



Superfund Engineering Issue

Considerations for Evaluating the Impact of Metals Partitioning During the Incineration of Contaminated Soils From Superfund Sites

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Introduction

The shortage of landfill space, EPA's land ban restrictions, and the demonstrated effectiveness of incineration are making incineration a preferred treatment for large volumes of contaminated soils. Because of the limited capacity in suitable RCRA incinerators, the advantage of using transportable incinerators on a "campaign basis," and its effectiveness, on-site thermal treatment of Superfund soils is being chosen frequently as the method of remediation in the Superfund Record of Decisions (RODs).

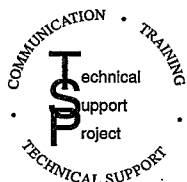
When Superfund soils containing metals are incinerated, the metals vaporize, react to form other metal species, or remain with the soil residuals. The vaporized metals can un-

dergo reactions to form other species or condense to form fine particulates and/or fumes. Some metals oxidize to form new species with lower oxidation states or react with other elements such as chlorine and sulfur. The new species will either volatilize or fall out as ash. The majority of metals will simply remain as ash or be entrained in the form of fly ash.

Metals in ash, scrubber sludge, and/or stack emissions, if improperly managed, can result in potential exposures and the resultant adverse health effects. Metals that remain with the ash have the potential to leach when disposed of in improper landfills [6]. Scrubber sludge must be stabilized before being landfilled if it exhibits leachability characteristics. Metal particles, vapors, and fumes can become environmental and health concerns when released from a stack. Table 1 shows metals of interest in stack emissions. The metals under the first column are metals for which EPA guidance on emissions has been issued [10]. The second column includes additional metal constituents that are listed in Appendix VIII of 40 CFR Part 261 [14]. Metals can also react with other elements in the feed stream, such as chlorine or sulfur, forming more volatile and toxic compounds than the original species [6].

Conducting treatability studies is an important step in the selection of treatment alternatives for the remediation of Superfund sites as well as other hazardous waste sites. By gaining valuable information on the feasibility and cost of treatment options, such as off-site or on-site incineration, the risk of failure at full-scale implementation due to the selection of an inappropriate technology can be minimized. Bench- and pilot-scale treatability testing, as well as limited full-scale testing, can provide valuable information in evaluating remedial alternatives [11].

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Table 1. Metals of Interest [4]

RCRA Guidance	Other RCRA Constituents
Antimony (Sb)	Osmium (Os)
Arsenic (As)	Nickel (Ni)
Barium (Ba)	Vanadium (V)
Beryllium (Be)	Selenium (Se)
Cadmium (Cd)	
Chromium (Cr)	
Lead (Pb)	
Mercury (Hg)	
Silver (Ag)	
Thallium (Tl)	

This paper provides guidance for Remedial Project Managers (RPMs) and On-Scene Coordinators (OCSs) considering incineration of soils containing metals. Important considerations impacting metals partitioning are addressed. If a treatability study is necessary, certain steps must be taken to ensure the success of the test and to define the fate of the metals in discharge streams; these steps are also addressed.

This paper examines the available metal partitioning data for incineration of soils from treatability studies of three Superfund sites (Baird and McGuire, Florida Steel, and McColl) and from synthetic soil matrix studies conducted at the U.S. Environmental Protection Agency's Incineration Research Facility (IRF) in Jefferson, Arkansas. (This facility was formerly known as the Combustion Research Facility, or CRF.) The rotary kiln incinerator at the IRF was used for the Baird and McGuire treatability study. A pilot-scale treatability study was conducted at the Ogden Environmental Services research facility using a circulating bed combustor to incinerate soils from the McColl site. Soil from Florida Steel was incinerated as part of a Toxic Substances Control Act PCB destruction demonstration at the site using an infrared incineration unit.

Overview

Incineration has been shown to be effective in treating soils, sediments, sludges, and liquids containing primarily organic contaminants. Organic contaminants are destroyed by subjecting them to temperatures typically greater than 800° C in the presence of oxygen, which causes the volatilization and combustion of these compounds. For any soils incineration system, the efficiency of the combustion process depends upon the following: the temperature the contaminated soil is subjected to, the time the soil is subjected to that temperature, and the degree to which the contaminants are exposed to oxygen during combustion through the mixing process.

Incineration systems are composed of several integrated unit operations. A generic flow diagram showing these operations is presented in Figure 1. A typical incineration system consists of a primary combustion chamber (PCC) such as a kiln

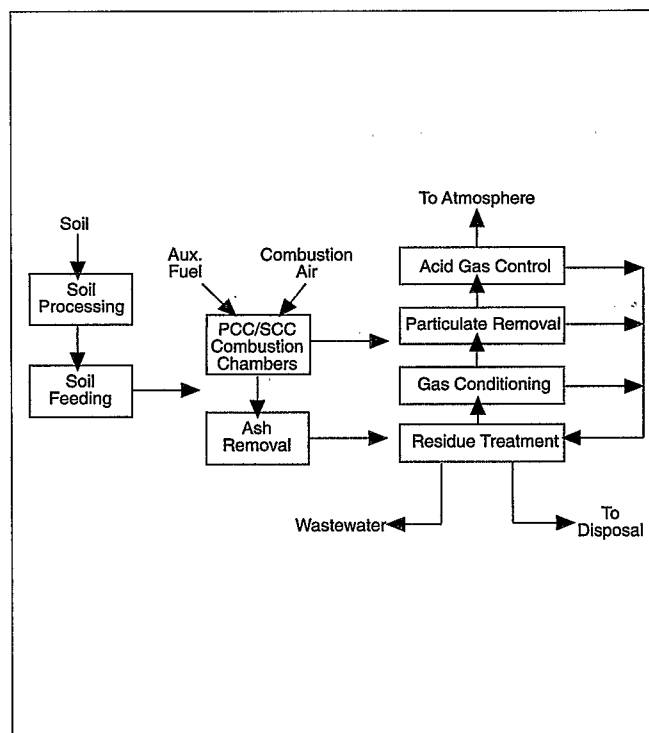


Figure 1. Incineration System Concept Flow Diagram [9]

or furnace, a secondary combustion chamber (SCC) or afterburner, and air pollution control devices (APCDs). The APCDs often consist of a venturi scrubber and/or packed tower scrubber for particulate and acid gas removal. The scrubbers may be followed by an electrostatic precipitator or fabric filter for additional particulate collection. Many other APCDs or APCD trains are also available.

