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Low-temperature desorption treatment of co-contaminated soils: TCLP as an evaluation technique

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Abstract

The evaluation of a rotary kiln incinerator utilized as a low-temperature thermal desorber was carried out at EPA's Incineration Research Facility (IRF). The effectiveness of employing a direct fired unit was tested in decontaminating soil containing various organic and metallic pollutants. Test parameters were: soil moisture content, treatment temperature, treatment time, solid bed depth and the degree of agitation.

The Toxicity Characteristic Leaching Procedure (TCLP) can be used as a way to show the change in mobility that metals experience as a result of low-temperature thermal treatment. The effects of low-temperature treatment varied, with treatment temperature having the biggest impact on the TCLP of metal residues.

Keywords: Thermal desorption; Soil remediation; Metal mobility; TCLP

1. Introduction

The hazardous/toxic nature of both Resource Conservation and Recovery Act (RCRA) wastes and Comprehensive Environmental Releases, Compensation and Liability Act (CERCLA) materials suggest that perhaps the Toxicity Characteristic Leaching Procedure (TCLP) [1] should be used as a means of establishing the potential environmental threat posed by regulated materials. TCLP is a laboratory technique that simulates waste disposal in "worst-case" landfill conditions, and therefore supports test conditions that encourage the migration of pollutants, particularly metal species. The residues from RCRA/CERCLA treatment techniques are usually earmarked for land disposal [2] and a way to use the TCLP characteristics of the residues relative to the operating parameters of the treatment technology employed would be valuable.

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RCRA and especially CERCLA samples are usually co-contaminated with both toxic metals and organic compounds. Low-temperature thermal desorption has been suggested as a way to separate the organic and inorganic fractions in the soil without entraining the metals in the off-gas [3]. Low-temperature thermal desorption is a treatment technique that has gained public acceptance and is being proposed for several Superfund Sites [3]. The advantage associated with the technology is the "gentle" thermal treatment conditions that volatilize the organics out of the soil, but retain the metals in the bottom ash (treated soil). The potential impact on the environment is greatly reduced [4] and the residue can be handled by other techniques if needed.

The application of established rotary kiln incineration technology to direct-fired low-temperature thermal desorption has been discussed, but little data existed on kiln operating conditions and their relationship to metals recovery and mobility. The information presented in this paper helps fill part of that void and shows that conventional direct-fired rotary kiln systems can be utilized in alternate ways to treat toxic or hazardous waste while retaining the metals in the residue.

2. Approach

The EPA Risk Reduction Engineering Laboratory (RREL) owns and operates an experimental pilot-scale hazardous waste incinerator and all the necessary ancillary equipment associated with its regulated operation. This unit is known as the Rotary Kiln System (RKS); and is located at the RREL Incineration Research Facility (IRF) in Jefferson, Arkansas. The temperature in the primary chamber was reduced and the incinerator performed as a direct-fired low-temperature desorber. A series of twelve parametric tests were completed under different operating conditions with treatment effectiveness being the main evaluation criteria. TCLP was one of the ways used to judge the treatment effectiveness of the low-temperature desorption process, and the test results are summarized in this paper.

3. Low-temperature desorption system

The rotary kiln system (RKS), depicted in Fig. 1, consists of a rotary kiln primary desorption chamber followed by a transition duct and a fired afterburner (secondary combustion chamber). Combustion gases exiting the afterburner are water-quenched and proceed to the primary air pollution control system (APCS) which is composed of a venturi scrubber and a packed tower/column scrubber. This system is followed by a secondary/backup APCS consisting of a demister, carbon bed adsorber, and high-efficiency particulate (HEPA) filter. Release to the atmosphere follows the secondary APCS. Nominal design characteristics of the RKS components may be found in Table 1.

Table 1
Design characteristics of the IRF rotary kiln incineration system

Characteristics of the kiln main chamber	
Length	2.26 m (7 ft 5 in)
Diameter, outside	1.37 m (4 ft 6 in)
Diameter, inside	nominal 1.04 m (3 ft 4.75 in)
Chamber volume	1.90 m^3 (67.2 ft^3)
Construction	0.95 cm (0.375 in) thick cold-rolled steel
Refractory	18.7 cm (7.375 in) thick high alumina castable refractory, variable
Rotation	Clockwise or counterclockwise, 0.2 to 1.5 rpm
Solids retention time	1 h (at 0.2 rpm)
Burner	North American Burner rated at 590 kW (2.0 MM Btu/hr) with liquid
Primary fuel	Natural gas
Feed system:	Positive displacement pump via water-cooled lance
Sludges	Moyno pump via front face, water-cooled lance
Solids	Metered twin-auger screw feeder of fiberpack ram feeder
Temperature	1010 °C (1850 °F)
Characteristics of the afterburner chamber	
Length	3.05 m (10 ft)
Diameter, outside	1.22 m (4 ft)
Diameter, inside	0.91 m (3 ft)
Chamber volume	1.80 m^3 (63.6 ft^3)
Construction	0.63 cm (0.25 in) thick cold-rolled steel
Refractory	15.2 cm (6 in) thick high alumina castable refractory
Gas residence time	1.2 to 2.5 s depending on temperature and excess air
Burner	North American Burner rated at 590 kW (2.0 MM Btu/hr) with liquid
Primary fuel	Natural gas
Temperature	1200 °C (2200 °F)
Characteristics of the afterburner extension	
Length, with transition	4.3 m (14 ft 6.5 in)
Diameter, outside	0.915 m (3 ft)
Diameter, inside	0.61 m (2 ft)
Chamber volume	1.19 m^3 (41.9 ft^3)
Construction	0.63 cm (0.25 in) thick cold-rolled steel
Refractory	15.2 cm (6 in) thick high alumina castable refractory
Temperature (max)	1200 °C (2200 °F)
Characteristics of the Venturi/packed-column Scrubber APCS	
System capacity, inlet	107 m^3/min (3773 acfm) at 1200 °C (2200 °F) and 101 kPA (14.7 in WC)
Pressure drop	
Venturi scrubber	7.5 kPa (30 in WC)
Packed column	1.0 kPA (4 in WC)
Liquid flow	
Venturi scrubber	77.2 l/min (20.4 gpm) at 50 kPa (10 psig)
Packed column	116 l/min (30.6 gpm) at 69 kPa (10 psig)
pH control	Feedback control by NaOH solution addition

