<62.5	<1,250	130	110	<62.5	2,200	2,400	<62.5	<62.5	<62.5	ND
Kiln ash, mg/kg	<0.01	0.02	<0.1	0.031	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	ND
Afterburner exit flue gas, µg/dscm	480	<23	<1.0	<1.0	<1.0	<9.8	<5.2	<3.0	<1.0	<2.4	<10	ND
Scrubber liquor, µg/L	<10	<5	<100	16	<5	<5	<5	<5	<5	<5	<5	ND
Scrubber exit flue gas, µg/dscm	92	<53	<1.0	<1.0	<1.0	<29	<6.3	<2.4	<1.0	<5.2	<21	ND

[a] ND = Not detected.
[b] "<" = Below the PQL noted.

Most of the entries in Table 4, as a result, indicate that POHC DRE was greater than this lower bound.

The test results summarized in Table 4 show that a greater than 99.99% DRE was clearly achieved in the lagoon 3 sludge tests for toluene and 3,3'-dichlorobenzidine in Test 1, 3,3'-dichlorobenzidine in Test 2, and benzene, toluene, and 3,3'-dichlorobenzidine in Test 3, as measured both at the afterburner exit and the scrubber exit. In addition, benzene and toluene DREs, as measured at the scrubber exit, were clearly greater than 99.99% in Test 2. The afterburner exit flue gas benzene level measured in Test 1 corresponded to a 99.96% DRE. No benzene was found in the scrubber exit flue gas, corresponding to a benzene DRE of greater than 99.97%. Clear compliance with the 99.99% DRE standard at the scrubber exit was shown for all three lagoon 3 sludge POHCs, with this one detection limit exception.

For the lagoon 8 sludge tests, method PQLs, combined with the low feed POHC concentrations, corresponded to lower bound DREs for 3,3'-dichlorobenzidine of 99.971% to 99.972%, as measured in the afterburner exit flue gas, and 99.974% to 99.975%, as measured in the scrubber exit flue gas.

Trace Metals

Table 5 summarizes the trace metal concentrations measured in each lagoon 3 sludge incineration test sample. The five metals found in lagoon 3 sludge samples are listed in the first five columns of Table 5; the five metals

Table 3. Concentrations of Volatile Organic Constituents for the Lagoon 8 Sludge Tests

Sample	Bromo methane	Trichloro-fluoro-methane	Methylene chloride	1,1,1-Tri-chloroethane	Benzene	Toluene	Ethyl benzene	Total xylenes	All others
Lagoon 8 sludge feed, mg/kg	<1.25 [b]	<0.625	<0.625	<0.625	<0.625	3.0	<0.625	<0.625	ND [a]
Test 4									
Kiln ash, mg/kg	<0.01	<0.005	0.065	<0.005	0.042	0.037	0.013	0.011	ND
Afterburner exit flue gas, µg/dscm	34	<14	<1.3	<35	<4.7	<1.9	<1.3	<3.9	ND
Scrubber liquor, µg/L	<10	<5	22	<5	<5	<5	<5	<5	ND
Scrubber exit flue gas, µg/dscm	320	<48	<1.2	<15	<18	<7.1	<1.8	<2.0	ND
Test 5									
Kiln ash, mg/kg	<0.01	<0.005	0.028	<0.005	0.044	0.036	0.011	0.009	ND
Afterburner exit flue gas, µg/dscm	22	<44	<2.0	<7.7	<4.8	<1.3	<1.0	<1.0	ND
Scrubber liquor, µg/L	<10	<5	34	<5	<5	<5	<5	<5	ND
Scrubber exit flue gas, µg/dscm	22	<64	<2.4	<12	<16	<2.4	4.5	<7.0	ND
Test 6									
Kiln ash, mg/kg	<0.01	<0.005	0.005	<0.005	0.039	0.038	0.012	0.013	ND
Afterburner exit flue gas, µg/dscm	27	<120	<31	72	<7.6	<2.9	<1.0	<7.3	ND
Scrubber liquor, µg/L	<10	<5	20	<5	<5	<5	<5	<5	ND
Scrubber exit flue gas, µg/dscm	1100	<59	<4.9	<1.0	<16	<3.6	<1.0	<1.0	ND

[a] ND = Not detected.
[b] "<" = Below the PQL noted.