The general combustion chamber operating conditions favorable to the destruction of contaminated soils are well established and are presented in Table 2. Oxygen (in the form of air) is supplied to the combustion chamber in excess of what is stoichiometrically required to compensate for incomplete mixing. There are several different types of incineration systems based on the design of the primary combustion chamber. The most common of these is the rotary kiln incinerator. Other types of incineration systems include fluidized bed, infrared, and liquid injection. Liquid injection incinerators will not be reviewed herein, since Superfund soils are not amenable to treatment by such systems.

Table 2. General Combustion Chamber Conditions Favorable to the Destruction of Contaminated Soils [9]

Combustion chamber temperature level:	800°C - 1500°C (1472°F - 2700°F)
Residence time:	Several minutes to 1/2 hour for solids/sludges
Excess combustion air:	60 - 130% of stoichiometric requirements

A rotary kiln incinerator is a long, inclined cylinder that rotates on its longitudinal axis. This rotating cylinder provides agitation to ensure that all of the soil is exposed to the oxygen present and to improve heat transfer. The contaminated soil and auxiliary fuels are usually introduced to the kiln at the high end and are transferred to the low end by gravity. Ash residue is collected at the low end of the kiln. Exhaust gases typically pass to a SCC or afterburner for further oxidation. Rotary kilns are used primarily for the treatment of solids; but liquids, sludges, and gases can be co-incinerated with solids [9].

Fluidized bed incinerators use high air velocity to suspend a bed of inert granular material. The bed is preheated by an auxiliary burner, and fuel and contaminated soil are introduced into the bed. Air passing through the bed causes turbulence which facilitates intimate mixing of the air, heated bed material, fuel, and contaminated soil. A modification of this technology, called circulating fluidized bed incineration, operates at higher velocities and with finer bed particles than fluidized bed combustors. The bed materials, including the contaminated soil, are passed through a combustion loop consisting of the combustion chamber and a second chamber (cyclone) where the flue gas is separated from the solid particles. A major portion of the solid particles separated in the second chamber is reinjected into the first chamber. Circulating fluidized beds do not require a SCC or afterburner. The technology is applicable for liquids and sludges and may be used for solids with small particle sizes [9].

Infrared radiation may also be used as a heat source for thermal destruction of contaminated soils. Contaminated soils are fed into the combustion chamber on a woven wire conveyor belt. Electrical resistance heating elements are used to generate thermal radiation within the chamber. Solids are carried through the chamber on the belt until reaching the

discharge end of the chamber where ash drops off into a hopper. Exhaust gases pass through a secondary combustion chamber. This technology is intended for treatment of solids, stabilized sludges, and contaminated soils. As with the fluidized bed incinerators, feed preparation must include specific sizing of the material to maintain a consistent layer on the belt [9].

Metals Behavior

A significant amount of research has been conducted on the incineration of contaminated materials. Although historically the primary focus has been on the destruction of organics, increased emphasis is being placed in the fate of metals. Unlike the organic portion, the metal fraction may change form but is not destroyed. Metals can remain with the ash when discharged from the primary combustion chamber [6]. They can also volatilize or oxidize to form fumes or fine particulates and pass through the incineration system [6][13]. Metal vapors, fumes, or particles can be collected by the APCDs, exit out the stack, or be deposited along the walls of the combustion chamber and remain in the incineration system [6][13]. Potential pathways for metals are illustrated in Figure 2. This distribution of metals into the various incinerator system components is called "partitioning." A number of factors affect how various metals will partition, or behave, during incineration.

Metals Partitioning

Partitioning is highly dependent on the volatility of the metal [2][6][13]. The temperature of volatilization of a metal can be predicted using basic laws of physical chemistry and the concentration of the metal in the waste stream. Volatility temperature is defined as the temperature at which the effective vapor pressure of the metal is 1×10^{-6} atm. At this vapor