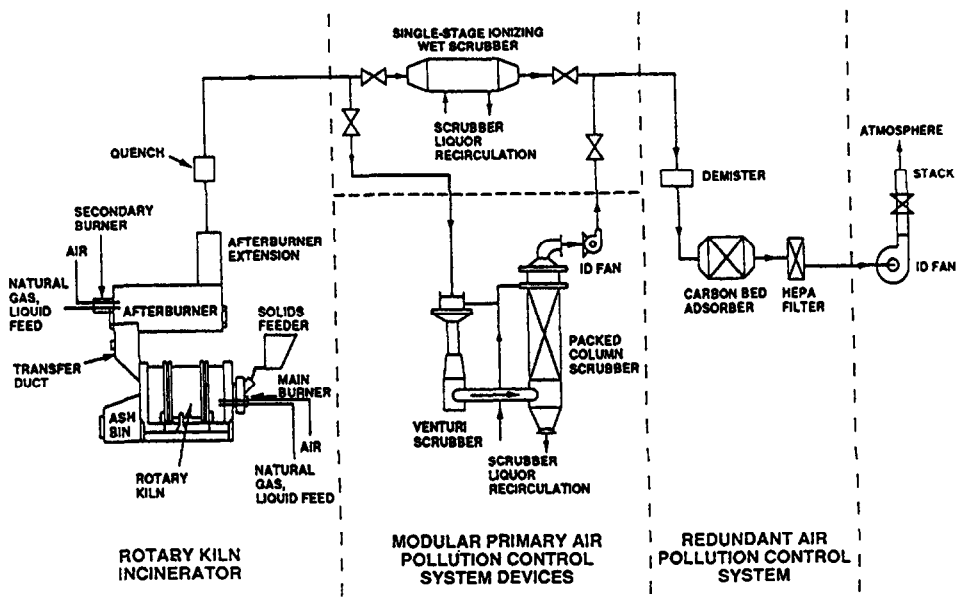


Fig. 1. Schematic of the IRF rotary kiln incineration system.

4. Waste mixture

Attempts to use local top soil as the base matrix for these tests were thwarted by materials handling problems associated with feeding this matrix into the low-temperature desorber. After several trials, a synthetic matrix formulation composed of the following materials was derived: dried local top soil was mixed with equal weights of attapulgite clay until homogeneous; organic contaminants were added as a combined organic solution (*n*-hexane, benzene, toluene, tetrachloroethylene, *n*-octane, chlorobenzene, naphthalene, phenanthrene, and pyrene); metals (arsenic, barium, cadmium, chromium, lead and mercury) were added in an aqueous solution; and additional water (as needed) was added to adjust the soil moisture content (to approximately 10% and 20%). If additional water was added to the mixture, it was homogenized in the same mixer used to compound the soil matrix.

The organic compounds included common volatile and semivolatile compounds found at Superfund Sites with boiling points ranging from 71 °C to 204 °C (160 to 400 °F). All metals were added as soluble nitrates (except As_2O_3) and added in a ratio of 0.11 kg of spike solution per kilogram of final contaminated mixture.

5. Test conditions

The test conditions consisted of three different kiln gas exit temperatures 316 °C, 482 °C and 649 °C (600 °F, 900 °F and 1200 °F), two soil feed rates 68 and 220 kg/h (150 and 500 lb/h) and three kiln rotation speeds 0.2, 0.5, and 1.5 rpm. Table 2 is a summary of the target test conditions, and the actual operating conditions achieved.

Table 2
Actual versus target operating desorber conditions

Test	Kiln exit temperature (°C (°F))		Kiln rotation speed		Feedrate (lbs/h)	
	Target	Actual	Target	Actual	Target	Actual
1	316 (600)	317 (602)	0.2	0.2	150	148
2	482 (900)	482 (900)	0.2	0.2	150	150
3	649 (1200)	648 (1199)	0.2	0.2	150	145
4	316 (600)	316 (601)	0.2	0.2	150	149
5	482 (900)	482 (900)	0.2	0.2	150	138
6	649 (1200)	648 (1199)	0.2	0.2	150	155
7	482 (900)	482 (900)	0.5	0.5	150	144
8	482 (900)	480 (896)	0.5	0.5	150	152
9	482 (900)	482 (900)	1.5	1.5	150	145
10	482 (900)	481 (897)	0.2	0.2	500	506
11	482 (900)	482 (900)	0.2	0.2	500	497
12	482 (900)	482 (900)	0.2	0.2	150	146

Afterburner exit temperature (°C (°F))

Test	Target	Actual	Minimum	Maximum
1	1093 (2000)	1097 (2006)	1089 (1993)	1103 (2017)
2	1093 (2000)	1096 (2005)	1091 (1995)	1102 (2015)
3	1093 (2000)	1096 (2005)	1088 (1991)	1101 (2013)
4	1093 (2000)	1096 (2005)	1088 (1991)	1102 (2015)
5	1093 (2000)	1096 (2005)	1085 (1985)	1100 (2012)
6	1093 (2000)	1096 (2005)	1088 (1991)	1102 (2015)
7	1093 (2000)	1096 (2005)	1089 (1993)	1102 (2013)
8	1093 (2000)	1096 (2005)	1087 (1988)	1109 (2029)
9	1093 (2000)	1096 (2005)	1090 (1994)	1101 (2013)
10	1093 (2000)	1096 (2005)	1026 (1878)	1161 (2122)
11	1093 (2000)	1096 (2005)	1078 (1972)	1103 (2017)
12	1093 (2000)	1096 (2005)	1089 (1993)	1101 (2013)

To allow for a more thorough evaluation of the treatment effectiveness, samples of bed solids material were taken concurrently at four axial locations along the kiln. These samples were in addition to the feed and solids discharge samples and corresponded to four different treatment times and/or locations for each test condition.

All of the tests were performed with the afterburner operating nominally at about 1093 °C (2000 °F), with a gas residence time in the afterburner of about 2 s.

6. Results

Low-temperature thermal desorption effectively separated the organic contamination from the inorganic contamination in this soil matrix [5]. As a result, the physical/chemical nature of the metals in the residual material was of considerable interest, and TCLP was used as a technique to follow the changes. Table 3 summarizes the