Table 4. Destruction and Removal Efficiencies (Percent) for the Principal Organic Hazardous Constituents

POHC	Measured at the afterburner exit			Measured at the scrubber exit		
	Test 1	Test 2	Test 3	Test 1	Test 2	Test 3
Lagoon 3 sludge						
Benzene	*99.961*	*>99.989*	*>99.9922*	*>99.974*	*>99.9930*	*>99.9914*
Toluene	*>99.9917*	*>99.984*	*>99.9959*	*>99.9953*	*>99.9913*	*>99.9970*
3,3'-Dichlorobenzidine	*>99.9958*	*>99.9950*	*>99.9942*	*>99.9959*	*>99.9949*	*>99.9946*
	Test 4	Test 5	Test 6	Test 4	Test 5	Test 6
Lagoon 8 sludge						
3,3'-Dichlorobenzidine	*>99.971*	*>99.972*	*>99.971*	*>99.975*	*>99.975*	*>99.974*

not found in any lagoon 3 sludge sample are listed in the last five columns. The data in Table 5 show that the metals absent in lagoon 3 sludge samples were not found in any other test program sample. Metals found in the lagoon 3 sludge samples were distributed among all other incineration residuals and flue gas samples, with the exception of arsenic, which was not found in the scrubber exit flue gas in Tests 2 and 3.

The data in Table 5 show that the concentrations of the five metals detected in the lagoon 3 sludge were comparable from test to test in the incinerator discharge streams with the exception of arsenic, barium, cadmium, and chromium in the scrubber liquor. Scrubber liquor concentrations for these four metals were unexplainably lower for Test 3 than for Tests 1 and 2. The data in Table 5 show that arsenic, barium, and chromium levels in the flue gas were generally less than 50 µg/dscm. Cadmium and lead levels, however, were significantly higher at 153 to 206 µg/dscm for cadmium, and 4,420 to 6,180 µg/dscm for lead.

All test kiln ash samples were subjected to the TCLP, and resulting leachates were analyzed. These results are shown in Table 5. The TCLP regulatory level used to establish the toxicity characteristic (TC) is also noted in the table. As shown, neither the lagoon 3 sludge nor the kiln ash resulting from its incineration had leachate metal concentrations that would make them TC hazardous wastes.

The lead concentrations in the bulk, unfiltered, scrubber liquor samples from all three tests exceeded the TCLP regulatory level; however, the three-test composite scrubber liquor TCLP leachate had a lead concentration below the TCLP regulatory level, as shown in Table 5.

Table 6 summarizes the trace metal analysis results for all lagoon 8 sludge incineration test samples. As was the case for the lagoon 3 sludge tests, no lagoon 8 sludge sample contained detectable antimony, beryllium, mercury, selenium, or silver. Levels of arsenic, barium, and chromium in the lagoon 8 sludge were in the same range as in the lagoon 3 sludge. No cadmium was found in the lagoon 8 sludge. Also, lagoon 8 sludge lead levels were much lower than those in the lagoon 3 sludge.

The data in Table 6 show that the metals absent in the lagoon 8 sludge were not found in any other test program sample, with the exception of cadmium, which was found at low levels in the scrubber exit flue gases of all three tests and in the scrubber liquors of two of the three tests. Metals found in the lagoon 8 sludge were distributed among all other incineration residuals and flue gas samples, with the possible exception of lead, which was found in the Tests 5 and 6 kiln ash samples at just greater than the method detection limit (MDL), and not found above the MDL in the Test 4 kiln ash samples. Incinerator discharge stream concentrations of the four metals detected in the lagoon 8 sludge were comparable from test to test with the exception of the scrubber liquor arsenic and lead concentrations and the scrubber exit flue gas lead concentrations, all of which steadily decreased from Test 4 through Test 6. The much higher lead concentration in the Test 4 scrubber exit flue gas, compared with the Tests 5 and 6 flue gases, is suspected to be the result of some residual lagoon 3 sludge material from Test 3 left in the afterburner.