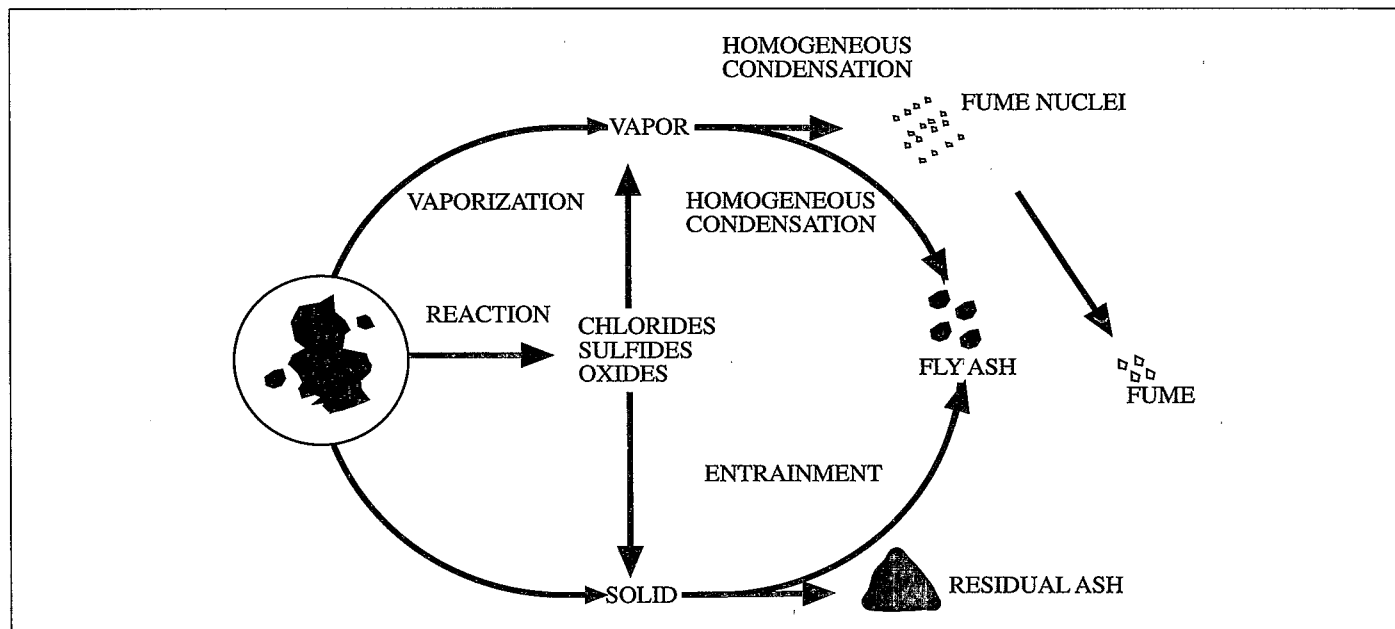


Figure 2. Metals Behavior in Combustion Devices [4]

Table 3. Predicted Metals Volatility Temperatures [4]

Metal	With 0% Chlorine		With 10% Chlorine	
	Volatility Temperature (°C)	Principal Species	Volatility Temperature (°C)	Principal Species
Chromium	1613	CrO ₂ /CrO ₃	1610	CrO ₂ /CrO ₃
Nickel	1210	Ni(OH) ₂	693	NiCl ₂
Beryllium	1054	Be(OH) ₂	1054	Be(OH) ₂
Silver	904	Ag	627	AgCl
Barium	849	Ba(OH) ₂	904	BaCl ₂
Thallium	721	Tl ₂ O ₃	138	TlOH
Antimony	660	Sb ₂ O ₃	660	Sb ₂ O ₃
Lead	627	PbO ₂	-15	PbCl ₄
Selenium	318	SeO ₂	318	SeO ₂
Cadmium	214	Cd	214	Cd
Osmium	41	OsO ₄	41	OsO ₄
Arsenic	32	As ₂ O ₃	32	As ₂ O ₃
Mercury	14	Hg	14	Hg

pressure, a measurable amount of vaporization is likely to occur [1]. Although total metal concentrations are typically determined, the specific form of the metal in the waste stream is generally not measured. Determination of the "volatility" temperature of the metal compounds within a given soil would require significant analytical costs; therefore, it is generally not done. Table 3 lists predicted volatility temperatures for the metals (except vanadium) from Table 1 and their principal species with and without the presence of chlorine [4]. Table 3 data are based on a model rather than actual field measurements. Volatility temperatures range from 14°C to 1613°C without chlorine and -15°C to 1610°C with chlorine. Those metals exhibiting volatilization temperatures below about 900°C are commonly referred to as volatile metals, while those having higher volatilization temperatures are referred to as refractory metals. The volatile metals are more likely to pass through the combustion chambers as vapor, fume, or fine particulates. The refractory metals are more likely to remain in the PCC ash, although they can vaporize or be entrained with the flyash under certain operating conditions (e.g., high temperature, high flue gas flowrate, high turbulence).

Fundamental Parameters

Table 4 lists fundamental parameters that influence metals behavior. These include those associated with the matrix to be treated, the operation of the incinerator, the design of the combustion chamber, and the type of APCD used [4].

Matrix

The concentration and species of metal in the contaminated soil help determine the degree to which the metal will volatilize. The soil matrix, organic constituents, and halogen content also impact the volatilization of certain metals. As the metal feedrate is increased, more metal will vaporize until a saturation point is reached, at which additional metal is partitioned to the ash rather than vaporized. The particle size distribution and propensity to fragment affect the amount of metals that can become entrained and carried from the PCC as fly ash [3].

Table 4. Fundamental Parameters That Influence Metals Behavior [4]

<p>Matrix Parameters</p> <ul style="list-style-type: none"> Type and Concentration of Metals Particle Size Distribution of Metals Propensity to Fragment Presence or Concentration of Organometals Halogen Content <p>Operational Parameters</p> <ul style="list-style-type: none"> PCC Temperatures SCC Temperatures Stoichiometric Ratio of Oxygen to Contaminant in Combustion Zone 	<p>Combustion Chamber Design Parameters</p> <ul style="list-style-type: none"> Degree of Mixing Combustion Zone Velocity <p>Air Pollution Control Device Parameters</p> <ul style="list-style-type: none"> Parameters that Control Fine Particle Capture - Specific to Type of Device Temperature at APC
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One metal compound in the feed may behave differently than another compound of the same metal. Volatilization temperatures for each compound may be significantly different.

One of the most important parameters affecting metals behavior is halogen (e.g., chlorine) content. Since chlorinated metal compounds are generally more volatile, the greater the chlorine content the greater the degree of vaporization for certain metal species [2][6].