Table 3
Temperature/treatment profile

Test	Feedrate (kg/hr (lbs/hr))	Volatile fraction (%)	Kiln gas exit temp. (°C (°F))	Treatment temperature (°C (°F))			Treatment time (min)			Total solids residence time (min)	Kiln volume used (%)	Rate of temperature change per minute			Kiln rotation speed
				0.61 m (2 ft)	1.1 m (3.5 ft)	1.5 m (5.0 ft)	0.61 m (2 ft)	1.1 m (3.5 ft)	1.5 m (5.0 ft)			0.61 m (2 ft)	1.1 m (3.5 ft)	1.5 m (5.0 ft)	
1	67.7 (148)	7	317 (602)	86 (186)	109 (228)	115 (239)	15	26	37	59	4.5	4.3 (7.7)	2.1 (3.8)	0.6 (1.0)	0.2
2	68.1 (150)	13	482 (899)	123 (253)	182 (359)	228 (443)	16	27	39	62	4.7	6.4 (11.4)	5.4 (9.6)	3.8 (7.0)	0.2
3	65.8 (145)	11	648 (1199)	267 (512)	393 (740)	434 (814)	18	31	44	71	5.4	13.7 (24.6)	9.7 (17.5)	3.2 (5.7)	0.2
4	67.7 (149)	21	316 (601)	69 (156)	88 (191)	98 (208)	18	32	46	73	4.7	2.7 (4.8)	1.4 (2.5)	0.7 (1.2)	0.2
5	62.7 (138)	22	476 (888)	113 (235)	204 (399)	260 (500)	16	28	39	63	7.9	5.8 (10.3)	7.6 (13.7)	5.1 (9.2)	0.2
6	70.4 (155)	27	648 (1199)	122 (251)	319 (606)	401 (753)	15	26	37	59	4.5	6.7 (12.1)	17.9 (32.3)	7.5 (13.4)	0.2
7	65.4 (144)	8	482 (899)	144 (292)	204 (400)	249 (481)	18	32	45	72	4.5	6.8 (12.3)	4.3 (7.7)	3.5 (6.2)	0.5
8	69.0 (152)	24	479 (895)	179 (355)	215 (419)	239 (462)	9	15	22	35	2.5	17.6 (31.7)	6.0 (10.7)	3.4 (6.1)	0.5
9	65.8 (145)	21	482 (899)	172 (341)	194 (382)	245 (473)	6	10	14	22	2.1	25.2 (45.2)	5.5 (10.3)	12.8 (22.8)	1.5
10	230 (506)	12	480 (896)	130 (266)	161 (321)	175 (347)	18	32	45	72	12.4	6.1 (10.9)	2.2 (3.9)	1.1 (2.0)	0.2
11	226 (497)	21	482 (899)	107 (224)	132 (269)	149 (300)	9	15	21	34	9.8	9.6 (24.9)	4.2 (7.5)	2.8 (5.2)	0.2
12	66.3 (146)	13	482 (900)	144 (291)	211 (412)	257 (495)	15	27	38	61	4.7	8.2 (14.7)	5.6 (10.1)	4.2 (7.6)	0.2

Table 4
Metals recovery data

Test no.	Feed concentrations (mg/kg)						Ash concentration (mg/kg)						Recovered (%)					
	As	Ba	Cd	Cr	Pb	Hg	As	Ba	Cd	Cr	Pb	Hg	As	Ba	Cd	Cr	Pb	Hg
1	24	185	8	50	33	6.4	22	195	8.5	45	36	5.4	92	105	106	90	109	84
2	26	235	11	49	47	13	30	240	11	47	42	5.9	115	102	100	96	89	45
3	45	339	14	62	90	7.5	30	188	6.1	33	29	3.9	67	55	44	53	32	52
4	28	218	10	42	37	9.1	38	259	13	55	54	6.3	136	119	130	131	146	69
5	32	244	11	55	48	11	34	265	12	60	50	9.5	106	109	109	109	104	86
6	36	262	13	55	47	8.9	30	209	9	50	37	2.5	83	80	69	91	79	28
7	24	217	9	51	41	12	31	261	11	83	47	9.3	129	120	122	163	115	78
8	26	208	9	53	37	11	33	237	11	53	44	5.8	127	114	122	100	119	53
9	31	175	7	44	49	9.8	31	220	8	43	37	4.6	100	126	114	98	76	47
10	28	226	10	52	41	17	21	222	10	53	43	9.1	75	98	100	102	105	54
11	24	229	11	50	43	9.4	20	211	9	45	41	5.2	83	92	82	90	95	55
12	26	235	11	49	47	11	11	210	9	50	38	8.6	42	89	82	102	81	78
Mean &SD	29±6	231±42	10±2	51±5	47±15	10.5±2.8	26±8	208±63	10±2	51±12	42±7	6.3±2.3	96±28	101±20	98±25	95±35	96±28	61±18
RSD =%	21	18	20	10	31	26	27	30	20	23	16	36	29	20	25	37	29	30

temperature/time profiles for the samples taken in all of the tests as well as the soil residence times, kiln volume and kiln rotation speed. The factors thought to contribute to TCLP variability were: the soil's treatment temperature, treatment time, solids bed depth, moisture content and degree of agitation.

7. Soil treatment temperature

7.1. Total metals concentration(s)

Soil treatment temperature is a critical parameter in the separation of the organic fraction from the soil, and also thought to contribute to the fate of the metals contamination and their mobility. Tests 1–12, summarized in Table 3, were a series of experiments in which the equilibrium soil temperature, treatment time, kiln volume utilized, moisture and agitation were varied. Tests 1–3 were temperature experiments conducted with the moisture content at about 10%, and Tests 4–6 were also temperature experiments, but conducted with a moisture content of about 20%. Tests 7–9 were experiments in which the kiln was rotated at different speeds to study the effects of soil agitation. Tests 10 and 11 were conducted to study effects of different feed rates (kiln volume) on the metals mobility. Test 12 was a duplicate of Test 2. Samples of the treated soil matrix were taken from the ash material and analyzed for total metals as well as TCLP. Table 4 summarizes the overall recovery efficiencies for the test metals (mass basis) and indicates the variable metals recoverability. In all of the cases studied, as the treatment temperature increased, the total amount of metals remaining in the bottom ash (expressed as % metals recovered) decreased. This effect can be seen in Tests 1–6 shown in Table 4 and Fig. 2. The data in Table 4 indicate a strong negative correlation (with the possible exception of Hg) of soil treatment temperature and metal retention for the temperature range studied with the regression analysis coefficients presented in Table 5. If rotary kiln systems are employed as low-temperature desorbers, care must be taken to determine the effective treatment temperature range where organics can be distilled off while retaining metals in the ash.

Table 5
Treatment temperature regression for total metal recovery

Figure	Metal	Slope	Intercept	r^2 value
2A	As	−0.08	137	0.61
2B	Ba	−0.09	139	0.93
2C	Cd	−0.13	152	0.93
2C	Cr	−0.09	136	0.65
2B	Pb	−0.15	161	0.85
2A	Hg	−0.07	92	0.48