The data in Table 6 further show that neither the lagoon 8 sludge feed sample nor any of the test kiln ash samples would be TC hazardous wastes based on the trace metal concentrations in their TCLP leachates. In addition, the trace metal concentrations measured in scrubber liquor samples were sufficiently low that no test's scrubber liquor discharge would be a TC hazardous waste, with the possible exception of the Test 4 unfiltered scrubber liquor.

Table 7 summarizes the test trace metal distributions among the three incineration system discharges: kiln ash, scrubber liquor, and scrubber exit flue gas. The distribution fractions in Table 7 have been normalized to the total amount of each metal measured in all the discharge streams analyzed. Thus, these normalized values represent fractions that would have resulted had mass balance closure in each case been 100%. Use of the distribution fractions normalized in this manner allow clearer data interpretation, because they remove variable mass balance closure as a source of test-to-test data variability. In other words, because variable and less than perfect mass balance closure is typically experienced, the use of normalized distributions represents a best attempt to quantify metal partitioning phenomena. Achieved mass balance closure levels ranged from 42% to 107% if the lead mass balance closure for Test 4 is excluded. As noted above, the high Test 4 scrubber exit flue gas lead concentration measured is suspected to have been affected by some residual lagoon 3 sludge material, from Test 3, left in the afterburner.

The distribution data in Table 7 show that barium and chromium exhibited relatively nonvolatile behavior in all of the tests. Between 84% and 96% of the barium discharged was accounted for by the kiln ash in the lagoon 3 sludge tests; even more, 96% to 99%, was accounted for in the lagoon 8 sludge tests. Similarly, between 86% and 97% of the chromium discharged was accounted for by the kiln ash discharges in all of the tests. The scrubber exit flue gas accounted for 1% to 5% of the chromium measured; the remaining 1% to 10% was found in the scrubber liquor.

In contrast, cadmium and lead were quite volatile in the lagoon 3 sludge tests. Only 6% of the cadmium discharged and 2% to 3% of the lead discharged were found in the kiln ash. Further, the major fraction of the cadmium and lead that escaped the kiln exited the scrubber system. About 60% of the cadmium discharged in Tests 1 and 2 and 92% in Test 3 were measured in the scrubber exit flue gas. Similarly, between 49% and 82% of the lead discharged in the lagoon 3 sludge tests was measured in the scrubber exit flue gas.

Lead was much less volatile in the lagoon 8 sludge tests. For Tests 5 and 6, as much as 40% to 69% of the lead discharged was measured in the kiln ash. Interestingly, the lagoon 8 sludge contained no measurable chlorine (<0.1%, dry basis). The lagoon 3