Increasing chlorine concentration gives the metal more opportunity to react and form chlorinated metal compounds. Tests at Florida Steel and at the IRF spanned significant variations in chlorine content of the waste stream. The tests with a high chlorine content showed an increase in metal volatility and a corresponding decrease in metal partitioning to the PCC ash. In addition to having a significant effect on the partitioning of metals, halogen content can also affect the efficiency of APCD's. These studies are discussed below.

Florida Steel—

In 1982, it was discovered that the soil of Florida Steel Corporation's metal-recycling plant at Indiantown, Florida, was contaminated with PCBs and metals, including cadmium and lead. In 1987, a Toxic Substance Control Act (TSCA) PCB-destruction demonstration was performed by OH Materials Corporation (OHM) using its 100 ton per hour transportable infrared unit. Table 5 summarizes the soil characteristics of the site. One of the objectives of the trial burn was to determine the impacts, if any, that chlorine has on the amounts of cad-

mium and lead that are volatilized. The test conditions for the demonstration are shown in Table 6. The chlorine content ranged from below 0.19 to 0.79 percent. PCC exhaust temperature was varied slightly while feedrate and retention time were kept relatively constant [7].

Metals emissions data for the furnace ash, scrubber water, and stack are given in Table 7. The normalized data for both metals are shown in Table 8 (in order to compare relative distributions, mass fractions were normalized to the total amount of metal measured in the output. Normalization of mass fractions results in mass balance closure of 100%, thereby eliminating significant test-to-test data variability). Based upon the results obtained in Table 8, cadmium and lead became slightly more volatile (mass fraction in PCC ash decreased) as the chlorine content rose. Cadmium seemed to be affected more by chlorine content than lead. (Note that volatility temperature predictions suggested a strong impact of chlorine on lead behavior and no impact on cadmium. A plausible explanation for this is that the metal species associated with the tests differed from those in Table 3.) The proportion of mass fraction of scrubber solids to mass fraction of stack particulate also decreased for both metals as the chlorine content increased [7].

Synthetic Materials Tests at IRF—

In 1989, a research project investigating the fate of trace metals in rotary kiln incineration with venturi- and packed tower-scrubber particulate control was conducted at the EPA's IRF in Jefferson, Arkansas. This testing was conducted in part to support the development of a metal partitioning model and to

Table 5. Florida Steel Soil Characteristics [7]

Test Run No.	1	2	3	4	5
Test Date	9/28/87	9/29/87	10/3/87	10/4/87	10/5/87
Ash, wt % ^a	87	87	87	87	87
Chlorine, wt %	<0.19	<0.26	0.79	0.68	0.71
Metals (ppm):					
Cadmium	8.3	9.9	7.4	11.3	7.9
Lead	375	459	332	434	352

^a Based on vendor information during phone conversation of October 1, 1990.

Table 6. Florida Steel Operating Conditions [7]

Test Run No.	1	2	3	4	5
Test Date	9/28/87	9/29/87	10/3/87	10/4/87	10/5/87
Soil Feedrate (kg/hr)	5203	5289	5351	5360	5508
PCC Temperature (° C) ^a	731	802	843	714	783
PCC Solids Residence Time (Min.)	22	25	23	23	23
SCC Temperature (° C)	1148	1111	1073	1057	1132
SCC Excess O ₂ (%)	6.9	7.0	7.0	6.9	6.0
SCC Gas Residence Time (Sec.)	5.58	5.77	5.18	5.45	5.35

^a Primary exhaust temperature.

Table 7. Florida Steel-Effluent Metal Concentrations [7]

Test Run No.	1	2	3	4	5
Furnace Ash, ppm^a					
Cadmium	10.9	9.0	6.0	7.2	7.0
Lead	772	489	494	447	510
Scrubber Water, mg/L					
Cadmium	1.57	2.12	0.97	1.18	0.892
Lead	7.96	7.73	9.73	11.9	9.92
Stack mg/m³					
Cadmium	0.517	2.38	0.89	5.74	1.34
Lead	13.5	1.07	10.7	1.34	11.7

^a Increase in concentration over feed material partially accounted for by weight loss during incineration.

Table 8. Normalized Mass Fraction of Metals for Florida Steel [7]

Test Run No.	1	2	3	4	5
Test Date	9/28/87	9/29/87	10/3/87	10/4/87	10/5/87
Cadmium					
PCC Ash ^a	83	75	61	69	65
Scrubber Solids ^a	7	9	4	6	4
Stack Particulate	10	16	35	25	31
Total^b	100	100	100	100	100
Lead					
PCC Ash ^a	99	97	93	94	94
Scrubber Solids ^a	0	1	1	1	1
Stack Particulate	1	2	6	5	5
Total^b	100	100	100	100	100

^a Used vendor estimate of 87% for ash content and 10 gpm for makeup water flow. Accumulation within system assumed to be negligible.

^b Normalized to 100% of emissions as basis.

evaluate the predictive capability of the model. The feed material consisted of a synthetic soil matrix made by adsorbing aqueous mixtures of trace metals onto a clay material [2].

Feed concentrations of various metals during the tests are summarized in Table 9. All tests were conducted at the same nominal exit flue gas oxygen content (12 percent), afterburner exit flue gas oxygen content (7.5 percent), synthetic soil feedrate (63 kg/hr), and kiln rotational speed. The normalized metal discharge distributions (percent of total measured) for the synthetic material tests are presented in Table 10 [2].