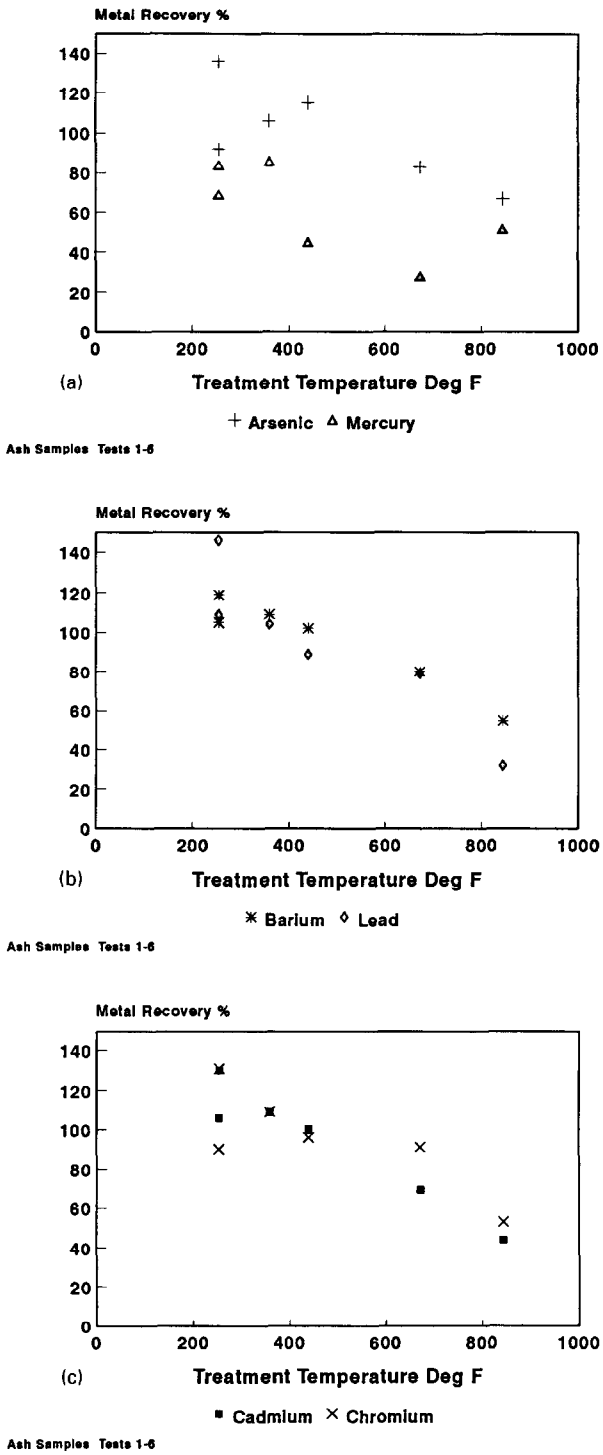


Fig. 2. Temperature effect on metals recovery.

Table 6a
TCLP recovery of metals tests 1–6 (percent retained)

	Feed	2 ft	3.5 ft	5 ft	Ash		Feed	2 ft	3/5 ft	5 ft	Ash
Test No. 1						*Test No. 4*					
Arsenic	78.3	56.6	70.9	82.8	68.2	Arsenic	72.9	76.7	67.2	42.9	81.1
Barium	56.7	34.2	45.5	26.1	44.6	Barium	40.5	40.5	−3.6	59.3	54.4
Cadmium	89.7	80.0	85.3	73.5	86.4	Cadmium	83.4	83.4	52.1	88.9	90.3
Chromium	99.0	98.6	96.7	97.9	96.7	Chromium	96.8	96.8	96.9	99.0	99.1
Lead	96.8	96.6	97.2	96.3	97.1	Lead	96.6	96.6	94.6	97.6	99.1
Mercury	85.6	96.6	96.9	96.4	97.6	Mercury	97.8	97.8	97.8	91.1	96.8
Test No. 2						*Test No. 5*					
Arsenic	73.1	54.1	75.9	79.3	84.0	Arsenic	70.0	70.0	75.0	84.7	85.9
Barium	52.3	32.5	52.5	42.3	50.0	Barium	50.8	50.6	52.1	54.9	55.5
Cadmium	87.6	78.0	89.2	85.7	86.5	Cadmium	80.0	76.4	80.0	80.0	80.0
Chromium	97.0	96.6	99.1	83.7	86.1	Chromium	99.1	99.1	96.7	85.6	82.0
Lead	97.9	96.7	97.6	97.5	97.5	Lead	97.5	97.2	97.0	96.7	97.7
Mercury	96.3	08.7	80.0	37.5	67.1	Mercury	99.1	96.4	97.9	96.1	98.9
Test No. 3						*Test No. 6*					
Arsenic	80.4	82.2	89.7	88.1	91.3	Arsenic	73.3	79.3	88.7	89.2	89.3
Barium	40.4	57.4	57.5	56.7	37.2	Barium	54.2	46.5	45.4	46.7	50.2
Cadmium	87.1	85.8	90.0	97.1	89.6	Cadmium	83.1	84.5	89.6	95.4	97.9
Chromium	99.2	91.8	81.6	80.0	72.1	Chromium	99.1	99.0	80.8	77.0	75.2
Lead	96.7	97.4	97.8	97.3	96.6	Lead	97.5	96.7	96.5	95.9	96.9
Mercury	94.4	60.7	88.7	83.6	93.8	Mercury	98.7	85.2	74.4	69.5	96.0

Table 6b
TCLP recovery of metals tests 7–12 (percent retained)

	Feed	2 ft	3.5 ft	5 ft	Ash		Feed	2 ft	3/5 ft	5 ft	Ash
Test No. 7						*Test No. 10*					
Arsenic	80.0	73.6	83.5	85.0	85.8	Arsenic	75.7	72.5	70.5	71.3	74.3
Barium	64.1	50.0	60.5	59.2	58.6	Barium	60.2	56.8	52.4	55.6	56.8
Cadmium	91.0	86.5	93.8	92.0	90.9	Cadmium	88.3	84.8	87.0	86.6	85.0
Chromium	99.0	96.9	96.5	89.1	91.6	Chromium	99.0	99.1	99.1	99.1	96.8
Lead	97.6	97.1	97.8	97.8	97.9	Lead	97.6	97.4	97.7	97.7	97.7
Mercury	99.2	95.7	73.4	79.6	80.9	Mercury	93.7	91.1	89.9	91.6	86.1
Test No 8						*Test No. 11*					
Arsenic	63.1	76.4	72.1	81.2	84.8	Arsenic	63.3	68.5	71.9	70.0	67.0
Barium	42.3	53.2	42.5	48.3	51.9	Barium	50.2	51.6	52.1	48.0	46.0
Cadmium	75.6	84.5	81.5	87.3	87.6	Cadmium	86.7	88.7	89.8	90.1	88.9
Chromium	99.1	99.2	96.6	87.7	82.3	Chromium	99.0	99.1	99.1	99.0	98.9
Lead	96.9	97.7	97.1	97.6	96.6	Lead	97.5	97.9	96.0	97.7	97.6
Mercury	99.1	91.5	82.9	37.5	66.9	Mercury	94.3	80.0	95.0	93.3	91.5
Test No. 9						*Test No. 12*					
Arsenic	83.9	80.9	75.5	85.2	84.5	Arsenic	73.8	40.0	71.8	65.7	63.6
Barium	45.1	55.3	35.2	52.6	45.5	Barium	76.1	61.0	55.9	55.8	55.2
Cadmium	85.0	89.7	78.7	86.0	80.0	Cadmium	96.2	97.6	91.8	81.7	90.0
Chromium	96.9	97.5	96.8	87.5	80.9	Chromium	96.8	99.0	96.1	92.7	85.2
Lead	98.0	96.2	97.3	97.7	97.3	Lead	97.5	97.1	97.7	97.9	97.4
Mercury	95.9	97.0	92.5	45.5	70.4	Mercury	99.1	96.3	73.5	75.3	95.1