Table 5. Concentrations of Trace Metals for the Lagoon 3 Sludge Tests

Sample	As	Ba	Cd	Cr	Pb	Sb	Be	Hg	Se	Ag
Average sludge feed, mg/kg	1.4	17	11	28	470	<10	<0.2	<1	<20	<1
Average sludge feed TCLP leachate, mg/L	<0.05	0.092	<0.005	<0.01	<0.15	<0.1	<0.002	<0.05	<0.2	<0.01
Test 1 (10/24/91)										
Kiln ash, mg/kg	12	42	2.3	79	30	<10	<0.2	<1	<20	<1
Kiln ash TCLP leachate, mg/L	0.056	0.19	<0.005	<0.01	<0.1	<0.1	<0.002	<0.05	<0.2	<0.01
Scrubber exit flue gas, µg/dscm	40-53	8-15	153	27-30	4,420	<35	<1	N.A.[a]	<66	<3
Scrubber liquor, mg/L	0.51	0.33	0.49	0.33	12	<0.1	<0.002	<0.05	<0.2	<0.01
Test 2 (10/29/91)										
Kiln ash, mg/kg	7.8	47	2.4	63	29	<10	<0.2	<1	<20	<1
Kiln ash TCLP leachate, mg/L	0.016	0.23	<0.005	0.03	<0.1	<0.1	<0.002	<0.05	<0.2	<0.01
Scrubber exit flue gas, µg/dscm	<22	6-12	167	10-12	4,600-4,620	<31	<1	N.A.	<62	<3
Scrubber liquor, mg/L	0.40	0.26	0.44	0.29	24	<0.1	<0.002	<0.05	<0.2	<0.01
Test 3 (10/31/91)										
Kiln ash, mg/kg	8.3	38	1.9	59	29	<10	<0.2	<1	<20	<1
Kiln ash TCLP leachate, mg/L	0.014	0.23	<0.005	0.043	<0.1	<0.1	<0.002	<0.05	<0.2	<0.01
Scrubber exit flue gas, µg/dscm	<74	12	206	10-12	6,180	<83	<1	N.A.	<170	<8
Scrubber liquor, mg/L	0.074	0.059	0.049	0.052	7.6	<0.1	<0.002	<0.05	<0.2	<0.01
Three test composite scrubber liquor TCLP leachate, mg/L	<0.1	<0.05	<0.005	<0.01	1.1	N.A.	N.A.	<0.002	<0.01	<0.01
TCLP regulatory level, mg/L	5.0	100	1.0	5.0	5.0	(b)	(b)	0.2	1.0	5.0

[a] N.A. = Not analyzed.
[b] Not a TCLP metal.

sludge contained 3.5% chlorine on a dry basis. The chlorine present in the lagoon 3 sludge would allow the formation of lead chlorides, which are much more volatile than lead metal or lead oxides. This most likely explains the significantly increased lead volatility (decreased kiln ash fraction) in the lagoon 3 sludge tests.

Particulate and HCl

Particulate levels at the scrubber exit were quite high, at 195 and 266 mg/dscm, corrected to 7% O_2, in Tests 1 and 2 with the lagoon 3 sludge. These levels exceed the hazardous waste incinerator performance standard of 180 mg/dscm. Particulate emission levels as high as those measured in Tests 1 and 2 would cause a hazardous waste incinerator to fail a trial burn. Scrubber exit particulate levels for Test 3 were lower, at 44 mg/dscm at 7% O_2. Scrubber exit flue gas particulate levels were also low, in the 11 to 25 mg/dscm range, for the three lagoon 8 sludge tests. These levels easily meet the hazardous waste incinerator performance standard.

Scrubber exit HCl levels ranged from 0.2 to 2.8 ppm for the lagoon 3 sludge tests, and were nondetectable at a PQL of 30 ppb for all three lagoon 8 sludge tests. Corresponding HCl discharge rates were 0.5 to 7.2 g/hr for the lagoon 3 sludge tests and less than 80 mg/hr for the lagoon 8 sludge tests. The hazardous waste incinerator performance standard minimum is a 1.8 kg/hr emission rate.

Conclusions

Test conclusions in terms of the objectives stated in the Introduction are as follows:

- Greater than 99.99% DRE of the POHCs in the lagoon 3 sludge was achieved under the incineration conditions tested. This was clearly shown for two of the three lagoon 3 sludge POHCs (toluene and 3,3'-dichlorobenzidine) in all three tests; and for the third POHC (benzene) in two of the three tests. Method PQL limitations allowed establishing only that the benzene DRE was greater than 99.974% in the third test.
- The lagoon 8 sludge POHC, 3,3'-dichlorobenzidine, was not detected in the flue gas; however, method PQL limitations, combined with low sludge POHC concentrations, only allowed firmly establishing that greater than 99.974% to 99.975% DRE was achieved.
- For the lagoon 3 sludge, the organic constituent decontamination effectiveness, based on treated sludge contaminant concentrations, ranged from at least 99.989%, for 3,3'-dichlorobenzidine to 99.99994%, for benzene and toluene.
- For the lagoon 8 sludge, the organic constituent decontamination effectiveness was 99.5% for toluene (present at 3 mg/kg in the sludge) and greater than 99.89% for 3,3'-dichlorobenzidine (present at 710 mg/kg in the sludge).
- Of the contaminant trace metals, barium and chromium were relatively nonvolatile. The kiln ash discharge accounted for nominally 85% to 95%, or greater, of the measured discharge amounts of these metals for both sludges tested.
- Of the contaminant trace metals, cadmium and lead exhibited relatively volatile behavior. The kiln ash discharge accounted for only 2% to 3% of the lead, and 6% of the cadmium, in the measured discharge amounts of these metals in the lagoon 3 sludge tests. The kiln ash discharge accounted for nominally 40% to 70% of the lead measured in discharges for the lagoon 8 sludge tests; cadmium was not present in the lagoon 8 sludge. The increased lead volatility in the lagoon 3 sludge tests may be attributable to different sludge chlorine contents; the lagoon 3 sludge contained chlorine whereas the lagoon 8 sludge did not. Significantly increased lead volatility in the presence of chlorine during incineration, as observed here, has been documented in past work.
- Neither of the sludges tested, nor the kiln ash resulting from their incineration, would be classified as TC hazardous waste based on leachable metals concentrations.
- Scrubber liquor metal concentrations were generally below TCLP limits. The unfiltered scrubber liquor from each lagoon 3 sludge test and from the first

Table 6. *Concentrations of Trace Metals for the Lagoon 8 Sludge Tests*

Sample	As	Ba	Cd	Cr	Pb	Sb	Be	Hg	Se	Ag
Sludge feed, mg/kg	0.82	38	<0.5	33	11	<10	<0.2	<0.2	<20	<1
Sludge feed TCLP leachate, mg/L	<0.001	0.085	<0.005	<0.01	<0.1	<0.1	<0.002	<0.05	<0.2	<0.01
Test 4 (11/5/91)										
Kiln ash, mg/kg	9.1	65	<0.5	59	<10	<10	<0.2	<1	<20	<1
Kiln ash TCLP leachate, mg/L	<0.001	0.38	<0.005	0.72	<0.1	<0.1	<0.002	<0.05	<0.2	<0.01
Scrubber exit flue gas, µg/dscm	8-9	3-9	5-7	23-25	270-290	<26	<1	N.A.[a]	<53	<3
Scrubber liquor, mg/L	0.17	0.18	0.052	0.22	10	<0.1	<0.002	<0.05	<0.2	<0.01
Test 5 (11/6/91)										
Kiln ash, mg/kg	4.2	74	<0.5	59	12	<10	<0.2	<1	<20	<1
Kiln ash TCLP leachate, mg/L	<0.001	0.41	<0.005	0.99	<0.1	<0.1	<0.002	<0.05	<0.2	<0.01
Scrubber exit flue gas, µg/dscm	6	8-15	2-3	14-17	4-32	<28	<1	N.A.	<56	<3
Scrubber liquor, mg/L	0.086	0.15	<0.005	0.15	1.1	<0.1	<0.002	<0.05	<0.2	<0.01
Test 6 (11/7/91)										
Kiln ash, mg/kg	3.8	69	<0.5	79	11	<10	<0.2	<1	<20	<1
Kiln ash TCLP leachate, mg/L	<0.001	0.38	<0.005	0.82	<0.1	<0.1	<0.002	<0.05	<0.2	<0.01
Scrubber exit flue gas, µg/dscm	3-4	7-14	2-3	13-15	64-89	<28	<1	N.A.	<56	<3
Scrubber liquor, mg/L	0.022	0.27	0.011	0.16	0.57	<0.1	<0.002	<0.05	<0.2	<0.01
TCLP regulatory level, mg/L	5.0	100	1.0	5.0	5.0	(b)	(b)	0.2	1.0	5.0

[a] *N.A. = Not analyzed.*
[b] *Not a TCLP metal.*

lagoon 8 test, however, had lead concentrations above TCLP limits. The TCLP leachate of a composite lagoon 3 sludge test scrubber liquid had lead concentration below its TCLP limit.