As chlorine content increased from 0 percent to 8.3 percent, the mass fraction of metals in the PCC ash (kiln ash) decreased for the lead and bismuth. Cadmium was not detected in the kiln ash from any of the tests. These three metals were considered to be the most volatile metals. One of the refractory metals, copper, showed an increase in volatility as the chlorine content increased. The other refractory metals showed

Table 9. Nominal Feed Metal Concentrations for IRF Tests^a [2]

Metal	Concentration (ppm)
Arsenic	50
Barium	50
Bismuth (Bi)	180
Cadmium	10
Chromium	90
Copper (Cu)	500
Lead	50
Magnesium (Mg)	17,000
Strontium (Sr)	300

^a Based on average clay matrix metals concentrations of Bi (12 ppm); Cr (53 ppm); Mg (2.2 percent); Sr (34 ppm).

no significant changes in volatility with increasing levels of chlorine in the feed. Apparent scrubber efficiencies for lead, cadmium, bismuth, and copper decreased as the chlorine content increased [2].

Operational

The operating conditions of any incinerator affect metals behavior. An important variable affecting metal volatilization is PCC temperature. The lower the PCC temperature, the less likely it is that the metal will volatilize. Although increasing combustion air in the PCC increases vaporization, the impact of this variable is small compared to bed temperature and chlorine content of the feed stream [6]. Other potential im-

pacts on partitioning and scrubber efficiency include SCC temperature and the stoichiometric ratio of air to feed in the combustion chamber. The feed rate and percent excess oxygen determine the stoichiometry in the combustion chamber. While no test data were reviewed that specifically studied the effect of changes in the feed rate, it can be expected that excessive feed rates would result in higher mass flowrates entering the APCD. Assuming APCD efficiency remains relatively constant, increases in metal feedrates can be expected to cause increases in stack emissions.

The temperature in the PCC has an effect on the partitioning of some metals. Generally, as the PCC temperature increases, the amount of metals that partition into PCC ash will decrease. Treatability studies in which PCC temperature effects

Table 10. Normalized Metal Discharge Distributions for IRF Tests [2]
(% of Total Measured)

Test Number:	1	4	8	7
Primary Variable: Feed Chlorine Content (wt %)				
Test Average:	0	3.8	4.6	8.3
Target Temperatures: PCC = 871°C; SCC = 1093°C				
Arsenic				
Kiln Ash	93.9	86.1	92.3	92.4
Scrub. Ex. Gas	1.7-2.2	3.8-5.8	2.3-4.1	4.0-4.8
Scrub. Water	3.9	8.2	3.6	2.7
Barium				
Kiln Ash	68.8	79.6	69.9	78.6
Scrub. Ex. Gas	2.0	2.2	5.5	2.4
Scrub. Water	28.8	18.2	24.7	19.0
Bismuth				
Kiln Ash	64.8	22.2	30.0	36.3
Scrub. Ex. Gas	15.7	41.1	35.2	38.4
Scrub. Water	19.5	36.7	34.7	25.4
Cadmium				
Kiln Ash	<29.3	<10.3	<12.9	<9.3
Scrub. Ex. Gas	42-54	56-61	42-45	68-74
Scrub. Water	29-46	34-39	45-55	68-74
Chromium				
Kiln Ash	95.7	94.1	85.9	92.1
Scrub. Ex. Gas	1.4	2.0	1.9	2.8
Scrub. Water	2.8	3.9	12.2	5.1
Copper				
Kiln Ash	97.6	75.8	76.2	58.0
Scrub. Ex. Gas	0.8	15.1	17.8	33.2
Scrub. Water	1.6	9.1	5.9	8.8
Lead				
Kiln Ash	83.7	15.0	13.7	6.0
Scrub. Ex. Gas	11.6	48.9	50.2	73.6
Scrub. Water	4.7	36.1	36.0	20.3
Magnesium				
Kiln Ash	99.6	99.3	99.3	99.4
Scrub. Ex. Gas	0.03	0.1	0.2	0.1
Scrub. Water	0.36	0.6	0.5	0.5
Strontium				
Kiln Ash	91.8	93.0	89.8	90.7
Scrub. Ex. Gas	2.5	1.7	3.5	1.6
Scrub. Water	5.7	5.3	6.6	7.7

were evaluated include studies of soil from the Baird and McGuire Superfund site and studies of a synthetic soil material.

Baird & McGuire—

Once a chemical manufacturing plant, the Baird and McGuire site was placed on the National Priorities List (NPL) by EPA Region I as a Superfund site. Pilot-scale incineration tests were conducted during late September through early October 1989 in the rotary kiln incineration system at EPA's IRF [5].

The primary contaminants of concern in the soil and sediments at the site were volatile organic compounds, polynuclear aromatic hydrocarbons, dioxins, pesticides, lead, and arsenic. For the IRF testing, soil was excavated and mixed at the site, then packaged in 55-gallon drums. One drum was used in each of the first four runs. The fifth run was a composite of soil from the four drums. The characterization of the feed soil for each day of testing is listed in Table 11. Table 11 shows arsenic levels in the feed soil ranged from 81 ppm to 93 ppm while lead levels were from 16 ppm to 27 ppm. One objective of this series of tests was to evaluate the effects of incinerator operating conditions on lead and arsenic distributions in the waste streams. Table 12 lists the operating conditions for the five tests conducted [5].

The normalized mass fractions of metals at Baird and McGuire are shown in Table 13. For the high PCC temperature tests (runs 3 through 5) the mass fractions of lead and arsenic in the PCC ash were significantly reduced [5].

During runs 3 and 4 at Baird and McGuire the percent oxygen was varied. The change in PCC percent oxygen from 10.4 to 7.5 percent has no significant effect on lead, but arsenic mass fractions in the kiln ash increased from 36 to 56 percent [5].