7.2. TCLP concentrations

In addition to the metals mass balance concern and their retention in the bottom ash, the mobility of the metals partitioned to the bottom ash was also thought to be an issue. The data summarized in Table 6 shows the TCLP results for all of the metals in Tests 1–12. This table shows the actual metals concentration (mg/kg) for the different sites sampled along the kiln's axis. Based on that number and the TCLP methodology, a maximum TCLP concentration was calculated and compared with the analyzed TCLP concentration. The percentage number in Table 6 is the amount of TCLP metal retained by the matrix. A sample calculation is provided below:

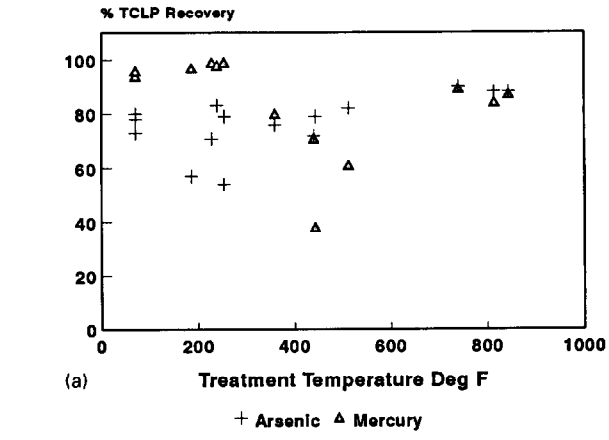
	Feed concentration (mg/kg)	Maximum TCLP (mg/l)	Actual TCLP (mg/l)	% TCLP retained
Arsenic	24	1.2	0.26	78.3
Barium	185	9.25	4.0	56.7
Cadmium	7.8	0.39	0.04	89.7
Chromium	50	2.5	0.025	99.0
Lead	33	1.65	0.052	96.8
Mercury	6.3	0.32	0.014	95.6

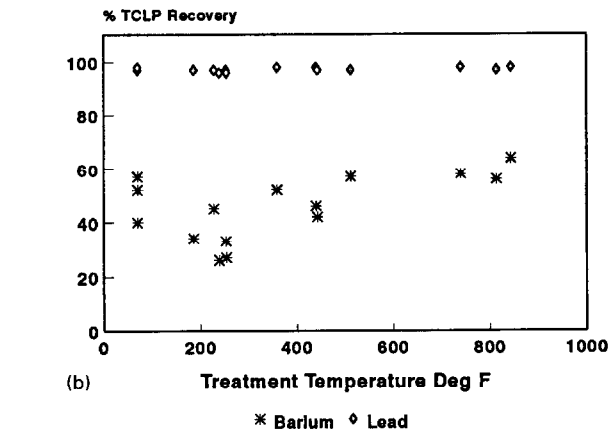
A retention number of 100% indicates that the metals were immobile. As the percentage retained decreases, the mobility and potential threat to the environment increase. In a manner similar to the illustration in Fig. 2, the data for all of the succeeding TCLP comparisons will be an illustration of the effect by ion pairs.

8. Treatment temperature

Fig. 3 illustrates the TCLP data taken for Tests 1–3 in which temperature was a variable for the 10% moisture soil, while Fig. 4 shows the TCLP data taken for the temperature tests on the 20% moisture matrix (Tests 4–6). They are both presented as a percentage of the maximum TCLP metal recovery (resistance to leaching) possible. As the treatment temperature increases, the percentage of metals retained by the soil matrix increased for arsenic, barium and cadmium, remained the same for chromium and lead and decreased for mercury. This effect is more obvious in Fig. 3, but still observable in the higher moisture soil in Fig. 4. Mercury appears to be more TCLP mobile as the treatment temperature increases. If landfill or re-interment is the ultimate disposition of the soil, low-temperature thermal desorption may be an acceptable treatment due to the fact that the leachability of arsenic, barium and cadmium were less after treatment above 600 °F and chromium and lead were not affected. If mercury is present, low-temperature treatment could promote mercury's mobility making it a less attractive treatment.

Therefore, treatment temperature even at low temperatures is an important kiln variable from the metals perspective as well as the organics. Higher treatment





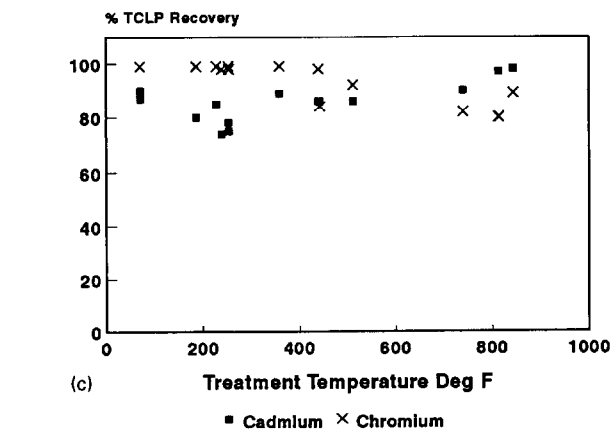
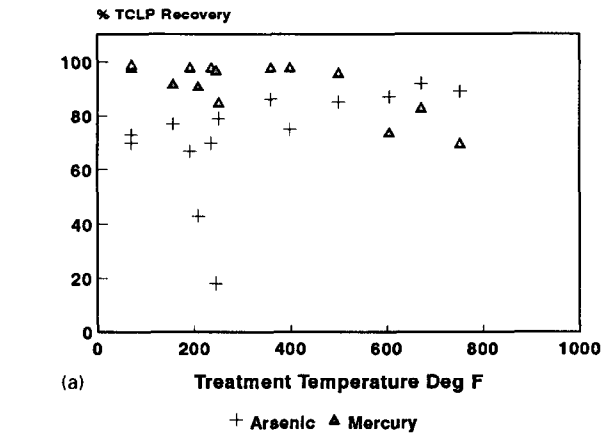
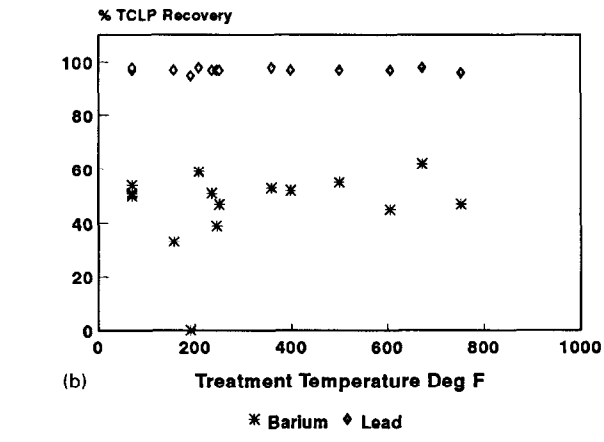


Fig. 3. Temperature effect on metals TCLP.