- Scrubber exit particulate levels were low for the lagoon 8 sludge tests at 25 mg/dscm, or less, at 7% O_2. Scrubber exit particulate levels were significantly higher in the lagoon 3 sludge tests — 195 and 266 mg/dscm at 7% O_2 for two of the lagoon 3 sludge tests. These values exceed the hazardous waste incinerator performance standard of 180 mg/dscm at 7% O_2.
- Scrubber exit HCl emission rates were acceptable during every test.

The test results suggest that incineration under the conditions tested represents an effective treatment option for the lagoon 8 sludge. Substantial decontamination of organics from the sludge was achieved; the POHC was not detected in the flue gas; and particulate and HCl emissions were low and in compliance with performance standards.

Incineration also appears to be an effective treatment option for the lagoon 3 sludge; substantial organic decontamination was achieved and the POHC DRE standard was met. A wet scrubber APCS of the type tested may not, however, be an appropriate choice for air pollution control. While HCl emissions were acceptable, particulate emissions were greater than those allowed by the incinerator performance standards. In addition, scrubber

Table 7. *Normalized Trace Metal Distributions — Percent of Metal Measured*

	Lagoon 3 sludge			Lagoon 8 sludge		
Trace Metal	Test 1 (10/24/91)	Test 2 (10/29/91)	Test 3 (10/31/91)	Test 4 (11/5/91)	Test 5 (11/6/91)	Test 6 (11/7/91)
Barium						
Kiln ash	84-86	89-91	93-96	98-99	98-99	96
Scrubber exit flue gas	2-4	2-4	4	<1	1	1
Scrubber liquor	12	7	<3	1	<1	3
Total	100	100	100	100	100	100
Cadmium						
Kiln ash	6	6	6	(a)	(a)	(a)
Scrubber exit flue gas	58	63	92	(a)	(a)	(a)
Scrubber liquor	36	31	2	(a)	(a)	(a)
Total	100	100	100	(a)	(a)	(a)
Chromium						
Kiln ash	86	87	97	93	96	96
Scrubber exit flue gas	5	3	3	3	2	1
Scrubber liquor	9	10	1	4	2	3
Total	100	100	100	100	100	100
Lead						
Kiln ash	3	2	3	<5	41-63	40-69
Scrubber exit flue gas	63	49	82	11	1-8	19-39
Scrubber liquor	34	49	15	84-89	33-55	<38
Total	100	100	100	100	100	100

[a] *Cadmium not found in feed sample.*

*U.S. Government Printing Office: 1993 — 750-071/60193

exit cadmium emission levels were in the 153 to 206 µg/dscm range, and lead emission levels were in the 4,420 to 6,180 µg/dscm range. Furthermore, the unfiltered scrubber liquor discharge exceeded the TCLP limit for lead; however, scrubber liquor filtrate concentrations may be below these limits. If a wet scrubber APCS is used, incineration at a kiln temperature lower than the 982°C (1,800°F) temperature tested might be warranted. A lower kiln temperature would likely reduce the amount of cadmium and lead volatilized and carried out of the kiln in the combustion gas.

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The complete report, entitled "Pilot-Scale Incineration of Contaminated Sludges from the Bofors-Nobel Superfund Site," (Order No. PB93-141034; Cost: $44.50, subject to change) will be available only from:
National Technical Information Service
5285 Port Royal Road
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The EPA Project Officer and Technical Project Monitor can be contacted at:
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