Synthetic Materials Tests at IRF—

During the same research project at the IRF mentioned earlier, tests runs were conducted to investigate the effect of PCC (kiln) temperature on the fate of metals. Data on these tests are presented in Tables 9 and 14 [2].

Minor effects due to variations in PCC temperature were observed for arsenic and lead.¹ For these two metals, the kiln ash distributions decreased slightly as the PCC temperature increased. PCC temperature effects on the other metals were not significant [2].

Table 11. Baird & McGuire Soil Characteristics [5]

Test Run No.	1	2	3	4	5
Test Date	9/26/89	9/29/89	9/27/89	9/28/89	10/5/89
Ash, wt %	83	83	83	84	a
Chlorine	<0.19	<0.28	<0.23	<0.18	a
Metals (ppm):					
Arsenic	82	83	93	81	84
Lead	21	16	27	17	20

^a Soil feed for Test 5 consisted of soils from the other 4 tests.

Table 12. Baird & McGuire Operating Conditions [5]

Test Run No.	1	2	3	4	5
Test Date	9/26/89	9/29/89	9/27/89	9/28/89	10/5/89
Soil Feedrate (kg/hr)	50	50	56	54	60
PCC Temperature (°C) ^a	832	844	994	994	839
PCC Excess O ₂ (%) ^b	11.3	6.8	10.4	7.5	11.2
PCC Solids Residence Time (Min.)	30 ^c	30 ^c	30 ^c	30 ^c	30 ^c
SCC Temperature (°C) ^a	1,094	1,089	1,105	1,099	1,083
SCC Excess O ₂ (%) ^b	7.9	6.3	7.4	7.3	8.1
SCC Gas Residence Time (Sec.)	1.8	2.7	2.0	1.9	2.0

^a Average exit temperature.

^b Average exit O₂, dry basis.

^c Approximate.

¹Cadmium not detected in ash; difficult to determine effect of PCC or SCC temperature.

Table 13. Normalized Mass Fractions of Metals for Baird & McGuire [5]

Test Run No.	1	2	3	4	5
Test Date	9/26/89	9/29/89	9/27/89	9/28/89	10/5/89
Arsenic					
PCC Ash	72	76	36	56	66
Scrubber Solids	23	22	55	38	29
Stack ^a	5	2	9	6	5
Total	100	100	100	100	100
Lead					
PCC Ash	89	93	69	69	91
Scrubber Solids	4	3	12	13	3
Stack ^a	7	4	19	18	6
Total	100	100	100	100	100

^a Method measured particulate and vapor-phase metals at stack.

The SCC (afterburner) temperature was also varied during the IRF tests. An effect of SCC temperature on partitioning was not measurable [2].

Combustion Chamber Design

The design of the combustion chamber can affect the partitioning and APCD efficiency. While such parameters as PCC or SCC temperature can be controlled with any type of incinerator, different types of combustion chambers have inherently different mixing capabilities and gas flowrates. Turbulent mixing and high air velocities can lead to entrainment of particles to the APCD rather than the kiln ash.

Mixing is generally greatest in fluidized beds or rotary kilns and least in infrared incinerators. Air velocities are greatest in fluidized beds and least in rotary kilns and infrared incinerators. An example of how the incinerator's design possibly affected the partitioning of metals is the McColl Superfund Site treatability study.

McColl—

The EPA selected contaminated materials from the McColl Superfund Site in Fullerton, California, as feed for a treatability study of circulating bed combustor (CBC) technology. The McColl soil treated had high sulfur content and elevated levels of barium, chromium, and nickel. EPA selected several drums that were representative of the soil to be used for the treatability tests. Soil from McColl was sent to the Ogden research facility in San Diego, California. The incineration system consists of a CBC that uses high-velocity air to entrain solids in a turbulent combustion zone. Soil characteristics, operating conditions, and the normalized mass fractions for the McColl treatability study are given in Tables 15 through 17. It can be seen from Table 17 that most of the metals partitioned to the flyash. Since these metals are predicted to be refractory, it can be speculated that the partitioning was not due to volatilization. The design of the CBC allows the metals to pass through the chamber as discrete particles rather than metal fumes. Because of their fine size, the metal particulates are not captured in the cyclone, but are transferred to the APCD [8].

Table 14. Normalized Metal Discharge Distributions for IRF Tests [2]

(% of Total Measured)