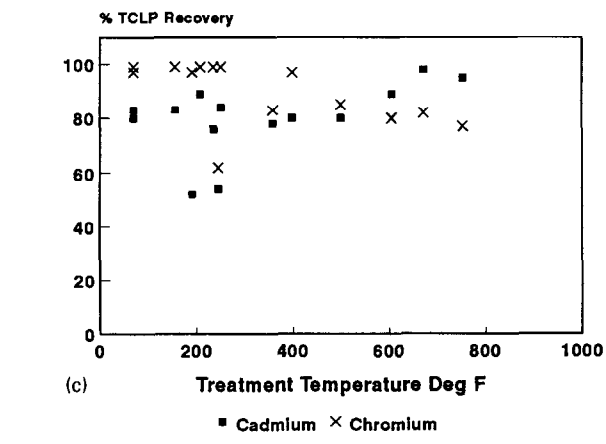


Fig. 4. Treatment temperature effect on TCLP.

temperatures favor less mobile TCLP metals, but also tend to push the metals out of the matrix into the gas stream. A treatment temperature of about 400 °F appears to minimize metal carryover, and metal residue TCLP mobility.

9. Treatment time

The length of time that a waste is treated at equilibrium desorption temperatures is important from the organics standpoint and could be an important TCLP consideration as well. The data in Table 5 show this effect. Fig. 5 illustrates the TCLP behavior of the test metals at low treatment temperatures.

As the soil treatment temperature rose to about 800 °F, the overall TCLP behavior of the metals changed slightly. Arsenic's behavior was reversed and a longer treatment time at the higher temperature seemed to dramatically improve the ability of the soil matrix to retain that metal. Mercury was not totally distilled off but its TCLP behavior was a little more erratic staying around the 80% retention level. Lead, cadmium and chromium showed very little metal mobility and were not significantly influenced by treatment time. Barium was still mobile at elevated treatment temperatures although a slight positive correlation can be seen with treatment time. Fig. 6 illustrates the behavior of the test metals at higher treatment temperatures.

10. Treatment volume

The rate at which waste material is fed to a thermal treatment system could influence all of the operating parameters, and make the difference between economic success or failure of a desorption project. Table 2 shows the target and actual feedrates for all of the parametric tests and in Table 3 the feed rates were converted into kiln volume occupied. Fig. 7 is a summary of the % TCLP recovery found for the different feed rates (kiln volumes). In all cases studied, there was no statistical correlation between % TCLP recovered (mobility of metals) and feedrate up to a kiln volume of 12%.

11. Moisture content

The moisture content of the soil matrix is important from several kiln operational perspectives, but was it related to the metals' mobility after treatment? The TCLP data presented in Table 6 was compared to the moisture content in the soil matrix for Tests 1–6 and this comparison is shown in Fig. 8. The data in Fig. 8 were not statistically significant for a linear and second-degree least squares fit for cadmium, chromium, lead or mercury. There was a slight positive correlation for both arsenic and barium.

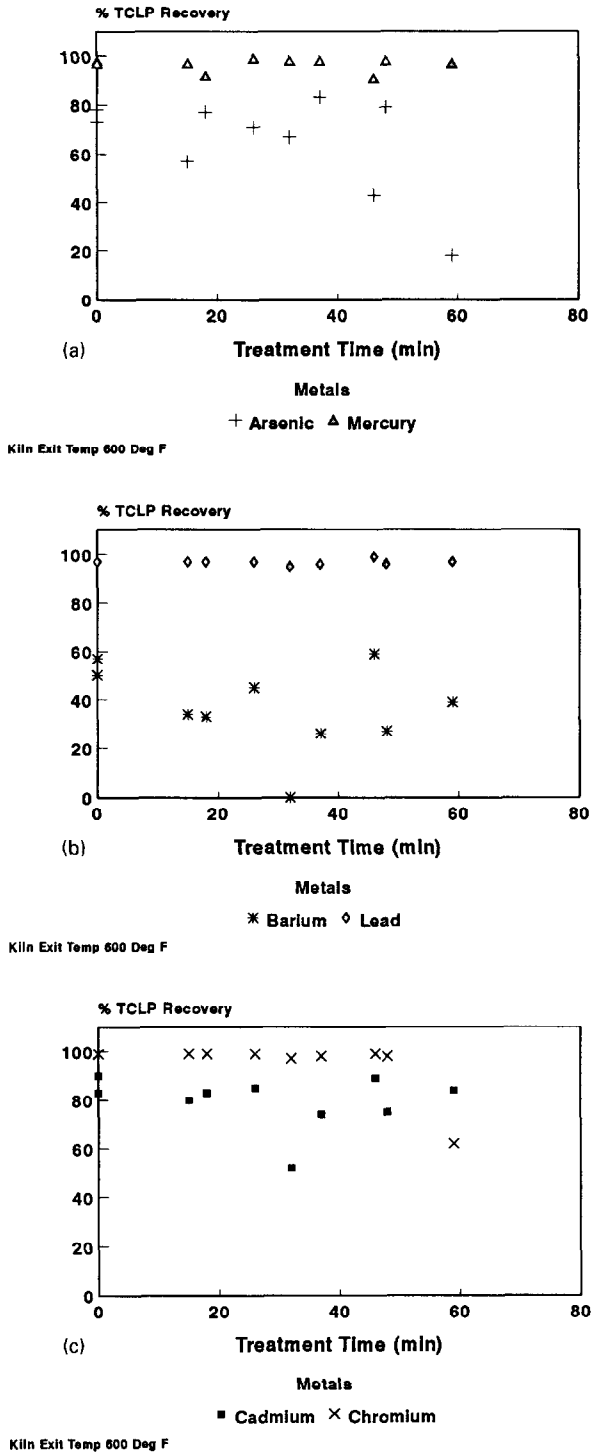


Fig. 5. Treatment time effect on TCLP.

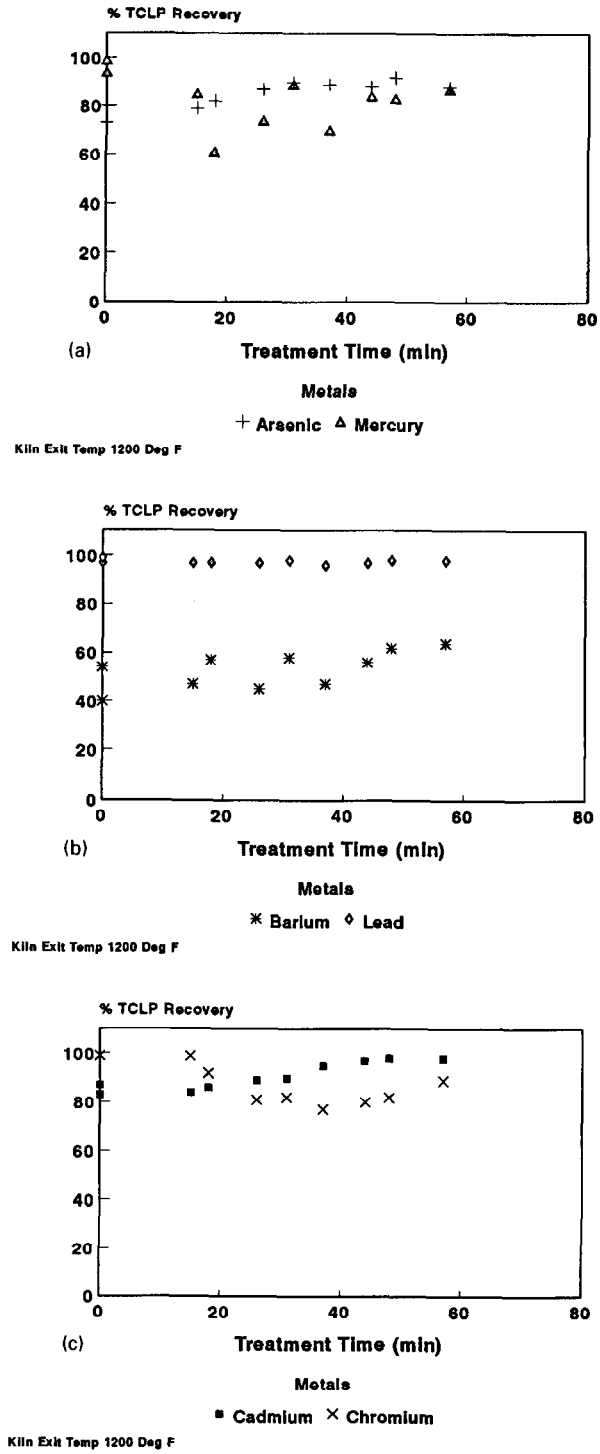
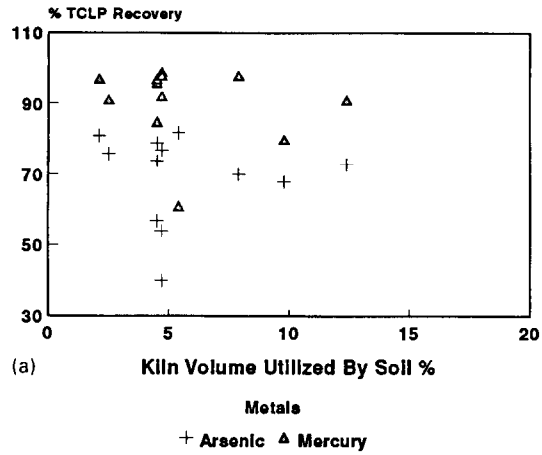
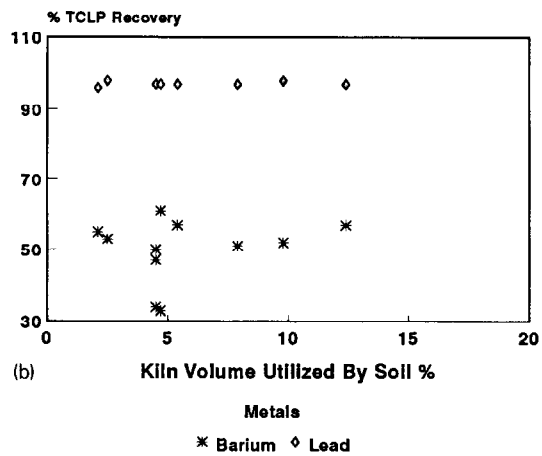


Fig. 6. Treatment time effect on TCLP.





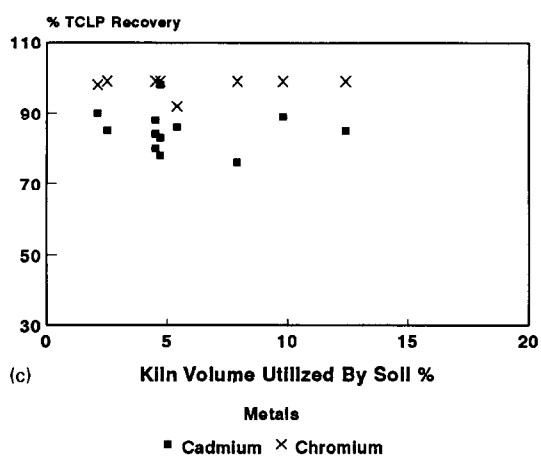
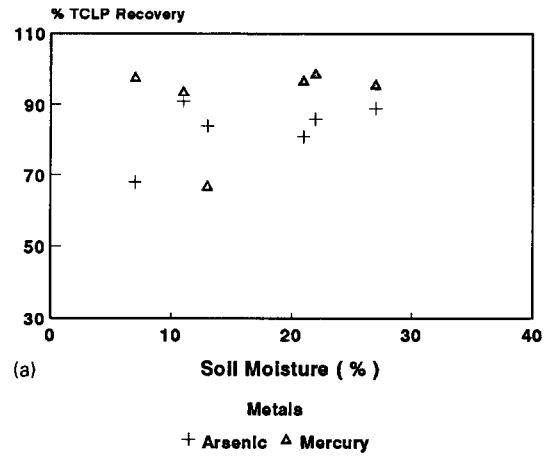
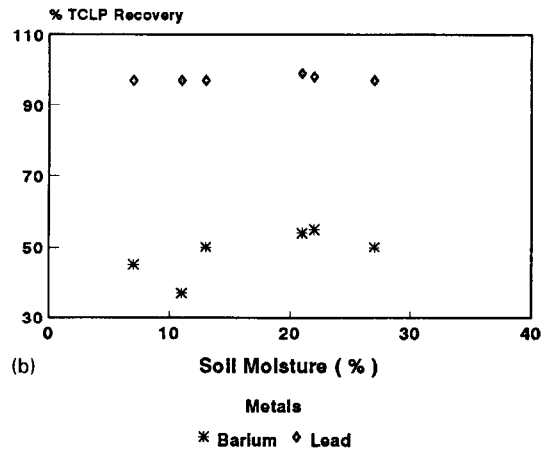


Fig. 7. Kiln volume effect on TCLP.