Test Number:	2	4	8	3	6	4	8	5
<i>Primary Variable:</i>	<u>PCC Exit Temperature (°C)</u>				<u>SCC Temperature (°C)</u>			
Test Average:	825	875	876	927	984	1088	1093	1196
<i>Targets:</i>	<u>SCC = 1093°C; Cl = 4%</u>				<u>PCC = 871°C; Cl = 4%</u>			
Arsenic								
Kiln Ash	94.4	86.1	92.3	84.0	93.6	86.1	92.3	91.2
Scrub. Ex. Gas	2.1-2.9	3.8-5.8	2.3-4.1	6.8-8.4	2.6-3.8	3.8-5.8	2.3-4.1	3.0-4.3
Scrub. Water	2.7	8.2	3.6	7.6	2.6	8.2	3.6	4.6
Barium								
Kiln Ash	74.3	79.6	69.9	69.9	85.2	79.6	69.9	86.9
Scrub. Ex. Gas	3.8	2.2	5.5	1.6	2.2	2.2	5.5	1.6
Scrub. Water	21.9	18.2	24.7	28.8	12.5	18.2	24.7	11.5
Bismuth								
Kiln Ash	25.8	22.2	30.0	22.9	20.9	22.2	30.0	30.1
Scrub. Ex. Gas	41.5	41.1	35.2	50.7	47.4	41.4	35.2	37.1
Scrub. Water	32.6	36.7	34.7	26.3	31.6	36.7	34.7	32.8
Cadmium								
Kiln Ash	<15.2	<10.3	<12.9	<10.7	<13.9	<10.3	<12.9	<14.5
Scrub. Ex. Gas	43-49	56-61	42-45	62-69	61-69	56-61	42-45	55-62
Scrub. Water	42-51	34-39	45-55	27-31	25-31	34-39	45-55	31-38
Chromium								
Kiln Ash	94.7	94.1	82.9	95.3	95.5	94.1	85.9	89.3
Scrub. Ex. Gas	3.0	2.0	1.9	2.1	1.1	2.0	1.9	4.2
Scrub. Water	2.3	3.9	12.2	2.6	3.4	3.9	12.2	6.6
Copper								
Kiln Ash	84.2	75.8	76.2	82.3	79.2	75.8	76.2	75.1
Scrub. Ex. Gas	12.9	15.1	17.8	14.1	15.2	15.1	17.8	16.0
Scrub. Water	3.0	9.1	5.9	3.6	5.6	9.1	5.9	8.9
Lead								
Kiln Ash	12.6	15.0	13.7	10.4	5.8	15.0	13.7	13.8
Scrub. Ex. Gas	50.4	48.9	50.2	67.2	60.6	48.9	50.2	45.0
Scrub. Water	37.0	36.1	36.0	22.4	33.6	36.1	36.0	41.1
Magnesium								
Kiln Ash	99.4	99.3	99.3	99.5	99.3	99.3	99.3	99.2
Scrub. Ex. Gas	0.2	0.1	0.2	0.1	0.1	0.1	0.2	0.1
Scrub. Water	0.4	0.6	0.5	0.4	0.6	0.6	0.5	0.7
Strontium								
Kiln Ash	82.9	93.0	89.3	90.1	94.3	93.0	89.8	81.9
Scrub. Ex. Gas	1.1	1.7	3.5	1.6	1.3	1.7	3.5	3.7
Scrub. Water	16.0	5.3	6.6	8.3	4.4	5.3	6.6	14.4

Table 15. McColl Treatability Study Soil Characteristics [8]

Test Run No.	1	2	3
Test Date	3/29/89	3/30/89	3/30/89
Ash, wt %	75.8	71.1	70.9
Chlorine, wt %	ND	0.02	0.08
Heating Value, BTU/lb	986	1430	1344
Metals (ppm)			
Barium	65	126	136
Beryllium	0.21	ND	0.7
Chromium	45	61	65
Nickel	15	17	19
Silver	ND	1.1	ND

ND - Not detected above the quantitation limit.

Air Pollution Control Devices

The type of APCD, or train of devices, that must be employed for incineration of a contaminated soil will depend on the type of incinerator and the characteristics of the soil incinerated or produced during incineration. Incinerators designed to treat soils with a high ash or toxic metals content will generally be equipped with an APC train consisting of two to four APCDs. A number of typical APC trains are as follows:

- Quench/wet scrubber
- Quench/spray dryer/cyclone/electrostatic precipitator
- Quench/spray dryer/cyclone/fabric filter
- Quench/wet scrubber/ionizing wet scrubber/mist eliminator
- Quench/wet electrostatic precipitator/venturi scrubber/packed scrubbers
- Fabric filter/wet scrubber.

Table 16. McColl Treatability Study Operating Conditions [8]

Test Run No.	1	2	3
Test Date	3/29/89	3/30/89	3/30/89
Soil Feedrate (kg/hr)	147.9 ^d	77.5	91.1
PCC Temperature (° C) ^a	938	941	932
PCC Excess O ₂ (%) ^b	11.0	9.9	11.8
PCC Solids Residence Time of Soil (Min.)	30 ^c	30 ^c	30 ^c
Chlorides in feed (ppm of feed)	ND	170	780

^a Mid PCC temperature.

^b Exit O₂, dry basis, measured downstream of the flue gas cooler.

^c Approximate values.

^d Includes 74 kg/hr of sand.

Table 17. Normalized Mass Fraction of Metals for McColl Treatability Study [8]

Test Run No.	1	2	3
Test Date	3/29/89	3/30/89	3/30/89
Barium			
PCC Ash	16	6	3
Fly Ash	84	92	97
Stack Particulate	0	3	0
Total^a	100	100	100
Chromium			
PCC Ash	15	3	4
Fly Ash	85	95	95
Stack Particulate	0	2	1
Total^a	100	100	100
Nickel			
PCC Ash	28	5	ND
Fly Ash	72	90	96
Stack Particulate	0	5	4
Total^a	100	100	100

ND - Not detected at levels greater than quantitation limit.

^a Normalized to 100% of emissions accounted for by analysis.

Operational and design variables that can impact the performance of APCDs include temperature, pressure drop, liquor flow rate, and number of ionizing stages. Most toxic metals, or their compounds, condense as solids if incinerator combustion gases are cooled. Because of this, a quench chamber is commonly used to cool incineration flue gas by the evaporation of water injected into the hot gas stream. The efficiency of venturi scrubbers, especially on submicron particles, increases as the gas stream pressure drop across the unit increases [10]. Lowering the liquid mass flow rate will negatively impact scrubber efficiency due to a corresponding decrease in the diffusional driving force. Multi-stage ionizing units are usually necessary for high efficiency removal of small particles. Up to four stages in series have been used in industry [10].

In addition, APCDs will have different efficiencies depending on the specific metals being treated and on the amount of chlorine present. In Table 18, various APCDs are given conservatively estimated efficiencies for particulates and toxic metals. It should be stressed that these estimates are intentionally biased low and that higher efficiencies than those shown in the table are achievable [10].

Material Balance Closure Issues

Complete mass balance closure for metals in combustion systems is rarely achieved. The limitations to closure include metals accumulation within the incineration system, difficulty in obtaining representative samples of heterogeneous streams, and potential limitations of analytical methods.

Steps can be taken to maximize the closure. The sampling methods used to determine metals concentrations from a particular inlet or outlet stream should be appropriate. For determination of multiple metals emissions in exhaust gases, it is recommended that EPA draft Method 0012 be used [12]. All metal-containing streams entering or exiting the incinerator should be analyzed for the metals of concern, using totals expressed as elemental metal. Care should be taken to obtain representative samples. Implementation of operational and/or design changes to minimize accumulation of feed or waste residual within the incineration system would also be beneficial.

Table 18. Air Pollution Control Devices (APCDs) and Their Conservatively Estimated Efficiencies for Controlling Toxic Metals [10]

APCD	Pollutant				
	Ba, Be	Ag	Cr	As, Sb, Cd, Pb, Tl	Hg
WS*	50	50	50	40	30
VS-20*	90	90	90	20	20
VS-60*	98	98	98	40	40
ESP-1	95	95	95	80	0
ESP-2	97	97	97	85	0
ESP-4	99	99	99	90	0
WESP*	97	97	96	95	60
FF*	95	95	95	90	50
PS*	95	95	95	95	80
SD/FF;C/FF	99	99	99	95	90
DS/FF	98	98	98	98	50
FF/WS*	95	95	95	90	50
ESP-1/WS; ESP-1/PS	96	96	96	90	80
ESP-4/WS; ESP-4/PS	99	99	99	95	85
VS-20/WS*	97	97	97	96	80
WS/IWS**	95	95	95	95	85
WESP/VS-20/IWS*	99	99	98	97	90
C/DS/ESP/FF;C/DS/ESP/FF	99	99	99	99	98
SD/C/ESP-A	99	99	98	95	85

* It is assumed that flue gases have been pre-cooled in a quench. If gases are not cooled adequately, mercury recoveries will diminish, as will cadmium and arsenic to a lesser extent.

** An IWS is nearly always used with an upstream quench and packed horizontal scrubber.

C = Cyclone

WS = Wet Scrubber including:
Sieve Tray Tower
Packed Tower
Bubble Cap Tower

PS = Proprietary Wet Scrubber Design
(A number of proprietary wet scrubbers have come on the market in recent years that are highly efficient on both particulates and corrosive gases. Two such units are offered by Calvert Environmental Equipment Co. and by Hydro-Sonic Systems, Inc.)

VS-20 = Venturi Scrubber, ca. 20-30 in W.G. Δp

VS-60 = Venturi Scrubber, ca. > 60 in. W.G. Δp

ESP-1 = Electrostatic Precipitator; 1 stage

ESP-2 = Electrostatic Precipitator; 2 stages

ESP-4 = Electrostatic Precipitator; 4 stages

IWS = Ionizing Wet Scrubber

DS = Dry Scrubber

FF = Fabric Filter (Baghouse)

SD = Spray Dryer (Wet/Dry Scrubber)

Conclusion

Contamination of Superfund site soils is rarely limited to one particular compound. Oftentimes, selection of remedial options must take into consideration a variety of both organic and inorganic contaminants. The effectiveness of incineration for the treatment of hazardous organic compounds has been well demonstrated; consistently high destruction and removal efficiencies for such compounds can be expected. In contrast, the fate of metals subjected to incineration is less certain.

In recent years, a considerable amount of research has been conducted in an attempt to better understand the behavior of metals during incineration. Theoretical predictions have been complemented by laboratory and pilot-scale studies of both real-world and synthetic contaminated soils. Current information suggests that estimation of metal behavior should not be over-simplified. It is dependent on a number of factors that should be considered on a case-by-case basis, among them: matrix parameters (e.g., type, concentration of metals); operational parameters (e.g., temperature, oxygen); design parameters (e.g., mixing, combustion zone velocity); and air pollution control device parameters (e.g., type, temperature).

Since incineration residuals (e.g., ash, scrubber water) are collected, they may be further treated following incineration in order to minimize adverse impacts of remaining metals. In contrast, stack emissions of metals, which are not collected, represent a potential risk element and should therefore be evaluated prior to undertaking remedial action. Risk assessments for metal emissions may be performed by examining estimated metal emission rates, site-specific dispersion factors, and health effects data.

As a result of soil-specific/site-specific factors, similar metal feedrates for two sites may yield very different metal emission rates. While conservative theoretical assumptions may be made, treatability studies are suggested as a means by which to develop a more accurate expectation of metal partitioning associated with a specific contaminated soil. It should also be noted that similar metal emission rates for two sites may yield very different risk estimates as a result of differences in terrain complexity, stack height, meteorology, and other factors; site-specific dispersion modeling is suggested in cases where the potential for significant metal emissions exists.

In summary, incineration of metal-bearing wastes should be approached with caution from two perspectives. On the one hand, care should be taken to avoid overlooking potential risks associated with stack emissions. On the other hand, one should avoid rejecting incineration from consideration based on generalized concepts (e.g., "arsenic is volatile") that may not always prove true.

Technology Contacts

The following individuals can be contacted with technical questions concerning treatability studies to evaluate the impact of metals partitioning during incineration:

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The Incineration Research Facility in Jefferson, Arkansas, has been involved in three major metal partitioning studies as well as a number of Superfund treatability studies for the EPA Regions. For information on the availability of the IRF for both bench- and pilot-scale treatability studies, the following individual can be contacted:

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