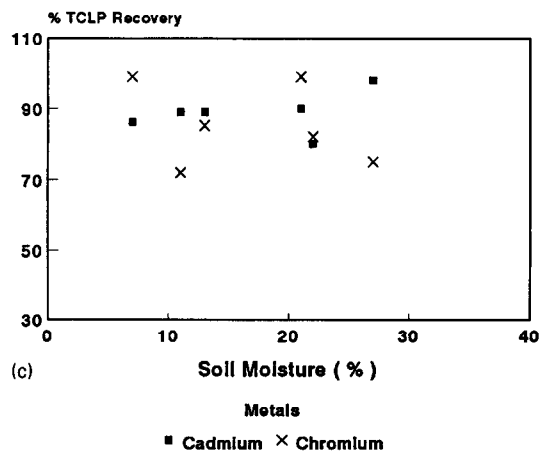


Fig. 8. Soil moisture relationship with TCLP.

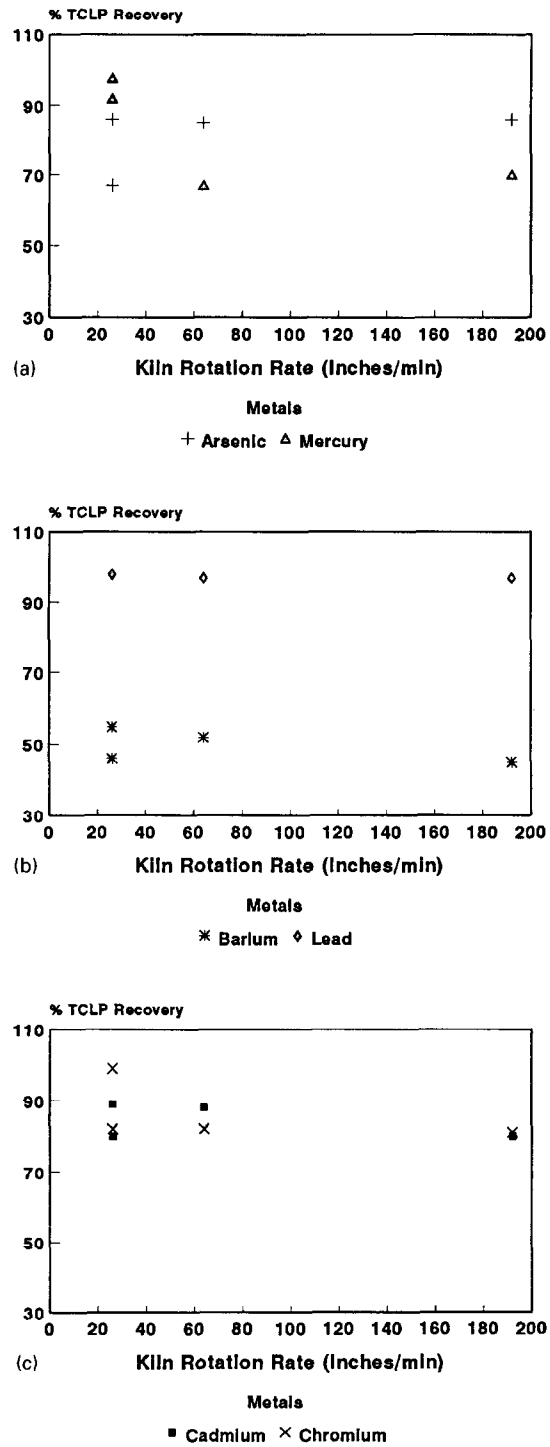


Fig. 9. Kiln agitation relationship with TCLP.

12. Degree of solids agitation

The degree to which the contamination in the soil is exposed to the treatment conditions in the desorber should impact the overall efficiency of the remediation effort. The agitation of the soil matrix may also play a role in the final physical/chemical condition of the metals in the matrix. The speed at which the kiln was rotated was a variable in Tests 5, 8, 9 and 11 with the TCLP recoverability for the metals was compared to the rotational velocity of the kiln. Fig. 9 shows the TCLP recovered when all of the treatment conditions were held constant except the kiln rotation speed. The data indicate that, with the possible exception of mercury, the degree of agitation produced by the speed of the rotating kiln was not a factor in the mobility of the treated metals as measured by TCLP.

13. Discussions and conclusion

Low-temperature thermal treatment of toxic and/or hazardous waste appears to be one of the better strategies available for reducing the potential negative environmental impacts associated with the high temperature incineration of co-contaminated waste. The hazardous organic fraction can be distilled off while leaving the toxic metals behind in the ash. The condition and stability of the residual metals is a major environmental concern since they probably will be interred onsite or at a controlled landfill. Metals mobility as defined by the TCLP technique and the published regulatory trigger concentrations are a way of evaluating the treatment effectiveness of low-temperature thermal desorption. Operating parameters consisting of treatment temperature, treatment time, soils bed depth, moisture content and agitation were compared with the observed TCLP retention efficiency and rated with 100% recovery being judged immobile. Treatment temperature had the most dramatic effect on the metal species. Higher treatment temperatures drove the metals out of the soil matrix, but also reduced the leachability of retained metal species. Mercury, however, was made more mobile by thermal treatment. All of the other kiln variables (treatment time, kiln volume, moisture content and agitation) were essentially independent of resulting TCLP values.

The concept of TCLP retention efficiency was used in the evaluation of the operating parameters so that all of the test parameters and the test metals were compared on an equivalent basis, without regard to varying concentration ranges, or initial sample size.

The biggest unknown in a study like this is the chemical reactions taking place in the soil between the mineral content and the metals. The degree to which a metal is held by the soil is related to how it is able to interact with the substrate (physically or chemically). The data for arsenic is a good example. At low treatment temperatures, the arsenic was fairly mobile, but at elevated temperatures it was relatively immobile. The reason for the change most likely lies within the matrix of the soil, and until an expanded study can be performed defining the relationships and reactions, it will remain a matter for conjecture.

Using the empirical data collected in this set of experiments, one can say that from a TCLP standpoint, treatment temperature is the most important low-temperature desorption variable. This variable can be optimized with treatment time, moisture content and feedrate to produce another soil treatment application for direct-fired rotary kiln incinerators. The TCLP associated with the residual samples may be a good overall evaluation technique, and it may help in showing the performance of rotary kiln systems as low-temperature soil desorbers.

References

[1] The Toxicity Characteristic Leaching Procedure (TCLP), Federal Register, 51 (1986).
[2] P. Esposito and R. Thurnau et al., JAPCA, 39 (1989).
[3] Guide for Conducting Treatability Studies under CERCLA: Thermal Desorption, EPA/540/R 92/0748.
[4] W. Troxler et al., JAWMA, 43 (1993).
[5] R. Thurnau and J. Manning, JAWMA, 46 (1996) 12.